

Identification and evaluation of phosphorus recovery technologies in an Irish context

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ENVIRONMENTAL PROTECTION AGENCY

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- Office of Evidence and Assessment
- Office of Radiological Protection
- Office of Communications and Corporate Services

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EPA Research Programme 2014–2020

**Identification and evaluation of phosphorus
recovery technologies in an Irish context**

(2014-W-DS-22)

EPA Research Report

Prepared for the Environmental Protection Agency

by

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ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The programme is financed by the Irish Government and administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

We would like to thank the members of the project steering committee for their helpful input: Noel Byrne (EPA), Dr Edmond O'Reilly (Irish Water), Dr Paul Butler (Enterprise Ireland) and Dr Dorothy Stewart (EPA). We would also like to thank Irish Water and wastewater treatment plant (WWTP) personnel for facilitating site visits and Dr Jean O'Dwyer, University of Limerick, for preparing GIS maps.

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014–2020
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-667-2

October 2016

Price: Free

Online version

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Executive Summary

Phosphorus (P) is essential for all life. Manufactured phosphorus fertilisers, produced from mined phosphate rock, are vital for food security. Of the approximately 22 million tonnes of phosphorus added to the world economy annually from mined fossil phosphate resources, approximately 80–90% is used as fertiliser in agriculture, 5–7% for animal feed additives and the remainder in various other applications. Phosphate rock is a limited non-renewable resource concentrated in a few countries and the supply is vulnerable to future scarcity, volatile pricing and geopolitical tensions. The economic importance and high supply risk of phosphate rock led to its inclusion in the European Union list of Critical Raw Materials in 2014. Phosphorus cannot be produced synthetically and has no substitute in food production. Owing to the dependence of food security on phosphorus availability and its potential to contribute to eutrophication in the receiving environment, there is a global need to promote more efficient use of phosphorus, as well as its recovery and reuse. Phosphorus recycling is supported by the Circular Economy Package published by the European Commission in 2015, which proposes measures to contribute to closing the loop of product lifecycles through increased recycling and reuse, with benefits for the environment and the economy. Almost all of the 3 million tonnes of phosphorus consumed in food per year by the global population enters the wastewater sector. It has been estimated that in 2009 the phosphorus available from urine and faeces could account for 22% of the total global phosphorus demand. Municipal wastewaters, therefore, represent a major point source from which to recover phosphorus and re-establish a circular economy. This project focused on identifying and evaluating current and developing phosphorus recovery technologies and assessing their viability in an Irish context.

A database of municipal wastewater treatment plants was generated containing details (where available) of phosphorus influent and effluent levels, capacity in terms of population equivalent value and any phosphorus treatment currently undertaken. Phosphorus removal, where undertaken, is mainly by chemical dosing with biological phosphorus removal, limited to a small number of wastewater treatment plants. The main outlet for wastewater sludge is agriculture, and

incineration of sludge is currently not undertaken in Ireland.

Phosphorus recovery technologies were identified that can be applied in the wastewater treatment process to recover phosphorus from the liquid phase, sewage sludge or mono-incinerated sewage sludge ash. The recovery approaches are based on crystallisation and precipitation and on wet chemical and thermochemical technologies. Wet chemical and thermochemical processes offer a higher phosphorus recovery potential (up to approximately 90% of wastewater treatment plants' influent) than approaches based on precipitation of phosphorus from sludge liquor (approximately 30% to 40%) but are more complex, have higher costs and are not as far advanced in their technical development as other technologies. Outputs from the project include a table of phosphorus recovery technologies summarising the details of 28 phosphorus recovery technologies identified in terms of the phosphorus source targeted, the phosphorus product produced, percentage phosphorus recovery, operational scale, technology readiness level, details of the supplying/developing company, and patent information, where relevant. Important considerations in identifying the most appropriate technology for implementation include quantity and phosphorus concentration of the waste stream, energy and chemical requirements, capital and operational costs, risk of "technological lock-in" and compatibility with the existing wastewater treatment plant infrastructure. The choice of suitable phosphorus recovery technologies, in an Irish context, is currently limited by the lack of enhanced biological phosphorus removal and mono-incineration within the Irish wastewater infrastructure, which are a prerequisite for several of the technologies identified.

The project also examined the potential market for recycled phosphorus products. Phosphorus recovered from municipal waste may be used directly as a fertiliser, processed further to produce fertiliser or used as a raw material substitute for mined phosphate rock. The recovered phosphorus must match the needs and requirements of potential users. Challenges identified for the market entry of recovered phosphorus include quality, price and regulatory barriers. At present, the

potential market for recovered phosphorus in Ireland is limited and implementation of phosphorus recovery will require co-ordination with relevant players, such as the fertiliser industry, and/or development of a niche market for recovered phosphate as struvite, a slow-release

fertiliser. Large-scale implementation of phosphorus recovery is likely to require international strategies and policy support, as well as clarification and harmonisation of existing legislation in relation to phosphorus recycling.

1 Introduction

We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation – but for phosphorus there is neither substitute nor replacement.

Isaac Asimov (1959), *Life's Bottleneck*.

to rising global population levels, increasing demands for high-quality food and the large increase in demand for biofuels from plants. Phosphorus exists naturally as phosphate rock at the surface of the Earth's crust and is finite and non-renewable. Phosphorus cannot be produced synthetically and has no substitute in food production (Science Communication Unit, 2013).

1.1 Overview of Phosphorus

Phosphorus (P) is a non-metal element of the nitrogen group; it is the eleventh most abundant element in the Earth's crust and is essential for all forms of life on our planet Earth. In 1840, Justus von Liebig, the German chemist, identified phosphorus as the main limiting factor for the growth of plants (von Liebig, 1840). Phosphorus, along with nitrogen and potassium, is one of the main macronutrients that are the foundation of inorganic fertilisers. The discovery of these three macronutrients and the practical means of adding these to soils helped launch the "green revolution". In recent years, there has been a big increase in the demand for fertiliser due

1.2 The Phosphorus Cycle

Phosphorus passes through a few cycles [both inorganic and organic (land and water)], which are connected to each other (Figure 1.1). The inorganic cycle consists of the erosion of phosphorus-containing rock and soils, the transportation of this eroded phosphorus to the oceans, sedimentation (creation of phosphorus-containing rock), tectonic activity and modification of phosphate-containing rock into a form of phosphate in the soil that is available to plants (Filippelli, 2002). The inorganic phosphorus cycle can take tens of millions of years and phosphate in

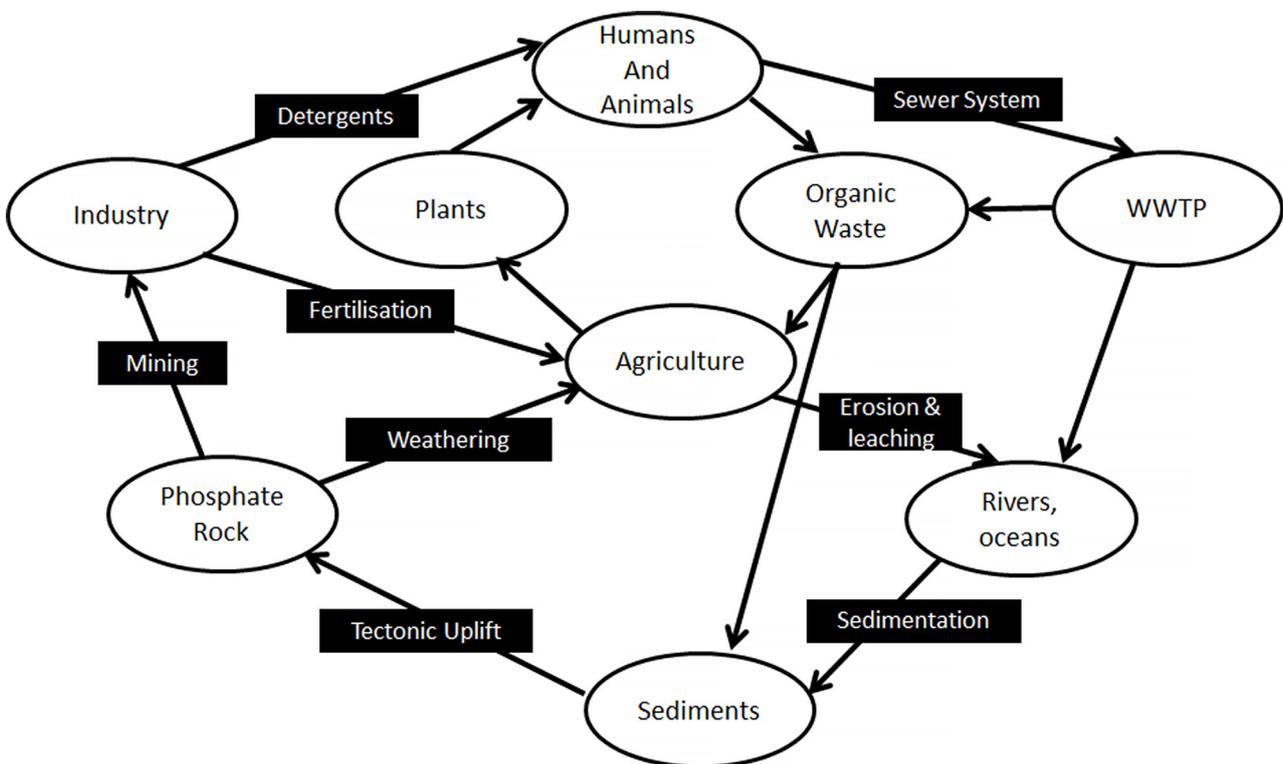


Figure 1.1. The phosphorus cycle (inorganic and land-based) including human impacts (adapted from Cornel and Schaum, 2009).

this cycle is considered to be “lost” for agrarian use. Alongside the inorganic phosphorus cycle, there are two organic cycles, one for land and another for water. Phosphorus passage through these cycles can take from a few weeks up to a year (Bennett and Carpenter, 2002). These closed “natural” cycles are broken when phosphorus contained in animal and human wastes is not applied to the land. Currently, the phosphate in wastewater is transported to the oceans, partly from wastewater treatment, or is locked in sewage sludge, which, if not land spread, is lost to the cycle. Only 50% of phosphorus consumed by animals worldwide is reported to be returned as waste to the land used to grow their feed. Instead of organic routes, the soil is replenished with phosphorus by the application of mineral fertiliser. Furthermore, the quantity of phosphate rock currently being mined to produce fertiliser is greater than the amount that can be replaced by the slow geological cycle (Science Communication Unit, 2013). On a timescale applicable by humans, phosphorus principally goes only one way through global food systems, from mined phosphate rock into the oceans by means of agriculture, at rates of over three times the natural flow, with losses at nearly every stage (Bennett *et al.*, 2001). Phosphorus is also a pollutant, and loss of phosphorus to water is an environmental concern

due its potential contribution to eutrophication, reduced water quality and effects on biodiversity (Withers *et al.*, 2015a). Removal of phosphorus from wastewater and phosphorus discharge limits are therefore necessary.

In a description of the major flows of phosphorus through the global food system (Figure 1.2), Cordell and White (2014) reported that the approximate quantity of phosphorus mined in phosphate rock per year amounts to $21 \pm 4 \text{ Mt/a P}$ (million tonnes of phosphorus per year), of which $18 \pm 3.5 \text{ Mt/a P}$ is used for fertiliser production and $3 \pm 0.6 \text{ Mt/a P}$ for industrial applications. Losses of 15–30% have been reported during mining and processing, and stockpiled phosphogypsum from fertiliser production accounts for $1.5 \pm 0.5 \text{ Mt/a P}$.

Quantities of phosphorus amounting to $16.5 \pm 3 \text{ Mt/a}$ are applied as fertiliser in agriculture. The amount taken up by plants from the soil equates to 11 Mt/a , while soil accumulation accounts for 12 Mt/a . Wind and water erosion removes $5 \pm 3 \text{ Mt/a}$ from soil to water or non-agricultural land. Phosphorus is introduced into the livestock sector via crops and supplements and the estimated content in manure is $16 \pm 1 \text{ Mt/a}$, of which approximately 50% is estimated to be reused on agricultural land while the remainder is lost to water or non-agricultural land. Approximately $9.5 \pm 2.5 \text{ Mt/a P}$ in

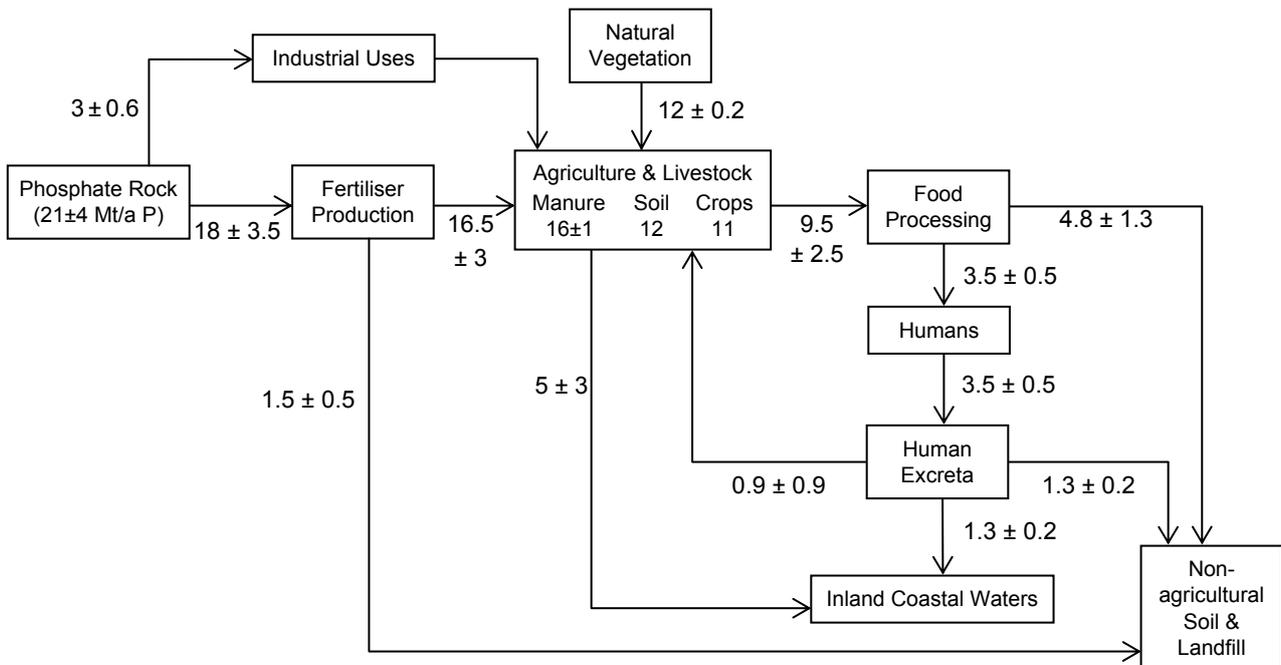


Figure 1.2. Major phosphorus flows in the global food system. Phosphorus expressed in units of million tonnes of phosphorus per year (Mt/a P) (adapted from Cordell and White, 2014).

crops and animal products is processed into food products, of which $3.5 \pm 0.5 \text{ Mt/a P}$ is consumed by humans, with the remaining $4.8 \pm 1.3 \text{ Mt/a P}$ mainly going to landfill/compost heaps in the form of, for example, inedible components or spoiled food. The phosphorus consumed by humans is excreted as urine and faeces (3.5 Mt/a P), some of which ($0.9 \pm 0.9 \text{ Mt/a P}$) is reused in agriculture. This data indicates that approximately 16% of the phosphorus mined from phosphate rock is consumed as food and excreted by humans and is subsequently available for recovery at wastewater treatment plants (WWTPs). Presently, depending on local discharge regulations, up to 90% of this phosphorus is removed in the form of sewage sludge (section 1.4.1), of which the amount returned to the land varies considerably (0–80% in Europe) (Withers *et al.*, 2015a).

1.3 Phosphate Rock

Society is currently dependent on phosphate rock to produce fertiliser and other phosphorus compounds. It is generally reported that approximately 80–90% of phosphate rock is used as fertiliser in agriculture, 5–7% for animal feed additives, 1–3% for food additives and the remainder in various industrial applications, for example detergents, cleaning agents, toothpastes, flame retardants, metal coatings, ceramics, leather, anti-freezing and anti-corrosion agents, medicines, paint ingredients and matches (Cordell and White, 2014; Heckenmuller *et al.*, 2014; Reijnders, 2014; Desmidt *et al.*, 2015). Phosphate rock is formed on the ocean floor in the form of calcium phosphate (hydroxyapatite and fluoroapatite) called phosphorite. This phosphorite is laid down in extensive layers that can cover thousands of square miles and lead to the formation of phosphate rock. After mining, phosphate rock is beneficiated to remove sand, clay, carbonates, organics, iron oxide and other materials (IPNI, 2010). The resulting phosphate rock is used to produce fertiliser and other products, mainly by conversion into phosphoric acid, as described in section 4.3. The mining and processing of phosphate rock has a negative impact on the environment in terms of land disturbance, air pollution, energy consumption and the generation of potentially radioactive phosphogypsum, which is generally stockpiled. Phosphate rock also contains cadmium and uranium, which, if not removed during processing, can contribute to soil pollution (Science Communication Unit, 2013).

Table 1.1. Global phosphate rock mined in 2013 and 2014 and current reserves (in 1000 tonnes) (USGS, 2015a).

Country	2013	2014 ^a	Reserves
Algeria	1500	1500	2,200,000
Australia	2600	2600	1,030,000
Brazil	6000	6750	270,000
Canada	400	–	76,000
China	108,000	100,000	3,700,000
Egypt	6500	6000	715,000
India	1270	2100	35,000
Iraq	250	250	430,000
Israel	35,000	3600	130,000
Jordan	54,000	60,000	1,300,000
Kazakhstan	1600	1600	260,000
Mexico	1760	1700	30,000
Morocco (Western Sahara)	26,400	30,000	50,000,000
Peru	2580	2600	820,000
Russia	10,000	10,000	1,300,000
Saudi Arabia	3000	3000	211,000
Senegal	800	700	50,000
South Africa	2300	2200	1,500,000
Syria	500	1000	1,800,000
Togo	1110	1200	300,000
Tunisia	3500	5000	100,000
United States	31,200	27,100	1,100,000
Vietnam	2370	2400	30,000
Rest of World	2580	2600	300,000
World Total	225,000	220,000	67,000,000

^aEstimated.

Currently, approximately 220 million tonnes of phosphate rock are mined worldwide every year (Table 1.1) (USGS, 2015a). The US Geological Survey states that the largest areas for phosphate rock mining were China, Morocco and the USA with the largest reserves of phosphate rock located in North Africa (Morocco), China, the Middle East and the USA (USGS, 2015a). In addition to land-based deposits, large amounts have been found in the continental shelves of both the Atlantic and Pacific Oceans. Extraction of these deposits (estimated at 6 trillion tons), however, is too expensive at current prices to justify the deep ocean mining that would be required. This may change as land-based phosphate rock deposits are depleted. Ocean-based deposits also come with potentially high environmental risks due to contamination with high levels of arsenic, cadmium, chromium, mercury, lead, uranium and vanadium (Smil, 2000).

Phosphate rock is geographically concentrated, with five countries (Morocco, China, Algeria, Syria and Jordan) controlling 85–90% of the world's remaining reserves. Furthermore, many sources of phosphate rock are in geopolitically sensitive regions. This is especially true in the case of the Moroccan reserves (the largest in the world), the majority of which are located in the disputed Western Sahara region. This makes other regions vulnerable to future phosphate scarcity, volatile pricing, monopolisation and geopolitical tensions (Science Communication Unit, 2013). With the exception of a small reserve in Finland, the EU is dependent on imported phosphorus. The economic importance and high supply risk of phosphate rock led to its inclusion in the EU list of Critical Raw Materials in 2014 (EC, 2014).

Nearly 70 years ago, M. King Hubbert (in 1949) demonstrated that oil production would, at some point in the future, reach a peak of production and then begin to decline. Production is inhibited by the effort in both energy and economic terms of extracting oil that is of lower quality and that is located in less accessible locations/reservoirs (Deffeyes, 2008). This critical point in time, referred to as “peak oil”, will occur before 100% of the resource is exhausted. “Peak phosphorus” is a highly similar concept that describes the time at which the maximum possible global phosphorus rock production rate is reached, the quality of the remaining reserves decreases (more contaminants, less phosphorus) and they become harder to access (moving from land-based deposits to ocean-based ones, for example). This would make it uneconomical to mine and process. This would result in a decline in supply, with a corresponding rise in price (Cordell *et al.*, 2009). Estimates for when peak phosphorus will be reached range from 2030 to 2350, with approximately 2100 being thought the most likely (Cordell *et al.*, 2011). Models also predict that, in most regions of the world, phosphate rock will be depleted (USA, Canada, etc.) leaving North African countries as the world's main suppliers (Van Vuuren *et al.*, 2010). The models used to calculate these dates are based on a wide variety of different factors, including past, current and projected phosphorus demand, levels and quality of phosphate rock reserves and various other assumptions, such as depletion of phosphorus in soil, efficiency of fertilisation methods and the deployment of phosphorus from other sources (manure, recovered phosphorus, etc.) (Cordell and White, 2014). Further details of the global phosphate rock market and costs are outlined in section 4.2.

1.4 Phosphorus in Wastewater Treatment

1.4.1 Removal of phosphorus

EU Directive 91/271/EEC (the Urban Waste Water Treatment Directive) defines the discharge limits for total phosphorus concentrations in WWTP effluent (EC, 1991). Where discharge is to sensitive waters, the following limits should be adhered to:

- 2 mg/L total phosphorus, where population equivalent (PE) 10,000–100,000;
- 1 mg/L total phosphorus, where PE > 100,000;

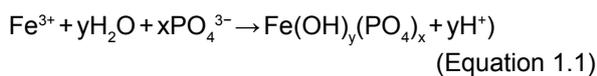
Environmental Protection Agency (EPA) discharge licence requirements may result in stricter phosphorus emission limits. The concentration of phosphorus (organic and inorganic) in municipal wastewater before treatment is generally 7–10 mg/L P (Hammer, 2008; Cornel and Schaum, 2009; Tarayre *et al.*, 2016), with an average of 8 mg/L reported for Germany (Petzet and Cornel, 2013). The phosphorus content of human excreta is 1.5–1.6 g P per person per day, of which approximately 67% is in the urine. Additional phosphorus comes from, for example, dishwasher tablets and industrial sources (Cornel and Schaum, 2009). During wastewater treatment, approximately 90% of the influent phosphorus load is transferred into the sewage sludge (Ewert *et al.*, 2014). At the primary treatment stage, approximately 11% of the incoming phosphorus is transferred to the primary sludge. Further phosphorus (approximately 20–30% of the incoming load) is incorporated into biomass during secondary treatment and removed with surplus activated sludge even in the absence of specific phosphorus removal processes (Desmidt *et al.*, 2015; Tarayre *et al.*, 2016). Petzet and Cornel (2013) report the removal of 48–74% of the phosphorus load without enhanced phosphorus removal due to biological and physical incorporation of phosphorus into the sludge. However, removal of additional phosphorus is necessary to satisfy the discharge limits outlined above and this is generally achieved by chemical or biological processes (sections 1.4.1.1 and 1.4.1.2, respectively) or a combination of both. Chemical phosphorus removal is used more widely (Tarayre *et al.*, 2016), with enhanced biological phosphorus removal (EBPR) used in approximately 30% of WWTPs in Europe (Science Communication Unit, 2013). Good separation of total solids from the effluent is necessary to achieve low concentrations of phosphorus in the

effluent, with membrane filtration required to achieve <0.1 mg/L (Petzet and Cornel, 2013).

1.4.1.1 Chemical phosphorus removal

The removal of phosphorus from wastewater by chemical precipitation is both simple and highly effective. The phosphorus present in the wastewater binds to coagulants (the “chemical”) containing polyvalent metal salts such as ferric (iron) chloride (FeCl₃), aluminium chloride (AlCl₃), aluminium sulphate [Al₂(SO₄)₃], or calcium hydroxide [Ca(OH)₂]. Some of the coagulant can be taken up in side reactions that are dependent upon the pH and the presence of trace elements. This means that the amount of chemical coagulant needed to remove phosphorus can only be estimated from molar ratios. The phosphorus removal processes may take place at three points within the overall wastewater treatment process: during primary wastewater treatment, contemporary with the secondary biological treatment (co-precipitation) or following secondary biological treatment (Figure 1.3). The most feasible step is usually following secondary treatment (Tchobanoglous *et al.*, 2003). Chemical dosing has been reported to result in an increase in sludge production of up to 25% (Irish Water, 2016).

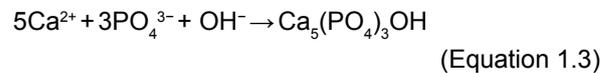
The most commonly used phosphorus removal chemical is ferric chloride (used in the majority of sites in Ireland that have chemical phosphorus treatment). However, iron in the ferric chloride also reacts with water to form ferric hydroxide:



The molar ratio of Fe:PO₄ for phosphorus removal is 1:1. Because of the formation of ferric hydroxide, however, an additional 10 mg/L iron is required (Peirce *et al.*, 1998). It is estimated that, in most cases, a dose in the range of 15–30 mg/L is needed for removal of 85–90% of influent phosphorus in municipal wastewater (Vesilind, 2003). The pH range 4.5–5 is optimal to carry out precipitation but phosphorus removal can still take place at greater than pH 7. Other commonly used chemical coagulants are aluminium compounds that have their minimum level of solubility between pH 5.5 and 6.5. The addition of aluminium sulphate to wastewater results in a lowering of the pH level, so it can be used in a pH-neutral area (Peirce *et al.*, 1998). The chemical equation for this reaction is:



Calcium is added to the water in the form of calcium hydroxide [Ca(OH)₂]. The quantities that are required to precipitate the phosphorus content of the wastewater depend upon the alkalinity of the wastewater. Following its addition, the calcium first reacts with any bicarbonate in the wastewater, creating calcium carbonate (CaCO₃). Only at higher pH levels (9–10) does the excess calcium react with phosphorus. This precipitates out hydroxyapatite (HAP) (Tchobanoglous *et al.*, 2003):



The floc contains calcium carbonate (CaCO₃); this is a dense compound and improves the settling characteristics of the floc. Low alkalinity in wastewater leads to smaller amounts of calcium carbonate being created, leading to a decrease in the settleability of the floc

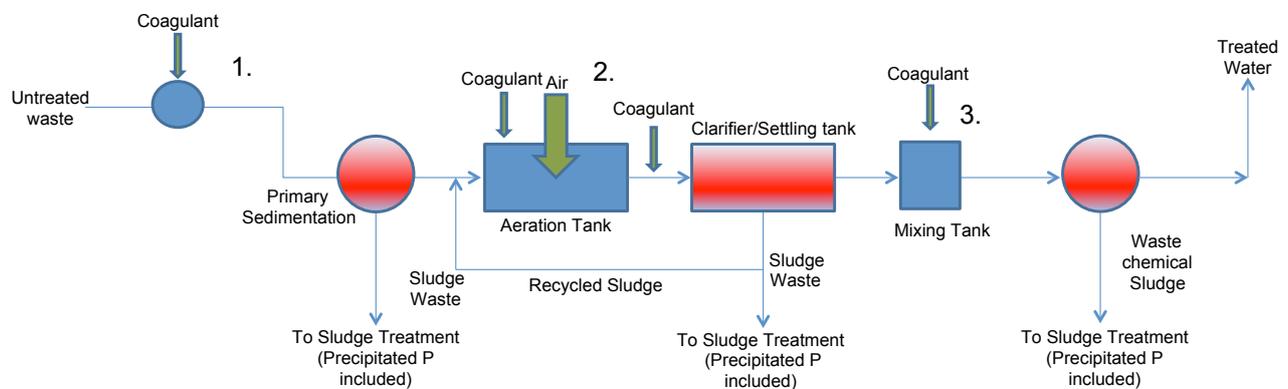


Figure 1.3. General overview of locations where phosphorus removal can take place in a generalised wastewater treatment process. Areas in red show where precipitation/settling occurs: 1, primary wastewater; 2, contemporary with the secondary biological treatment; 3, following secondary biological treatment.

(Peirce *et al.*, 1998). Levels lower than 1 mg/L total phosphorus can be achieved using chemical dosing; however, this requires much larger quantities (theoretically four times the amount of ferric chloride) of the chemical precipitant (Tchobanoglous *et al.*, 2003). If levels below 0.5 mg/L are necessary, then additional phosphorus removal processes are required, as chemical dosing is ineffective below this level.

1.4.1.2 Biological phosphorus removal

Enhanced biological phosphorus removal is a sewage treatment configuration applied to activated sludge systems for the removal of phosphorus. EBPR takes advantage of phosphorus-accumulating organisms (PAOs). These microorganisms can store surplus amounts of phosphorus (in the form of polyphosphates) under aerobic conditions and they can also grow under anaerobic conditions (Figure 1.4). As these PAOs are able to grow under anaerobic conditions, this provides a competitive advantage over other aerobes. This is because after they leave anaerobic conditions and re-enter aerobic ones they can begin utilising available substances straight away. One of the most-studied bacterium in the biological removal of phosphorus is *Candidatus Accumulibacter phosphatis*, although it was previously thought that *Acinetobacter* spp. were the species involved (Martin *et al.*, 2006). Under anaerobic conditions, PAOs use their polyphosphate reserves as an energy source to help utilise fermentation products found under anaerobic conditions such as volatile fatty acids (VFAs). PAOs take up the VFAs and convert them into carbon polymers such as polyhydroxybutyrates (PHBs). When undergoing this process, these organisms release phosphorus as orthophosphates (PO_4P) along with much smaller quantities of calcium, potassium and magnesium. When PAOs enter the aerobic tanks, they use the organic matter and phosphorus

present in the waste immediately (as they have energy available from the breakdown of PHBs). This allows them to create polyphosphates from the phosphorus in the wastewater (Tchobanoglous *et al.*, 2003). EBPR can also take place in biofilm (attached) growth processes.

EBPR has several advantages over chemical phosphorus removal. Smaller amounts of sewage sludge are produced (Ewert *et al.*, 2014) and sludge from EBPR is better for agricultural use, as it has a higher amount of plant-available phosphorus. There can be savings in operating costs, as there is no need for expensive chemical precipitants (Stratful *et al.*, 1999). It also means that it is possible to use a side-stream phosphorus recovery process; phosphorus recovery in combination with biological phosphorus removal has been reported to be particularly successful (Cornel and Schaum, 2009). In contrast, chemical phosphorus removal is not compatible with some approaches for phosphorus recovery, as outlined in Chapter 3. However, EBPR does not have the flexibility of the chemical process and may sometimes have problems in reaching the strict values required in WWTP effluent, necessitating the use of chemical treatments in addition to the biological process (Tchobanoglous *et al.*, 2003). These plants can also have problems with the formation of struvite (discussed in section 3.2.2.1) in piping or pumps if sludge is anaerobically digested.

1.4.1.3 Adsorption techniques for phosphorus removal

Adsorbents or ion-exchange (IEX) resins can selectively remove phosphorus and achieve effluent concentrations as low as 0.02 mg/L (Petzet and Cornel, 2013). The removal of phosphorus from wastewater can be achieved by adsorption using various adsorbents but widespread use is limited by high operating costs and removal efficiency (Karunanithi *et al.*, 2015). Low-cost

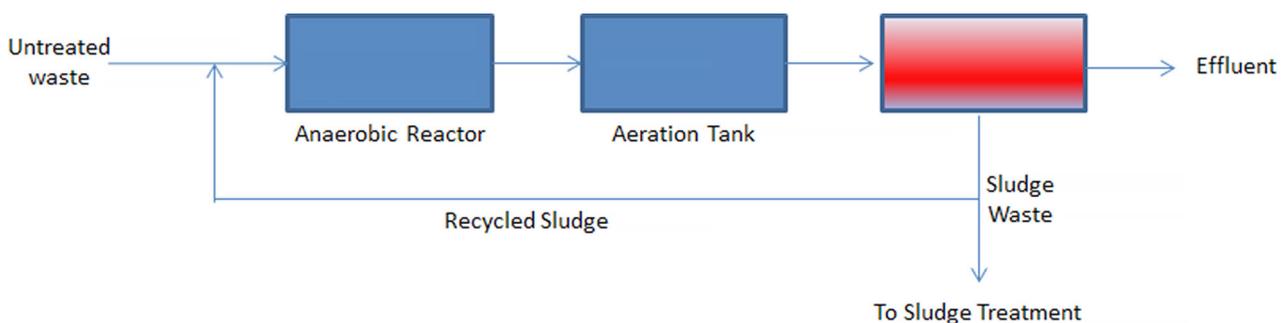


Figure 1.4. A generalised overview of the enhanced biological phosphorus removal procedure.

adsorbents such as natural materials (minerals, rocks, soils and marine sediments), modified natural materials treated to optimise phosphorus adsorption capacity and waste materials/industrial by-products (for example slag materials) may be used (Westholm, 2006; Mortula *et al.*, 2007). Adsorption has been described as a promising phosphate removal method, particularly for wastewater with a low phosphate concentration, and is associated with less sludge generation, ease of operation and high efficiency (Choi *et al.*, 2016). Phosphorus adsorption varies depending on the type of adsorbent, surface area, pH and time (Karunanithi *et al.*, 2015). Adsorbents examined include aluminium oxides, iron oxides, mesoporous silicates, red mud, alum sludge, apatite and clinoptilolite (Choi *et al.*, 2016). Abundant, low cost and non-toxic agricultural waste/by-products have also been investigated as substrates for developing phosphorus biosorbents with modification (by cationisation or activation) necessary to improve phosphate removal ability, which is based on phosphorus being adsorbed via ligand and IEX mechanisms (Nguyen *et al.*, 2014).

1.4.2 Management of sewage sludge

As outlined above, phosphorus-enriched sludge (containing up to 90% of the influent phosphorus) is produced by sewage treatment. In 2014, Irish Water's WWTPs produced 53,543 tonnes (dry solids) of sewage sludge, of which over 98% (including composted sludge) was reused in agriculture (EPA, 2015). The Sewage Sludge Directive (86/278/EEC) promotes and regulates the use of sewage sludge in agriculture so as to prevent negative effects on soil, vegetation, animals and humans. Treated sludge is defined as having "undergone biological, chemical or heat treatment, long-term storage or any other appropriate process so as to significantly reduce its fermentability and the health hazards resulting from its use" and the application of untreated sludge to agricultural land is prohibited unless injected or incorporated into the soil. Additional restrictions apply in relation to soil used to grow fruit and vegetables, and grassland for grazing or harvesting. The Sewage Sludge Directive is implemented in Ireland through the Waste Management (Use of Sewage Sludge in Agriculture) Regulations (SI No. 148) of 1998 and Amendment (SI No. 267) of 2001. This introduces limits on the quantities of specified heavy metals that can be applied yearly based on a 10-year average. A nutrient management plan is also required for use of sewage sludge in agriculture and it must be ensured that the quality of

soil, surface water and groundwater is not impaired. In addition to the Sewage Sludge Directive, the Nitrates Directive (Directive 91/676/EEC) and the Waste Framework Directive (WFD) (Directive 2008/98/EC) are also relevant to the management of wastewater sludge. More stringent controls on the use of wastewater sludge are expected in future legislation. Standards from the European Committee for Standardisation (CEN) give recommendations for sludge management in relation to treatment, reuse and risk assessment. In Ireland, a Code of Practice for Use of Biosolids in Agriculture was produced by the Department of the Environment, Community and Local Government (DECLG) (Irish Water, 2016).

After sludge volume reduction by sludge thickening (using, for example, picket fence or drum thickeners) and/or dewatering processes (for example centrifugation or belt pressing), the sludge is treated in line with the regulatory requirements outlined above to produce biosolids. This may be achieved via mesophilic anaerobic digestion with pasteurisation, thermophilic (an)aerobic digestion, thermal drying, composting or lime stabilisation (Healy *et al.*, 2015; Irish Water, 2016). When applied to land, treated sewage sludge acts as a source of nutrients and metals necessary for plant growth and may improve soil physical and chemical characteristics as well as increasing water absorbency and potentially reducing the potential for soil erosion (Healy *et al.*, 2015). Although the simplest method of phosphorus recycling, the use of treated sewage sludge as a fertiliser is encountering increasing resistance due to concerns in relation to contamination with pathogens, heavy metals and toxic organic compounds, as well as because of the debate about the plant availability of sewage sludge phosphorus from chemical precipitation (Healy *et al.*, 2015; Tarayre *et al.*, 2016). In many countries, including Ireland, companies involved in food and drink production will not accept raw materials produced on land on which treated sewage sludge was applied (Healy *et al.*, 2015). Agricultural application has become increasingly unpopular and is already limited or phased out in some European countries such as the Netherlands, Sweden, Germany and Finland because of stringent regulations about its quality and heavy metal content (Donatello and Cheeseman, 2013; Science Communication Unit, 2013). As a result, sewage sludge is increasingly being incinerated in these areas (Donatello and Cheeseman, 2013). In 2012, 92.6% of sewage sludge produced from urban wastewater in the Netherlands was incinerated,

with none disposed of by agricultural use, whereas in Germany in 2013 approximately 57% was incinerated and 27% used in agriculture (Eurostat, 2016). Other thermal conversion technologies for sludge, for example pyrolysis and gasification, are also under development. Disposal to landfill has decreased as a result of the Landfill Directive (99/31/EC) and concerns in relation to landfill leachates.

1.5 Aims of Study

Phosphorus is a vital resource for food production. The depletion of global phosphorus deposits, widening supply–demand gap and security of supply risks have economic, social and environmental implications, especially in relation to food production and security for a growing population. Mihelcic *et al.* (2011) reported that in 2009 the phosphorus available from urine and faeces, if collected, could account for 22% of the total global phosphorus demand and that the phosphorus produced (in urine and faeces) per capita in Ireland was in the range 0.55–0.62 kg per year. Municipal wastewaters, therefore, represent a major point source for the recovery of phosphorus. Phosphorus recovery from wastewater using novel technologies represents a means of potentially:

- returning phosphorus into the phosphorus cycle in an environmentally sustainable manner, improving resource efficiency and re-establishing a circular economy;

- generating marketable recycled phosphorus products, reducing the requirement for mined phosphorus and improving food security;
- reducing phosphorus pollution of waterways and ensuring compliance with EU Directives and EPA wastewater discharge authorisations;
- enhancing phosphorus security and reducing EU dependency on imported phosphorus;
- creating jobs and economic growth.

The main aim of this project was to identify and evaluate current and developing technologies to recover phosphorus from municipal wastewater with a view to assessing the viability of the most appropriate technologies in an Irish context. Specific objectives were:

- to identify the major sites in Ireland responsible for generating/processing/treating significant quantities of waste phosphorus, availability of phosphorus for recycling and any recycling technologies currently used (Chapter 2);
- to identify and evaluate established and emerging phosphorus recovery technologies (Chapter 3);
- to identify the current global demand for phosphorus by sector and associated technical specification required and cost (Chapter 4);
- to draw evidence-based conclusions as to which subset of recovery technologies would be most suitable in an Irish context (Chapter 5);
- to disseminate the information generated among relevant stakeholders.

2 Municipal Wastewater Treatment in Ireland and Availability of Phosphorus for Recovery

2.1 Background and Aims

Municipal wastewater represents a potential point source to recover phosphorus and re-establish a circular economy. The aim of this part of the study was to examine the existing wastewater infrastructure and potential availability of phosphorus for recovery in Ireland by identifying the major sites within Ireland responsible for processing significant quantities of waste phosphorus, their quantitative annual output and any recycling technologies currently used.

2.2 Methods

Individual municipal WWTP sites in Ireland were identified and profiled using the Waste Water Discharge Application Licence Search Tool, available on the EPA website (<http://www.epa.ie/terminalfour/wwda/index.jsp#.VaZbEKRVhHw>). Industrial sites in Ireland (for example those classified under food and drink, dairy or pharmaceutical) releasing high levels of phosphorus were identified using the Industrial Emission Licences (IEL/IPC) search tool (<http://www.epa.ie/terminalfour/ippc/index.jsp?disclaimer=yes&Submit=Continue>). Further information on total influent and effluent phosphorus levels, plant PE and any phosphorus treatment undertaken was obtained, where available, from Annual Environmental Reports (AERs). PE values and phosphorus influent levels are not available for industrial sites. Site visits were undertaken to selected WWTPs (Limerick, Cork and Ringsend) to gain further knowledge of existing wastewater treatment configurations and the potential for incorporation of phosphorus recovery.

2.3 Results and Discussion

2.3.1 *Generation and analysis of database of municipal wastewater treatment plants*

In accordance with the licensing and authorisation process for wastewater discharges in Ireland, discharges from urban areas with a PE of 500 or more require a wastewater discharge licence; discharges from areas with a PE of 500 or less require a certification of

authorisation (EPA, 2015). A tailored database of municipal WWTPs possessing either a discharge certificate or a discharge licence was generated. The database includes 520 WWTP locations with a Waste Water Discharge Licence (including licence applications currently being processed) and 556 WWTP locations with a Waste Discharge Certificate. For the WWTP locations holding a Waste Water Discharge Licence, the following data was extracted from AERs and licence applications: phosphorus influent and effluent levels (kg per year) between 2010 and 2014 (where available), PE values for each treatment plant and any phosphorus treatment technologies reported. Phosphorus influent/effluent data could not be obtained for plants that possess a Discharge Certificate, as these WWTPs are not required to submit AERs. The database also includes information on the phosphorus effluent of 26 industrial locations in Ireland. A sample of the data compiled in the database is shown in Table 2.1. The full database is available on the EPA Research Data Archive SAFER-Data at <http://erc.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=3124>. A visual representation of selected data from the database showing WWTP PE and proportion of influent and effluent phosphorus in 2014 is shown in Figure 2.1

The time period 2010–2014 was selected for study to take into account any yearly fluctuations in phosphorus levels and to provide the most up-to-date data. Full influent and effluent data were either not reported or not available for all sites over the chosen years. Pre-2012 influent data was only reported for six sites, and from 2012 only 93 sites (18%) had full influent data, rising to 34% from 2013. Complete effluent data for all years (2010–2014) was available for only 43 out of 520 licence-holding sites (8% of sites). Full effluent data were available for 36% of all sites in 2013/2014. This coincided with the transfer of sites from local authority control to Irish Water control. In some cases (equating to 8.5% of all data values extracted) the data values reported in the AER differed somewhat from the values reported in the AER returns workbook. In these cases, both values were included in the database (as can be seen in Table 2.1). These discrepancies could, in some

Table 2.1. A sample of the data compiled in the database on Irish municipal WWTPs, showing PE, phosphorus treatment type and phosphorus influent and effluent levels for representative plants with a Discharge Certificate or Discharge Licence. Where data values reported in the AER differed from those in the AER returns workbook, both values are shown

Agglomeration name	Population equivalent	Phosphorus treatment	Annual reported phosphorus influent/effluent (kg)				
			2014	2013	2012	2011	2010
<i>Authorisation type: discharge certificate</i>							
Ballylanders	473	None	n/a	n/a	n/a	n/a	n/a
<i>Authorisation type: discharge licence</i>							
<i>Phosphorus effluent</i>							
Ennis North	17,000	None	16,913	21,716	17,207	9078	3665
Castletroy	29,477	Ferric dosing	1568	2834	3783	–	–
				1522	2546		
Limerick	130,000	Ferric dosing	34,907	38,777	22,326	47,890	26,349
			30,712	29,565			
Cork City	413,200	None	92,256	101,265	91,945	82,867	83,724
					87,108		
Ringsend	1,640,000	None	546,000	575,837	516,745	526,867	552,129
<i>Phosphorus influent</i>							
Ennis North	17,000	None	20,256	14,773	14,759	–	–
Castletroy	29,477	Ferric dosing	8,198	9704	15,026	–	–
Limerick	130,000	Ferric dosing	229,422	101,105	91,500	–	–
Cork City	413,200	None	–	–	147,864	–	–
Ringsend	1,640,000	None	822000	–	853,878	–	–

n/a, not available; –, no values present.

instances, potentially be due to data entry errors. For certain years at a few WWTPs, the levels of phosphorus reported in the effluent were actually higher than those reported for the corresponding influent. This may possibly be due to desludging activities at those plants or possibly data entry errors.

Analysis of the database indicates that, of the plants with a wastewater discharge license, 175 (33%) use ferric dosing (section 1.4.1.1) to reduce phosphorus concentrations to levels acceptable for release, with one plant using aluminium sulphate. Potential reasons why the other plants do not have phosphorus removal could include low levels of influent phosphorus, different requirements for phosphorus levels in the effluent, varying efficiency of phosphorus removal in primary and secondary treatment activities, etc. Biological phosphorus removal is in place in only a small number of WWTPs (Irish Water, 2016). Phosphorus effluent levels were found to be low for the majority of pharmaceutical and food and beverage sites (<300 kg per year). In Ireland (outside municipal WWTPs) the top

emitters of total phosphorus (from 2010 to 2014) to water (through sewers) were Diageo Ireland (brewing company, 14,732–28,991 kg/year) and Pfizer Ireland Pharmaceuticals (3826–7548 kg/year). However, waste from both facilities is released to sewers with minimal treatment on site. This is then treated at the Ringsend WWTP, Dublin, and is therefore accounted for in the Ringsend data. This was similar for most sites, though dairy processors were a notable exception and effluent figures for these are included in the database.

2.3.2 Wastewater treatment infrastructure in Ireland

In 2014, approximately 94% of the national wastewater load received at least secondary treatment, with 4.6% receiving no treatment or only preliminary treatment, 1.2% and 68.6% receiving primary and secondary treatment, respectively, and a further 25.7% receiving secondary treatment and nutrient reduction (EPA, 2015). Monitoring conducted by the EPA in 2014 of 263 WWTPs with at least secondary treatment reported

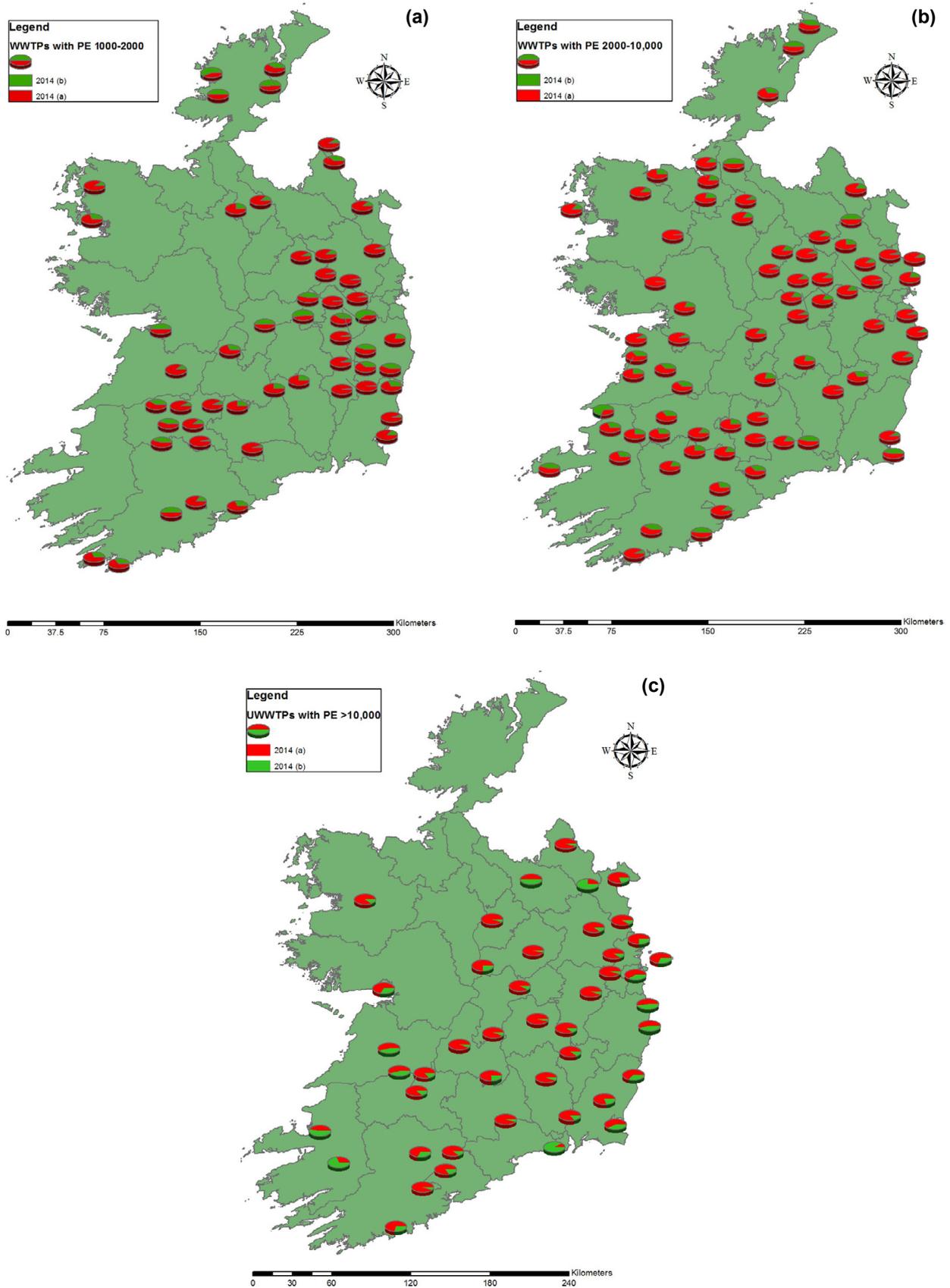


Figure 2.1. Visual representation of selected data from the database of municipal WWTPs generated, showing the location of WWTPs with a PE of (a) 1000–2000, (b) 2000–10,000 and (c) >10,000 in 2014 and, in each case, the proportion of influent (red) and effluent (green) phosphorus for 2014. The data were visually displayed using ArcMap 10.3.1.

compliance of 73% of samples with all effluent quality standards in the licence, while 89% and 86% compliance was reported for total phosphorus and orthophosphate, respectively. To protect receiving waters, secondary treatment and nutrient reduction is required in urban areas with a PE in excess of 10,000 discharging directly to sensitive areas with set limits on the effluent concentrations of phosphorus and/or nitrogen. In 2014, 16 urban areas were required to meet both phosphorus and nitrogen effluent standards, while phosphorus standards alone applied in 14 areas. The effluent quality standard for phosphorus was met by 27 of these 30 areas (90%) (EPA, 2015). Capital investment in the wastewater infrastructure ranged from approximately €270 million per year in the period 2000–2011 to €140 million per year in the period 2012–2014, with further investment in infrastructure necessary to eliminate the discharge of raw sewage and for compliance with the EU Urban Waste Water Treatment Directive and with requirements of waste water discharge authorisations (EPA, 2015).

2.3.3 Availability of phosphorus for recovery

For economic viability, WWTPs with PE > 100,000 are considered most suitable for phosphorus recovery (P-REX, 2013). Based on analysis of the database of Irish municipal WWTPs, there are nine sites that meet this criterion, only two of which had any type of phosphorus removal as of November 2015, both of which use chemical means (Table 2.2). In 2014, the combined phosphorus influent of these plants (not including Cork city, Shanganagh and Bray, as relevant data were not available) amounted to 1,213,128 kg. Ringsend alone accounted for 68% of this total. It is noteworthy that the Ringsend Wastewater Treatment Plant upgrade project

includes implementation of Nereda technology (Royal HaskoningDHV), based on aerobic granular biomass. Among the distinctive characteristics of the technology is the simultaneous biological removal of organic, nitrogen and phosphorus components.

A large proportion of phosphorus (up to 90%) entering a WWTP ends up in sewage sludge (Ewert *et al.*, 2014) and several phosphorus recovery technologies are based on using sewage sludge or sewage sludge ash (SSA) from mono-incineration (Chapter 3). The amount of sewage sludge produced by Irish wastewater treatment plants amounted to 72,429 tonnes (dry solids) in 2012, 64,546 tonnes in 2013 and 53,543 tonnes in 2014 (EPA, 2014a,b, 2015). The amount of sludge produced is expected to rise because of upgrade works at WWTPs and increased volumes of sludge from individual domestic wastewater treatment systems, with predicted sludge quantities of 75,150 tonnes, 84,820 tonnes and 96,442 tonnes per year in 2020, 2030 and 2040, respectively (Irish Water, 2016).

The geographical distribution in terms of sewage sludge treated per county in 2014 is shown in Figure 2.2, which is of interest in the context of potential implementation of phosphorus recovery at a central location as opposed to at individual WWTPs. A “Sludge Hub Centre and Satellite Site” system is in place in a number of counties, facilitating economies of scale and increased flexibility in selection of treatment processes. Sludge from smaller WWTPs is transported to Sludge Hub Centres for treatment. There are currently 24 WWTPs where full treatment of sludge to biosolids is provided, with 20 of these acting as Sludge Hub Centres and accepting sludge imports. It is intended that these be used to maximum capacity, unrestricted by county boundaries (Irish Water, 2016). Currently, the

Table 2.2. Municipal WWTPs with a design capacity > 100,000 PE in Ireland

Agglomerate	County	Plant design PE	Chemical phosphorus removal
Ringsend	Dublin	1,640,000	None
Cork city	Cork	413,000	None
Waterford city	Waterford	190,600	None
Shanganagh	Dublin	186,000	None
Bray	Wicklow	186,000	None
Dundalk	Louth	179,000	None
Limerick	Limerick	130,000	Yes
Kilkenny city	Kilkenny	107,650	Yes
Drogheda	Louth	101,000	None

main outlet for sewage sludge is agricultural land as a fertiliser or soil enhancer. Agriculture accounted for 79.3% of the total quantity generated in 2014, along with composting (17.3%), landfill (0.7%) and storage awaiting landspreading (2.7%) (EPA, 2015). Agriculture was also the main use of sewage sludge in 2012 and 2013, accounting for 94.3% and 80.6% of the total quantity produced, respectively (EPA 2014a,b). Disposal to landfill has decreased significantly from 35% in 2003 to 0.7% in 2014 (EPA 2015). Currently, only sludge from Shannon town is disposed of in landfill because of its potential high heavy metal content (Irish Water, 2016).

In 2014, the most commonly used sludge treatment to produce biosolids was thermal drying (39.7%) followed by lime stabilisation (36.1%), composting (11.6%), anaerobic digestion and pasteurisation (7.9%), thermal hydrolysis and anaerobic digestion (2.9%) and autothermal thermophilic aerobic digestion (0.4%), with 1.4% receiving no treatment (Irish Water, 2016). Advanced anaerobic digestion is the preferred future option. As discussed in section 1.4.2, the use of treated sludge in agriculture is encountering increasing resistance, mainly due to the perceived risk of contamination. In an Irish context, this has been reflected in quality assurance schemes operated by Bord Bia and the Irish Grain Assurance Scheme, which exclude the use of wastewater sludge. There are additional restrictions on the agricultural use of wastewater sludge in relation to groundwater vulnerability, cadmium and nickel soil levels and proximity to Natura 2000 sites

and areas affected by flooding (Irish Water, 2016). The Draft National Wastewater Sludge Management plan released by Irish Water in March 2016, setting out the short-, medium- and long-term strategy for management of sludge produced at WWTPs under the control of Irish Water recognises the importance of exploring alternative outlets for sewage sludge to reduce the risks associated with relying solely on agriculture. In terms of thermal processes, the main alternative outlet identified is incineration but because of the significant capital and operating costs involved this will be a preferred option only if land use is no longer available (Irish Water, 2016).

2.3.4 Site visits

Site visits were undertaken to Bunlicky (Limerick City), Carrigrennan (Cork City) and Ringsend WWTPs, details of which are included in Table 2.1. A number of criteria were applied when choosing these sites, including site size/capacity, the presence or absence of phosphorus treatment technology at the location, practical considerations and input from the project steering committee. The sites visited, which had PE values ranging from 130,000 to 1,640,000, are of sufficient scale for potential phosphorus recovery. The plants visited differed in terms of treatment approach and configuration, highlighting the fact that a one-size-fits-all approach is not likely to be feasible in terms of implementing phosphorus recovery at individual WWTPs.

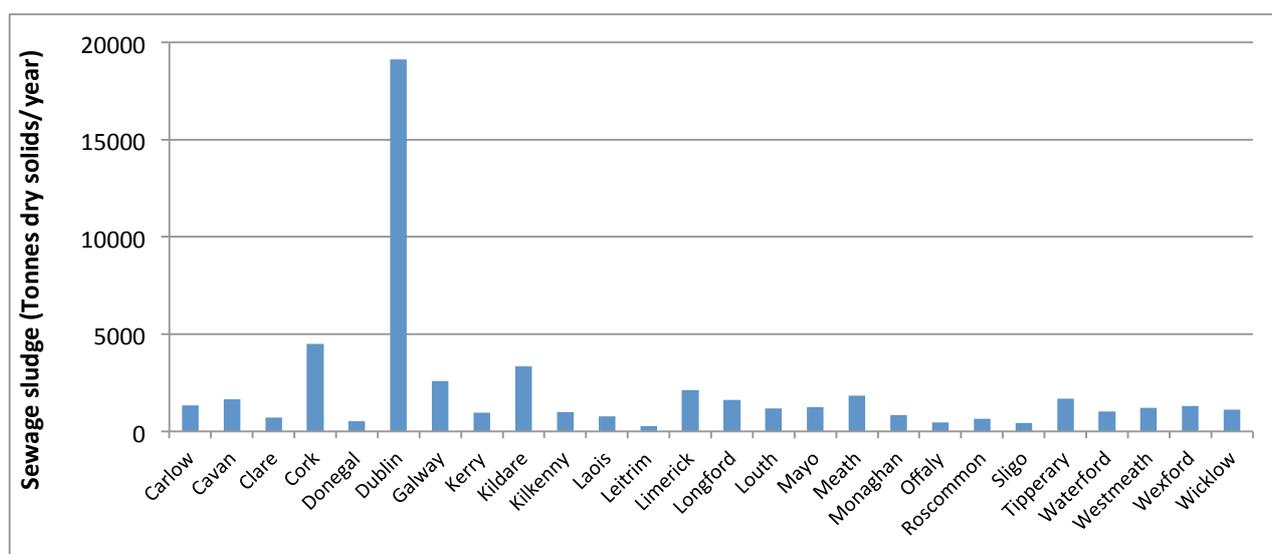


Figure 2.2. Quantity of sewage sludge treated per county in 2014, expressed in tonnes of dry solids per year (data from EPA, 2015).

2.4 Conclusions

A significant level of phosphorus is available for recovery from municipal waste in Ireland and, while phosphorus removal is carried out at some WWTPs, phosphorus recovery is currently not undertaken. Of the WWTPs included in the database generated for this report, nine were potentially of a suitable scale (>100,000 PE) for implementation of phosphorus recovery. Analysis of influent phosphorus levels and quantities of sewage sludge generated indicate that the largest proportion of phosphorus available for recovery is geographically concentrated in Dublin,

which could be favourable in terms of implementation of phosphorus recovery technology. The limited use of biological phosphorus removal as a means of phosphorus removal and the lack of availability of facilities for mono-incineration of sewage sludge are noteworthy in terms of selecting phosphorus recovery technologies for potential implementation. Considering the existing wastewater infrastructure in Ireland, future capital investment is likely to favour essential improvements that will be necessary for regulatory compliance over implementation of phosphorus recovery for some time.

3 Phosphorus Recovery Technologies

3.1 Background and Aims

One of the main aims of this project was to identify and evaluate established and emerging phosphorus recovery technologies that could be of potential use in an Irish context. Relevant phosphorus recovery technologies were identified by searches of scientific literature and patent databases, as well as publications from other sources including the European Sustainable Phosphorus Platform (ESPP) and the EU Seventh Framework Programme (FP7) P-Rex project. For the various phosphorus recovery technologies identified, information collected and subsequent evaluation focused on how the technologies worked, where they can be integrated in the wastewater treatment process, the raw material/phosphorus source required, necessary pre-treatments required (if any), phosphorus recovery levels achievable, phosphorus product outputs, costs and barriers to installation. The main outputs from this work include a table of phosphorus recovery technologies (Table 3.1) summarising the details of 28 phosphorus recovery technologies identified, as well as a more detailed description of 12 technologies considered to be of particular interest (section 3.3).

3.2 Phosphorus Recovery

3.2.1 Phosphorus recovery in practice

There are three main types of phosphorus recovery technologies: (1) crystallisation and precipitation technologies, (2) wet chemical technologies and (3) thermochemical technologies. Crystallisation and precipitation methods are highly similar, with the main difference being the reaction speed: precipitation is the faster of the two and produces an amorphous product, whereas crystallisation takes more time and produces a crystallised product. The two methods both require an excess of the reacting ions. Creation of crystals needs two steps: nucleation (beginning of particle/crystal formation) and crystal growth. Crystal growth is the step during which ions accumulate on the surface of the crystal and integrate into the crystal structure. Nucleation can be accelerated by using seed material (for crystal growth), such as sand/silica grains or small struvite particles. By adding this seed material,

less time and energy is required, as the crystal growth happens on a pre-existing surface. The seed material is particularly useful in wastewater, as large amounts of impurities are present that can interfere with particular formation (CEEP, 2001). In the context of phosphorus recovery, both processes require a phosphorus-rich flow. Wet chemical processes involve the treatment of sewage sludge or mono-incinerated sludge ash (ashes from sludge incinerated separately from other waste). The phosphorus in the sludge is released by treating it with acids or bases in combination with high temperature if necessary. The heavy metals present in the sludge are usually re-dissolved as well. Insoluble material is removed from the dissolved sludge liquor and the phosphorus can then be recovered (Cornel and Schaum, 2009). Wet chemical treatment can also be carried out on sludge ash. Thermochemical technologies involve the mono-incineration of sludge. The sludge ash remaining after this contains very high levels of both phosphorus and heavy metals. The ash can then be fed into a process where chlorine compounds (KCl , $MgCl_2$, $CaCl_2$) are added and temperatures are raised to between 850 and 1000°C for a set period of time. The chlorides react with the heavy metals to form heavy metal chlorides. These become gaseous and evaporate, thereby removing the heavy metals from the ash (Adam *et al.*, 2009).

Phosphorus recovery processes have undergone development for the treatment of both industrial and municipal wastewater. These processes can be used at many locations within the treatment process (as with more traditional chemical flocculation removal methods discussed in section 1.4). Phosphorus can be recovered from (1) liquid phases (reject sludge water, digester water, etc.), (2) sludge phase (EBPR/chemical sludges) and (3) mono-incinerated sludge ash (Cornel and Schaum, 2009). Large quantities of the influent phosphorus load of the waste influent are incorporated in sewage sludge, as outlined in section 1.4.1. The recovery rates for phosphorus from liquid phase recovery may be between 40 and 50% (of the phosphorus in the liquid rather than of influent phosphorus). Rates of recovery from sludge and ash from incinerated sludge can be up to 90% (Cornel and Schaum, 2009). Figure 3.1 shows some of the possible stages at which

Table 3.1. Phosphorus recovery technologies identified. Every effort has been made to ensure that the information is as accurate and up to date as possible

Technology name	Technology type	Product	Target	Phosphorus recovery from raw sludge (%)	Phosphorus recovery from target of recovery process (%)	Scale	TRL	Company	Location	Patent no.	Contact details of patent/licence holder
AirPrex (Berliner Verfahren)	Precipitation	Struvite (MAP)	Anaerobically digested EBPR sludge	7.2%	n/a	Industrial (7 locations)	9	cnp-Technology Water and Biosolids GmbH	Germany, the Netherlands, China	EP2028161 B1	www.cnp-tec.com rudolf.bogner@cnp-tec.com
ANPHOS	Precipitation	Struvite	Anaerobically digested wastewater	n/a	80–90%	Industrial (4 locations)	9	Colsen bv	The Netherlands	n/a	www.colsen.nl Info@colsen.nl
Fix-Phos	Precipitation	CaP/calcium silicate hydrate	Anaerobically digested EBPR sludge	n/a	21–31%	Industrial (1 location)	8	Technische Universität Darmstadt	Germany	WO2011151397 A1	s.petzet@iwar.tu-darmstadt.de
PRISA	Precipitation	Struvite	EBPR sludge liquor	n/a	40%	Pilot	6	Institute of Environmental Engineering (ISA) of RWTH Aachen University	Germany	DE102006043246 A1	montag@isa.rwth-aachen.de
Crystalactor	Crystallisation	Calcium phosphate	EBPR sludge liquor	n/a	70–80%	Industrial (2 locations, both shut down)	9	DHV Water bv	The Netherlands	EP0279964 A3	www.dhv.com info-water@dhv.com
NuReSys	Crystallisation	Struvite	Anaerobic digested EBPR sludge	n/a	85%	Industrial (10 locations)	9	NuReSys	Germany, Belgium, Italy, the Netherlands	EP2619144 B1	www.nuresys.be/ wm@nuresys.com
Pearl	Crystallisation	Struvite	EBPR sludge liquor	11.8%	n/a	Industrial (8 locations plus 4 in development)	9	Ostara	Canada, USA, UK, Belgium	US20120261338 A1	www.ostara.com info@ostara.com
Phosnix	Crystallisation	Struvite	Anaerobic digestion effluent	n/a	90%	Industrial (2 locations)	9	Unitika Ltd	Japan	n/a	www.unitika.co.jp/e/ engi-info@unitika.co.jp

Table 3.1. Continued

Technology name	Technology type	Product	Target	Phosphorus recovery from raw sludge (%)	Phosphorus recovery from target of recovery process (%)	Scale	TRL	Company	Location	Patent no.	Contact details of patent/licence holder
PHOSPAQ	Crystallisation	Struvite	Anaerobic and sludge digested effluent	n/a	70–95%	Industrial (4 locations)	8	Paques bv	The Netherlands, UK	EP2511243 A1	www.paques.nl info@paques.nl
Phostrip	Crystallisation	Struvite or calcium phosphate	EBPR sludge liquor	n/a	n/a	Industrial		Phostrip Abwasser Technik GmbH	The Netherlands	WO1994000388 A1	www.veolia.com herve.paillard@veolia.com
P-ROC	Crystallisation	Calcium phosphate	EBPR sludge liquor	n/a	n/a	Pilot	6	Forschungszentrum Karlsruhe GmbH	Germany	EP1541531 B1	ute.berg@itc-wgt.fzk.de
Struvia (modified Phostrip)	Crystallisation	Struvite	EBPR sludge liquor	11.4	n/a	Industrial (3 locations in Japan, Struvia)	7	Veolia Environment	Japan	20150068976	www.veolia.com herve.paillard@veolia.com
PHOSIEDI	Ion exchange in combination with eletrodialysis	Phosphoric acid	n/a	n/a	n/a	Demo	5	Karlsruhe Institute of Technology (KIT)	Germany	n/a	erhard.hoffmann@iwg.uni-karlsruhe.de
Seabome/Gifhorn process	Acidic dissolution and precipitation	Struvite/hydroxyl-apatite	Digested sewage sludge (EBPR)	48.7%	n/a	Industrial (1 location)	7	Seabome Environmental Research Laboratory	Germany	WO2009004027 A1	www.asg-gifhorn.de abwasserreinigung@asg-gifhorn.de
Stuttgart process	Acidic dissolution and precipitation	Struvite	Digested sewage sludge (both EBPR and chemical sludge)	45%	n/a	Demo	6	University of Stuttgart	Germany	DE102014207842 B3	www.iswa.uni-stuttgart.de/isww heidrun.steinmetz@iswa.uni-stuttgart.de
LOPROX/PHOXAN	Low pressure acid oxidation, membrane phosphate separation	Phosphoric acid	n/a	n/a	n/a	Demo	6	RTWH Aachen	Germany	n/a	Project abandoned

Table 3.1. Continued

Technology name	Technology type	Product	Target	Phosphorus recovery from raw sludge (%)	Phosphorus recovery from target of recovery process (%)	Scale	TRL	Company	Location	Patent no.	Contact details of patent/licence holder
AQUA RECI	Supercritical water oxidation	Calcium phosphate	Digested sewage sludge (both EBPR and chemical sludge)	n/a	n/a	Pilot	6	Feralco AB	Sweden	n/a	Project abandoned
CAMBI/KREPRO	Wet chemical leaching	Phosphoric acid	Digested Sewage sludge (both EBPR and chemical sludge)	n/a	n/a	Pilot	6	Helsingborg wastewater treatment plant	Sweden	n/a	bgh@aom.kth.se
SEPHOS	Wet chemical leaching	Calcium phosphate	Mono-incinerated sludge ash (both EBPR and chemical sludge)	n/a	n/a	Demo	6	Technische Universität Darmstadt,	Germany	DE102012015065 B3	c.schaum@iwar.tu-darmstadt.de
SESAL-PHOS	Wet chemical leaching	Calcium phosphate	Mono-incinerated sludge ash (both EBPR and chemical sludge)	n/a	n/a	Demo	6	Technische Universität Darmstadt,	Germany	DE102012015065 B3	s.petzet@iwar.tu-darmstadt.de
PASH	Wet chemical leaching	Calcium phosphate or struvite	Mono-incinerated sludge ash	80%	80%	Pilot	6	MEAB Chemie Technik GmbH,	Germany	WO2014178788 A1	www.meab-mx.com contact@meab-mx.com
BIOLEACHING	Use of bacteria	Struvite	Digested sewage sludge	n/a	n/a	Demo	6	Georg Fritzmeier GmbH + Co. KG	Germany	EP2324118 B1	jennifer.zimmermann@rwth-aachen.de
BIOCON	Ion exchange	Phosphoric acid	Mono-incinerated sludge ash	n/a	n/a	Demo	6	Royal Institute of Technology	Sweden	n/a	bwolfgang.dot@post.rwth-aachen.de Project abandoned

Table 3.1. Continued

Technology name	Technology type	Product	Target	Phosphorus recovery from raw sludge (%)	Phosphorus recovery from target of recovery process (%)	Scale	TRL	Company	Location	Patent no.	Contact details of patent/licence holder
Mephrec	Thermo-chemical	Silico-phosphates	Mono-incinerated sludge ash (chemical sludge)	80.5%	n/a	Pilot/full plant planned	7	ingitec GmbH	Germany	DE102012003504 A1	www.ingitec.de info@ingitec.de
AshDec	Thermo-chemical	Calcined phosphates (CaNaPO ₄)	Mono-incinerated sludge ash (both EBPR and chemical sludge)	98%	n/a	Pilot/full plant planned	7	Outotec/BAM	Austria	US20090183543 A1	ludwig.hermann@outotec.com www.outotec.com christian.adam@bam.de www.bam.de
Leachphos	Wet chemical leaching	CaP or Struvite	Mono-incinerated sludge ash (both EBPR and chemical sludge)	70.1%	n/a	Pilot	6	BSH Umweltservice AG	Switzerland	EP2602013 B1	www.bsh.ch alois.sigrist@bsh.ch nina.eicher@bsh.ch
Thermphos	Electrothermal P furnace	P4 Elementary P	Mono-incinerated sludge ash	n/a	n/a	Industrial (1 location, shut down)	9	Thermphos	The Netherlands	n/a	n/a (process was running; however, company went bankrupt)
EcoPhos	Wet chemical leaching and ion exchange	Phosphoric acid, dicalcium phosphate	Mono-incinerated sludge ash (both EBPR and chemical sludge)	97%	n/a	Pilot/full plant planned	7	EcoPhos	France	US6989136 B2	www.ecophos.com/ nfo@ecophos.com

TRL, technology readiness level.

phosphorus recovery technologies can be integrated into WWTPs. Recovery from the liquid phase is usually by crystallisation and precipitation, wet chemical processes are used for recovery from the sludge phase and thermochemical processes are usually used to recover phosphorus from sludge ash.

The normal level of phosphorus in influent from municipal sources is approximately 10 mg/L. In order to be economically viable, recovery of phosphorus needs a liquid phase containing more than 50 mg/L phosphates (Cornel and Schaum, 2009). Therefore, recovery processes from the liquid phase require concentrated side streams. These side streams can include dewatered sludge (1a, Figure 3.1), following anaerobic post-treatment (1b), and dewatered anaerobically digested sludge (1c). WWTPs with biological phosphorus removal processes (section 1.4.1.2) are excellent candidates for phosphorus recovery, as the polyphosphates stored in bacterial cells can be partially released in anaerobic conditions. This considerably raises the phosphate levels in the system. The phosphate content in WWTPs with EBPR and anaerobic digestion of EBPR sludge can range from 75 to 300 mg/L (Garcia-Belinchon *et al.*, 2013).

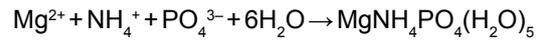
Phosphate recovery from wastewater sludge, which contains phosphorus that is in either chemical and/or biological form, includes recovery from the digester sludge before (2a) and after (2b) dewatering.

Phosphorus may also be recovered from incinerated SSA (3), which allows the highest levels of recovery.

3.2.2 Products of phosphorus recovery

3.2.2.1 Struvite (magnesium ammonium phosphate)

Struvite is a white crystalline material that is made up of magnesium, ammonium and phosphorus in equimolar concentrations ($MgNH_4PO_4(H_2O)_5$). Struvite is formed by the following reaction:



Struvite was first discovered as a problem in 1939 during the anaerobic digestion of sludge, when crystalline deposits were found in piping (Rawn *et al.*, 1939). Struvite formation has continued to be a severe problem, especially with the introduction of EBPR, with extensive reports of struvite scaling-associated problems being described (Doyle and Parsons, 2002). In EBPR, micro-organisms take up excess phosphate that they release under anaerobic conditions, such as digesters or the anaerobic reactors of the EBPR plants. The excess levels of phosphorus present can lead to its precipitation as struvite and cause scaling in pipes, pumps, etc. that lead to a rise in both operational and maintenance costs. Struvite, initially considered a problem (Borgerding, 1972; Doyle *et al.*, 2003) was

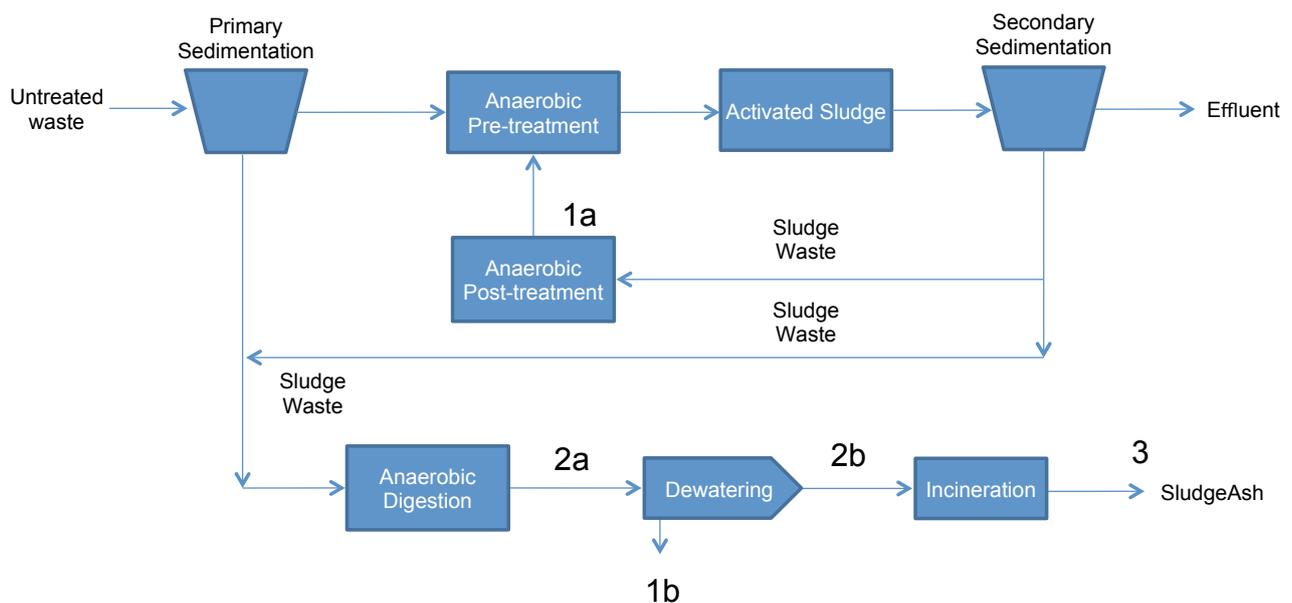


Figure 3.1. Stages at which phosphorus recovery technology can be integrated into wastewater treatment.

found to be of use as a fertiliser, which led to research into the potential controlled recovery of the substance (de-Bashan and Bashan, 2004; Desmidt *et al.*, 2009). Struvite crystallisation is controlled by several variables, including pH (which must be greater than 8), magnesium concentration (the limiting factor in most WWTP), presence of metal ions (higher conductivity) and retention time. Struvite precipitation occurs in a 1:1:1 ratio $Mg^{2+}:NH_4^+:PO_4^{3-}$ as in the reaction above. In most WWTPs, magnesium is the restrictive element, and is added to processes designed to recover struvite as magnesium chloride ($MgCl_2$), magnesium hydroxide ($Mg(OH)_2$) or magnesium oxide (MgO). These various magnesium compounds have both positive and negative aspects. The advantage of the addition of MgO and $Mg(OH)_2$ is that they can be used simultaneously as a means for pH adjustment and as a source of magnesium. However, both have a very low solubility and are normally added to the process as a slurry instead of a solution, requiring a higher volume for the reaction zone or a longer retention time. The use of a slurry can create other problems, such as the blockage of pipes. $MgCl_2$ does not have these problems, as it is highly soluble in water, but its use requires the addition of $NaOH$ to raise the pH. This can be done in conjunction with the stripping of CO_2 from the waste stream, which can also lower the pH. The saturation point (the point at which

struvite crystals start to form) of a solution requires the pH to be alkaline (usually >8). A generalised overview is shown in Figure 3.2.

The recovered struvite can be used as a fertiliser usually after further processing (drying, bagging, etc.) or as a raw material in the fertiliser industry, as outlined in Chapter 4.

3.2.2.2 Calcium phosphate

Calcium phosphate has the advantage of being directly comparable to rock phosphate and can be used directly by the phosphate industry (Driver *et al.*, 1999; Cornel and Schaum, 2009). The precipitation of calcium phosphate is very complex and involves numerous variables. Precipitation depends on the concentration of calcium and phosphate ions, temperature, pH and time (Song *et al.*, 2002; Montastruc *et al.*, 2003). Calcium phosphate can crystallise in many different forms depending on pH and kinetics (Montastruc *et al.*, 2003). However, in the case of recovery of phosphorus from wastewater, it is most likely that the precipitated phase will be the thermodynamically stable hydroxyl apatite (Kibalczyk, 1989). Kinetics plays the most important role in calcium phosphate precipitation (a more important role than thermodynamic equilibrium considerations). Spontaneous precipitation of calcium phosphate from solution usually

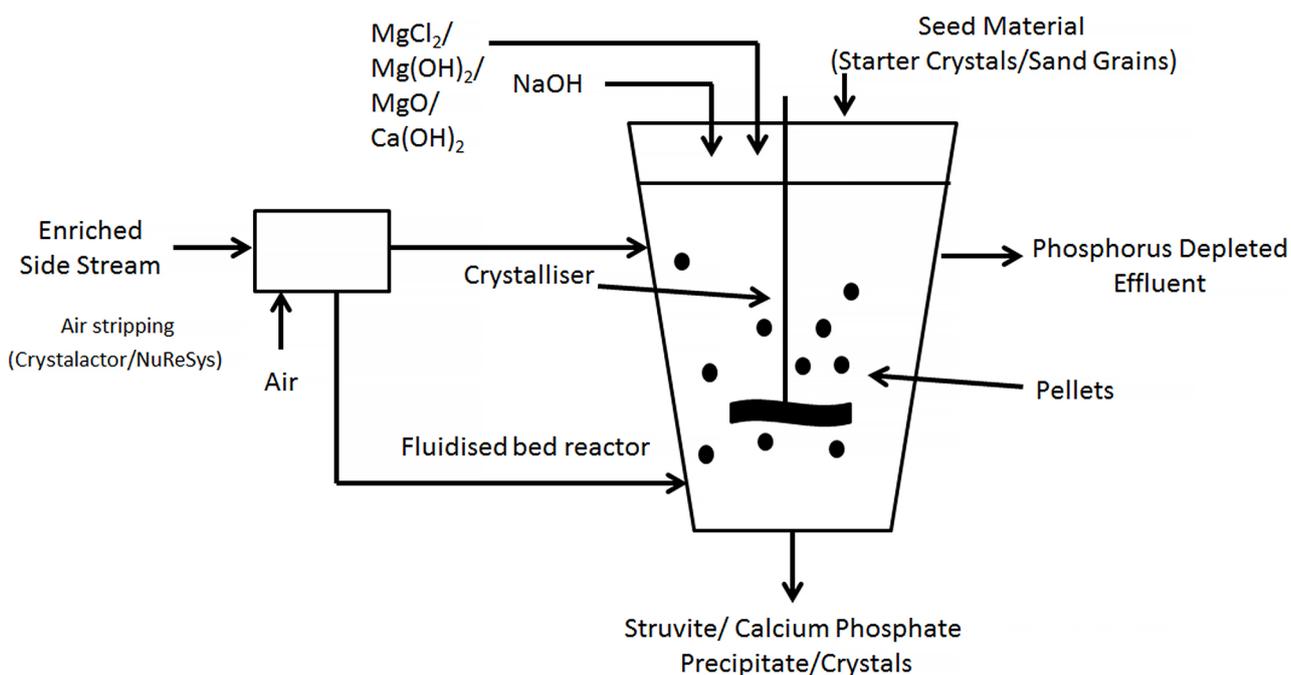
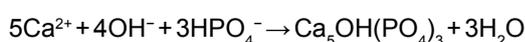
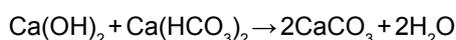
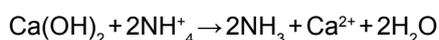


Figure 3.2. Generalised overview of phosphorus recovery from side-stream liquid waste during wastewater treatment.

does not occur at all or occurs only with very high levels of calcium oversaturation and/or the addition of seed material such as sand (Cornel and Schaum, 2009). The presence of inhibitors is thought to be the reason for this. Carbonate and ammonium alkalinity are the most important chemical components in wastewater, adding to the buffering capacity in the alkaline pH range. If, for example, calcium hydroxide [Ca(OH)₂] is added to wastewater to raise the pH to allow the precipitation of calcium phosphate, any hydroxide present will react with any bicarbonate present in the solution to form carbonate (CO₃²⁻) and with ammonium to create ammonia (NH₃), as well as with phosphate to form phosphate-containing precipitates (Szogi and Vanotti, 2009). The use of calcium hydroxide leads to the following reactions:



The first is complete at pH ≤ 9.5, while the second starts at pH > 7.0, but progresses slowly below pH 9.0. Above pH 9, excess calcium ions react with the phosphate present and lead the phosphorus to precipitate out of solution as HAP. In wastewater that contains high ammonium concentrations, large amounts of lime are required to elevate the pH to the required values, since ammonium reaction tends to neutralise the hydroxyl ions:



Song *et al.* (2002) found that at pH 8 the precipitation rate for phosphate was stunted by carbonate and the corresponding precipitation efficiency also decreased, but at pH values ≥ 9 the effect of carbonate on the precipitation of phosphate was very small. This indicated that carbonate decreased the precipitation rate of calcium phosphate, but the solution pH value was still a key factor influencing the precipitation process.

Carbonate may be co-precipitated with phosphate from the solution, especially at pH 9–11, and this will decrease the relative phosphorus content of the precipitate. Therefore, lime requirements for the precipitation of calcium phosphate are less dependent on phosphate concentration, but are more related to wastewater alkalinity. The increase of both the solution pH value and the Ca:P ratio are two approaches to overcome the negative influence of carbonate on the precipitation of phosphate.

3.3 Phosphorus Recovery Technologies

Details of the 28 phosphorus recovery technologies identified are summarised in Table 3.1. These processes are either commercially available or in development (at pilot or lab demonstration phase) and are based on the three main types of technology: crystallisation and precipitation, wet chemical and thermochemical technologies. Other potential technologies that are in development include IEX and electro dialysis (REPHATER project) (EC, 2016). A technology readiness level (TRL) was assigned to each technology in Table 3.1 to quantify technology maturity status, ranging from TRL 1 (basic principles observed) to TRL 9 (proven in operational environment). TRL values were assigned based on the criteria laid out by the European Commission in 2014. The assigned TRL values range from 5 to 9. Twelve technologies considered to be the most appealing in terms of development status and applicability in an Irish context are described in greater detail in section 3.3.1 (commercially available processes) and section 3.3.2 (pilot scale processes). These include liquid, sludge and ash-based recovery processes.

3.3.1 Commercially available processes

3.3.1.1 The Pearl and Waste Activated Sludge Stripping to Remove Internal Phosphorus (WASSTRIP) processes

The Ostara Pearl method was created by the University of British Columbia (Canada) in the early 2000s. The enriched side stream for this process requires reject sludge water from an EBPR process that has undergone anaerobic digestion. These values allow the production of struvite. Phosphate levels as low as 20 to 30 mg/l can be treated but the preferable concentration is > 60 mg/l PO₄P. The process can remove up to 85% of phosphorus and between 10 and 15% of ammonium (in the form of struvite) from the waste stream (EBPR sludge reject water) (Ostara, 2015). The first pilot tests took place in 2001 and were followed by tests in six different pilot plants over testing periods of 1 to 8 months. Following these successful pilot studies, a large-scale reactor was opened in Edmonton, Canada, in May 2007, with seven more plants being operational by 2015, including one in Slough, UK (270,000 PE), with four further plants in development in the USA and

Europe. The plant in Slough cost £2m to build and is expected to save approximately £200,000 per year in operating costs (due to reduced struvite deposits blocking pipes and valves, chemical savings, etc.). The plant recovers approximately 10% of the total phosphorus entering the sewage works and is expected to produce approximately 150 tonnes of struvite per year (ESPP, 2013). The Pearl process involves the addition of magnesium chloride ($MgCl_2$) and sodium hydroxide (NaOH) to the enriched waste side stream in a fluidised bed reactor. The magnesium chloride is added in a ratio of 1:1, with sodium hydroxide in order to raise the pH. Minuscule particles of struvite start to form and these particles then grow until the preferred size is reached (between 1.0mm and 3.5mm). The pellets are very pure crystalline struvite. The Ostara Group markets this struvite as a fertiliser under the brand Crystal Green (section 4.4.4.4).

The Pearl process can be used in conjunction with WASSTRIP (Waste Activated Sludge Stripping to Remove Internal Phosphorus), which can be integrated into wastewater treatment systems to treat waste activated sludge (WAS) upstream of thickening and anaerobic digestion. This is done to prevent struvite formation in the anaerobic digester. Use of WASSTRIP results in up to 70% of the phosphorus and 75% of the magnesium being removed from the WAS when diverted into one or more Pearl reactors. The first plant operating the WASSTRIP process was opened in 2013 in the Saskatoon Wastewater Treatment Plant, Canada (ESPP, 2013).

3.3.1.2 NuReSys

NuReSys (Nutrient Recycle System) was created by the Belgian company Akwadok. The technology operates in several WWTPs at dairy processors, potato processors and pharmaceutical manufacturers [Milchunion (dairy processor), Clarebout Potatoes Agristo (french fries manufacturer), Aquafin (construction materials), and Genzyme (pharmaceutical manufacturer)] as well as at municipal WWTPs. The enriched side stream for this process comes from the anaerobic digestion of wastewater (Moerman *et al.*, 2009). The first full-scale NuReSys plant began operating at the Milchunion dairy processing company in northern Germany in 2006. This system can produce up to 1580 kg struvite per day and remove up to 85% of the phosphorus from the

side stream. Additional industrial scale plants, both at potato-processing companies in Belgium, were constructed at Agristo NV and Clarebout Potatoes NV, with the former producing up to 1425 kg struvite per day. This process uses $MgCl_2$ as the magnesium source and uses 29% NaOH solution to raise the pH to optimum levels. The crystallisation reactor has a blade impeller and a computerised control process that guaranteed that optimal pH levels (8–8.5) for struvite formation were maintained through dosing and variation of the mixing speed. This allows crystal growth upon existing crystals and prevents scaling of the reactor. The struvite pellets that are created are removed at various intervals (Moerman *et al.*, 2009). The process is continuous in a continuous stirred-tank reactor (CSTR). The struvite produced by this process is used as fertiliser (section 4.4.4.4). The process, with a starting concentration of 45 mg/L phosphate (the minimum for the process), can have running costs that are equal to those of traditional chemical precipitation. Less sludge is produced, which also has cost savings (Moerman, 2011).

3.3.1.3 The STRUVIA process

The STRUVIA process is a highly modified version of the Phostrip process that was originally developed by Showo Kankyo Systems K.K. (SKS). In 2011, SKS was purchased by Veolia Water, which has modified the process into its current configuration and rechristened it as STRUVIA. The process can recover either struvite or calcium phosphate from the reject water of thickened EBPR sludge or from the liquor of anaerobically digested sludge of an EBPR process. The process has also been tested on Athos-treated (a thermal hydrolysis process) sludge and high-phosphorus-containing industrial wastewater. It requires a phosphorus input of greater than 50 mg/L to be effective. Three plants operate successfully in Japan. A pilot plant also operated at Brussels North WWTP. Struvite is normally recovered thanks to its ease of use and of recovery (except in one of the Japanese plants). The process has a reaction time of 1 hour, operating at pH 8 and a molar ratio of Mg:P of approximately 1:1 (this can vary from 1.1:1 to 2:1 depending on the quality of the liquor). The process can recover between 70 and 80% of the phosphorus in the waste stream. The technology exists in two different configurations: Turbomix and Turboflo. The Turbomix configuration operates in two steps: crystallisation happens in the Turbomix reactor (a CSTR that operates at

30–300 rpm), while the separation of the crystals takes place in a separate lamella settler. In the Turboflo configuration, the two steps take place in the one chamber, the Turboflo reactor. The mixing zone is highly similar to the Turbomix reactor; however, lamella packing has been added above the mixing zone to retain the struvite particles (P-REX, 2015a). After dosing of $MgCl_2$ and NaOH (amounts released are controlled by pH probe) for adjustment to pH 8, struvite is precipitated. The struvite can be dried at temperatures of between 40 and 50°C before storage.

3.3.1.4 Phosnix

The Phosnix process was created by the Environmental Engineering Division of the Japanese company Unitika Ltd. This process enables the recovery of phosphorus from anaerobic digester wastewater as struvite (Nawa, 2009; Ueno and Fuji, 2001). The enriched side stream should have a phosphorus content of 100–150 mg/L. Two industrial-scale struvite recovery plants are operational at Japanese WWTPs: Fukuoka City West Wastewater Treatment Centre and Shimane Prefecture Lake Shinji East Clean Centre. These came on line in the 1990s (Ueno, 2004). The side stream is piped into the bottom of a fluidised bed reactor containing a bed of granulated struvite. This struvite is a seed material allowing quicker crystal growth. The magnesium source for struvite creation is magnesium hydroxide (MOH), which is added in a ratio of 1:1 (magnesium:phosphorus) and, using sodium hydroxide and airstripping to remove CO_2 , the pH is adjusted to 8.2–8.8 (Ueno and Fuji, 2001). The crystals are retained for 10 days to allow the pellets to grow to 0.5–1.0 mm in size. Following this, the pellets are collected from the bottom of the reactor. Any smaller granules of struvite are returned to the reaction column. These act as seed material to grow more pellets (Ueno and Fuji, 2001; Ueno, 2004). The recovered pellets are dried (water content is reduced to < 10%). This system can recover up to 90% of the phosphorus from the enriched side stream. The reactors can create 500–550 kg per day of struvite (Ueno and Fuji, 2001). Struvite obtained from this process is registered as High Performance Complex Fertilisers (Ueno, 2004) and used by the fertiliser industry, as outlined in section 4.4.4.4. The operational costs per year for this process are estimated to be €27,300 per year compared with €198,300 per year for traditional coagulant addition processes (based on 1000m³ per day).

3.3.1.5 Crystalactor

The Crystalactor process was initially developed in the 1970s by the Dutch company DHV to treat calcium-rich potable water (hard water). The process was soon adapted to eliminate other substances from water sources, such as phosphate and heavy metals (zinc, nickel and aluminium have been removed using this process from industrial process water, potable water and other wastewater streams) (Giesen and Molen, 1996). For recovery of phosphorus from wastewater using the Crystalactor process, a concentrated side stream must be created by using EBPR/reject water from gravity-thickened sludge. The phosphorus-rich side stream must contain between 60 and 80 mg/L PO_4P . Any carbonates (CO_3^{2-}) present in the side stream (which may impede calcium phosphate precipitation) are removed before the side stream enters the Crystalactor. The removal of the carbonate happens as the pH is adjusted to 3.5 with sulphuric acid (96% H_2SO_4) (Gaastra *et al.*, 1998). The Crystalactor itself consists of a cylindrical fluidised bed reactor. Quartz sand is used as seed material to start crystal growth. The wastewater is then fed into the reactor in an upwards direction at a high velocity (40–100 m/hr) keeping the pellet bed in a fluidised state. Efficient calcium phosphate [$Ca_3(PO_4)_2$] crystallisation needs a pH of 9. To achieve this, a calcium hydroxide [$Ca(OH)_2$] solution is added to the reactor in a pH-controlled manner. Through pH control and the addition of calcium hydroxide, calcium phosphate crystals form on the sand particles. As these crystals grow, they fall to the bottom of the reactor. The largest pellets are collected at regular intervals and fresh seed material (sand) is added (Giesen and Molen, 1996). By selecting the most suitable process conditions, high-purity calcium phosphate crystals are created (Giesen, 1999). The recovery rate can potentially reach 70% of phosphates present in the side stream (Cornel and Schaum, 2009). In 1988, the first large-scale phosphate recovery using this technology was brought online at the Westerbork WWTP (12,000 PE) in the Netherlands. The plant gave effluent phosphorus levels of below 1 mg/L with no sludge production from the Crystalactor process. The calcium phosphate pellets were then used by the fertiliser industry. However, the process proved to be economically unviable when phosphate-free detergents were introduced in the Netherlands in the early 1990s. The influent phosphorus levels in raw municipal wastewater fell considerably and, following this, the plant at Westerbork was closed

(Giesen, 1999). The cost of this phosphorus recovery process has been projected as being approximately 22 times greater than recovering phosphorus from phosphate rocks (Roeleveld *et al.*, 2004). Two other industrial-scale plants using the Crystalactor process were built in the Netherlands at Geestmerambacht (230,000 PE) and Heemstede (35,000 PE) (Piekema and Giesen, 2001). However, the plant at Heemstede has since ceased operations (Desmidt *et al.*, 2015). The Crystalactor plant at Geestmerambacht produced 200–300 tonnes per year of phosphate pellets (containing approximately 13% phosphorus). The pellets of calcium phosphate were used in the manufacture of feed for poultry (Gaastra *et al.*, 1998) and as a raw material for the Thermphos processes (Thermphos is a phosphate rock processing company) (Desmidt *et al.*, 2015). The Crystalactor process has not gained widespread use because of necessity of carbonate stripping, the high pH (>9) required to attain precipitation, the intricacy of the process and the large investment costs needed both to set up and to run the process.

3.3.1.6 *The AirPrex process*

The AirPrex process was developed by Berliner Wasserbetriebe (BWB) and is used at the WWTP Waßmannsdorf (1.2 m PE) in Berlin. The process was originally designed to help in the prevention of struvite formation in the pipes after the sludge dewatering in some WWTPs that utilised EBPR and had anaerobic sludge digestion. The formation of struvite led to the blocking of pipes and damage to pumps (Heinzmann and Engel, 2006). A solution to this problem was found by developing a process that allowed struvite precipitation to occur in a controlled manner. This plant produces approximately 700 tonnes of struvite per year. The German company cnp-Technology Water and Biosolids GmbH has licensed the technology and sells it as AirPrex. Six other plants (83,000–1,000,000 PE) have since gone into operation in Germany, the Netherlands and China. In the AirPrex process, the digested sludge is fed into a cylindrical reactor. The reactor is composed of an outer and inner cylindrical zone with a settling zone between them. In the inner cylindrical zone the contents are mixed by air upflow. The air lifts the sludge upwards into the middle of the reactor. After leaving the inner cylindrical zone, the sludge settles in the settling zone. Ammonium ions (NH_4^+) and phosphate ions (PO_4^{3-}) present allow struvite formation with the addition of magnesium. Magnesium is added in the form of

magnesium chloride (MgCl_2) to the reactor. Air is added for two reasons: it raises the pH by stripping CO_2 from the digested sludge and provides mixing, allowing time for the struvite crystals to grow. When the crystals are large enough, they can settle. Part of the internal flow can also be diverted to another tank where smaller struvite crystals can settle. The pellets of struvite are constantly removed from the bottom of the two tanks (Heinzmann, 2009). Tools that had been designed to wash sand have been specially adapted to clean the recovered struvite from the remaining sludge. This permits any potential organic contamination of the struvite to be <0.5% of the overall mass (CEEP, 2012a). The process also has the advantage of reducing the sludge's water-absorbing capacities (owing to the decrease in phosphate ions). This allows a more stable floc. The process is estimated to save approximately €450,000 per year in sludge disposal costs alone (Forstner, 2015) thanks to smaller sludge volumes, which mean lower transportation and disposal costs. The investment for this process was €2.5 million (Nieminen, 2010)

3.3.2 *Pilot-scale processes*

3.3.2.1 *The Seaborne/Gifhorn process*

The Seaborne/Gifhorn process was created by the Seaborne Environmental Research Laboratory to treat anaerobically digested sewage sludge, permit phosphorus and nitrogen recovery and allow the separation of heavy metals (P-REX, 2015b). The original Seaborne process had to be modified, as it was found not to be practical at industrial scale. This modified process is called the Gifhorn process. The process separates nutrients from the sewage sludge to create a fertiliser that contains insignificant amounts of heavy metals or organic pollutants. The first step in the process is the addition of sulphuric acid (H_2SO_4). This is added to lower the pH to 4.5–5 (originally this was to be pH 2 but proved too expensive) to dissolve solid materials and release any heavy metals present along with phosphorus and nitrogen. The next step is the removal of heavy metals (RoHM). In this step, the dissolved heavy metals are precipitated as sulphides [by dosing with sodium sulphide (Na_2S)] following adjustment to pH 5.6 with NaOH (Müller *et al.*, 2007). Solids and liquids are separated with a decanter/centrifuge (flocculent can be added to help separation); the solid residue can be disposed of by incineration, thermal drying and composting. The liquid is then dosed with $\text{Mg}(\text{OH})_2$ (made

on site by mixing MgO with water), which initiates the precipitation of phosphorus as a mix of struvite/calcium phosphate at pH 9 (adjusted with NaOH). Magnesium is added to just below the stoichiometric ratio to encourage complete calcium precipitation. This prevents scaling in the stripping reactor but produces hydroxylapatite along with struvite. The phosphorus product is harvested by a second solid–liquid separation. The process can recover up to 49% of phosphorus in the sludge (P-REX, 2015b). An optional nitrogen recovery step can be integrated into the process. The process requires air stripping to recover ammonia (NH₃) at pH 10.5. The recovery of the ammonia in sulphuric acid creates diammonium sulphate [(NH₄)₂SO₄] (P-REX, 2015b). The treated process stream is then sent back and mixed with the influent of the WWTP. The products of the process, struvite and diammonium sulphate can be used as fertiliser (Günther *et al.*, 2008). A pilot plant was first built in 2006 at the WWTP at Gifhorn (50,000 PE) in lower Saxony (Germany). Estimates for nutrient recovery (for phosphorus and nitrogen) were that approximately 90% could be recovered by this process. Phosphorus would be recovered as struvite, and nitrogen both as struvite (just under a third of the nitrogen content) and as ammonium sulphate. In ideal circumstances, the plant would produce approximately 580 kg of struvite and 1300 kg of ammonium sulphate per day (CEEP, 2012b). However, for economic reasons (chemical costs) the plant is producing only approximately 270 kg struvite per day (P-REX, 2015b). The cost associated with this process of producing 1 kg of phosphorus is estimated at €46 (Nieminen, 2010).

phosphorus from the sludge ash which could be available to plants. The ASH DEC brand and the technology were purchased by Outotec in 2011 (Desmidt *et al.*, 2015). An overview of the process can be seen in Figure 3.3. The process works as described above, with mono-incineration of the sludge followed by thermochemical reactions. The first step completely destroys the organic pollutants and creates ashes that contain high levels of phosphorus (Adam *et al.*, 2009). The second step is the thermochemical reaction, where the ash is mixed with an alkali metal chloride (KCl), an alkaline earth metal chloride (MgCl₂ or CaCl₂) or a combination of these in either aqueous or powder form and heated to approximately 1000°C for 20–30 minutes. A surplus of chloride is required compared with the concentrations of heavy metals for the process to be effective (Berg and Schaum, 2005). At this temperature, the heavy metals in the ashes (which can include cadmium, copper, lead, mercury and zinc) react with the alkali metal chlorides, become gaseous and then evaporate. The necessary amount of chlorine to add is dependent upon the level of heavy metals present in the ash and the removal rate needed to meet national fertiliser legislation criteria in European countries (Günther *et al.*, 2008). Magnesium chloride (MgCl₂) was found to be the most favourable alkaline earth metal chloride, as it forms magnesium phosphates and magnesium calcium phosphates that are much more available to plants than the phosphate compounds created with other additives. In greenhouse and field experiments, the MgCl₂-treated ashes showed a good fertilisation performance on acidic soils, but they work poorly on soils that have either neutral or alkaline pH.

3.3.2.2 AshDec

The company ASH DEC Umwelt AG (2009) developed a thermochemical method to remove heavy metals from mono-incinerated sludge ash and concurrently make

An updated form of the process has replaced magnesium chloride (MgCl₂) with sodium sulphate (Na₂SO₄). This leads to the creation of CaNaPO₄ in the thermally treated ash. This process is based on the Rhenania

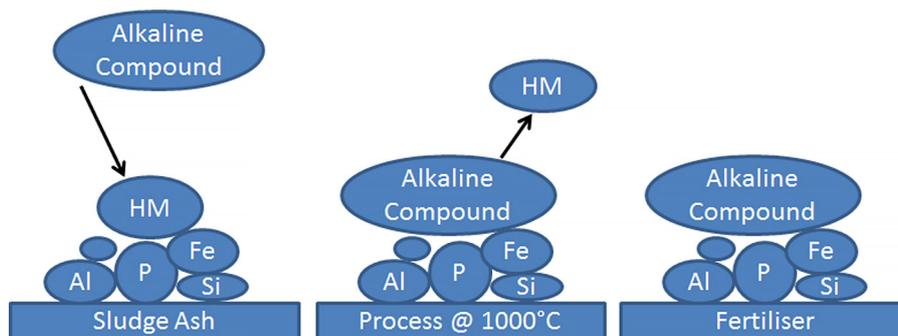


Figure 3.3. Overview of the process of phosphorus recovery from ash using the AshDec process.

phosphate process (Stemann *et al.*, 2015). This process is a thermally based fertiliser production method that was used from 1918 to 1982 (Stemann *et al.*, 2015). In this process, soda (Na_2CO_3) was used to break down phosphate rock and create CaNaPO_4 . The CaNaPO_4 is biologically available to plants. In the modified AshDec method, sodium sulphate is used instead of soda for cost reasons. The modified AshDec method requires dried sewage sludge as reducing agent for the reduction of sodium sulphate and of any metal compounds. If this were not present, the sodium sulphate would not react with the phosphorus present in the sludge ash. In the most energy-efficient form of the process, ash is fed directly into the process as hot ash ($>850^\circ\text{C}$) from mono-incineration. If not added immediately following mono-incineration, the ash must be pre-heated to approximately 100°C before entering the AshDec process. The ash is then fed into the rotary kiln along with the dried sludge. The sodium sulphate is added to the kiln following pre-heating with the hot kiln off-gas (450°C). The gas is first purified using an electrostatic precipitator (an air filtration device that removes fine particles), and dust particles that are kept in the filter are discharged to waste. The thermochemical reaction is carried out in the heated rotary kiln in counter-flow. Holding times and transport rates of materials through the kiln can be controlled by changing the slope of the kiln and speed of rotation. The part of the kiln where the burner is located reaches $900\text{--}950^\circ\text{C}$. An industrial-scale recovery plant is currently in the planning stages in Zurich. In the original process, after the removal of the heavy metals, the treated ash was mixed with other nutrients (NH_4NO_3 , K_2SO_4 , KCl) and turned into pellets; this was called PhosKraft (Adam, 2009; Hermann, 2009). PhosKraft contained much less cadmium and uranium than the majority of phosphate rock-derived fertilisers and was as effective in both crop yield and nutrient uptake by crops (Desmidt *et al.*, 2015). This process has also has the potential be used on the ashes of sludge from chemical phosphorus removal.

3.3.2.3 The EcoPhos process

The EcoPhos process was first developed by the phosphate industry as a means of processing low-grade phosphorus-containing material (e.g. phosphate rock with high levels of contamination with heavy metals) into a high-quality phosphorus product (phosphoric acid). The process was modified for the use of

mono-incinerated ash as input material. A full-scale plant for processing of a feedstock mix of low-grade rock phosphate (75%) and mono-incinerated SSA from two Dutch incineration plants (Sonveaux, 2014) into a phosphorus product is currently under construction in Dunkirk, France. The plant will use 60,000 tonnes of mono-incinerated sludge ash per year in its process. The EcoPhos process is based on the digestion of ash (with HCl) into a large excess of phosphoric acid (H_3PO_4). Following acid digestion, insoluble residues are removed by filtration and disposed as inert material. The liquid solution contains a high amount of phosphoric acid and high levels of dissolved impurities from the ash. This solution is then purified by a multi-stage IEX process. The IEX process removes metal salts (Mg , Ca), metals (Fe , Al) and heavy metals. The resins for the IEX process are regenerated with hydrochloric acid, thus introducing the acid equivalents into the process which are required for ash digestion. The solutions from regeneration of the IEX resins have the potential to be valuable by-products. These can be recovered as a Ca/Mg solution or an Al/Fe solution; other impurities are disposed as wastewater. After purification of the solution, a part of the phosphoric acid is recycled back to the ash digestion, whereas another part is recovered as phosphoric acid product and is further concentrated using steam. The final product is a phosphoric acid solution with high concentration and low impurities (EcoPhos, 2015a). The EcoPhos process can produce various phosphate products including dicalcium phosphate (DCP), monocalcium phosphate (MCP), phosphoric acid (fertiliser, feed, technical, food, electronic grade), nitrogen-phosphate-potassium (NPK), phosphate-potassium (PK) or nitrogen-phosphate (NP) fertilisers from low-grade phosphate rock and/or other phosphorus sources including SSA (EcoPhos, 2015b).

3.3.2.4 The Leachphos process

The technical feasibility of carrying out phosphorus recovery from SSA using the Leachphos process was verified in Bern by BSH Umweltservice GmbH in 2012. The process is based on the FLUWA (filter and fly ash washing, translated from German) hydrometallic leaching process. This process is used to treat ash from the incineration of municipal waste to recover heavy metals. This process has been operated at an industrial scale for 15 years or more and has been employed in 12 plants across Europe. The process was carried out using an adapted FLUWA plant (the plant had been

decommissioned) at Warmbächli incinerator at Berne (Adam *et al.*, 2015). The Leachphos process has both a leaching and a precipitation step. The leaching step is carried out first with the digestion of the mono-incinerated sludge ash with dilute sulphuric acid (H_2SO_4). This process is carried out in a stirring reactor for between 30 minutes and 2 hours. The concentration of sulphuric acid along with the ratio of ash to sulphuric acid can be varied. This digestion step is followed by the separation of the solids and liquid. This can be performed using either a vacuum belt filter or a filter press. Both methods have advantages and drawbacks. Vacuum belt filters can be run continuously and they also allow a high level of automation. Filter presses cannot be automated to a high degree but they can achieve a higher dry matter content than the vacuum belt filter (Adam *et al.*, 2015, P-REX, 2015c). After separation of the liquid and solids, the liquid (which contains the phosphorus) is pumped into another separate stirred batch reactor. The phosphorus is precipitated out of solution by adding lime (CaO) or sodium hydroxide (NaOH) to raise the pH. The alkaline pH results in a greater level of phosphorus precipitation but also can lead to the precipitation of dissolved heavy metals. Lime is less expensive than sodium hydroxide but its use can lead to gypsum ($CaSO_4 \cdot 2H_2O$) formation during lime dosing. However, this forms a distinct product that can be easily dewatered. The final phosphorus product is separated from the remaining liquid by a second filtration stage. The heavy metals are precipitated at pH above 9 with a precipitating agent and then separated for proper disposal. The phosphorus recovered is a mixture of aluminium, ferric and calcium phosphate which contains acceptable levels of heavy metals. For future industrial-scale plants, calcium phosphates or struvite are being targeted as the phosphorus-containing outputs (P-REX, 2015c).

3.3.2.5 *The Mephrec process*

The Mephrec (Metallurgical Phosphorus Recovery) process has been under development by the German company Ingitec for over 10 years. It was based on a process used to create "Thomas Flour", a calcium-silico-phosphate form of iron, produced from slag. The original tests (carried out in 2002 in a modified small cupola furnace) used briquetted sewage sludge as an input, producing iron metallic wastes, a liquid phosphorus slag and a raw off-gas (which had high calorific

values). Tests carried out on the liquid slag (Mephrec slag) showed that the phosphorus contained had high solubility in citric acid and that it had low heavy metal content. The success of these trials led to further trials in Freiberg, Germany. These trials used both sewage sludge that had been briquetted and SSAs, along with coke, as process inputs. This material is fed into the top of the furnace and falls to the bottom, where the liquid metal and slag melt separate from each other because of their different densities. The furnace is heated to approximately $1450^\circ C$ around the nozzle area; however, where the heated air and oxygen are injected, temperatures can be up to $2000^\circ C$. The furnace has a counter-flow set-up where the hot air heats up the material added at the top. This cools the raw off-gas down to temperatures of approximately $200^\circ C$. The high temperatures melt the metals and they separate from the slag melt at the bottom of the furnace as a result of their high density. The metal-containing slag is then removed at regular intervals. The phosphorus-containing slag is siphoned into a water basin where a scraper is used to create a uniform grain size. This can then undergo processing (pellet formation, addition of nitrogen or potassium, etc.) to be ready for use. The metal-containing slag contains small amounts of toxic elements such as As, Cd, Hg, Pb, Zn. This is because these elements evaporate and are separated by gas phase. Other heavy metals (non-volatile elements) such as copper, nickel and chromium are separated from the metal-containing slag by a density separation process. The success of these trials has led to the building of a pilot plant in Nurnberg, called the "KRN-Mephrec" (www.nuernberg.de/internet/krn_mephrec). Any potential utilisation of the raw off-gas from this process to create energy depends upon whether sludge or ash is the process input. The raw off-gas of the Mephrec process using mono-incinerated ash has a low calorific value and, therefore, would not be usable as an energy source. The off-gas from sludge, however, has a high calorific value and can be used for energy creation potentially by several different means including an Organic Rankine cycling (ORC) process, a Combined Heat and Power (CHP) process or a Refuse-Derived Fuel (RDF) process. Each of these would require the gas to undergo processing before use (Mephrec 2015). The pilot plant was capable of treating 8 tonnes of briquettes per hour. For the process to be feasible it requires a minimum capacity of 40,000 tonnes per year of briquettes (Nieminen, 2010).

3.3.2.6 The PASH process

The PASH (Phosphorus recovery from Ash) process was developed at the Institute of Applied Polymer Science (IAP) at Aachen University (Germany). The process recovers phosphorus as calcium phosphate from incinerated SSA and can also be used for meat and bone meal ash. The process utilises a liquid extraction method to remove both heavy metals and iron following acid leaching with hydrochloric acid (HCl). This solution is then filtered and the filter cake washed with water and then dewatered to help remove as much phosphorus as possible. The liquid filtrate (along with the water from the dewatered sludge cake), contains phosphorus, calcium and other metals. This filtrate is then treated by solvent extraction to recover selected metals, followed by phosphate precipitation. If the aluminium content of the leaching solution is very high, pH adjustment (to a pH of 2) is carried out. By doing this, aluminium phosphate is precipitated and can be removed (Montag and Pinnekamp, 2009). Precipitation is carried out by the addition of lime to the solution at pH 3.6 with a reaction time of 15 minutes. This creates calcium phosphate. The phosphorus content is 16%. Heavy metal content in the precipitated phosphate compounds are below the limits set out for German fertiliser use. Montag and Pinnekamp (2009) experimented on the best way to solubilise phosphorus with NaOH, H_3PO_3 , H_2SO_4 and HCl, with results of 25%, 50%, 80% and 90% phosphorus recovery. HCl (8%) achieved the highest rate of phosphorus recovery, with a retention time of 60 minutes. Heating is not required for this process, as near total dissolution of phosphorus was found with temperatures as low as 35–40°C. Any temperature of above 40°C was found to have an undesirable effect on the process, as the concentration of released iron increased significantly. Capital expenditure (CAPEX) costs for this system are estimated to be €5m, with operating expenditure (OPEX) costs of €4m per year. The first full-scale plant has a design capacity to treat 30,000 tonnes of sludge ash per year and aims to recover 700 tonnes of phosphorus per year.

3.4 Cost of Phosphorus Recovery Processes

The German Water Association (DWA) published costs for phosphorus recovery processes based on several research projects (at lab and pilot scales). The costs of phosphorus recovery from sludge water were in

the range €9–15 per kg recovered phosphorus (kg P) (equivalent to €1–3 per total population per year) while costs for recovery from sewage sludge and SSA were in the ranges €2–25 per kg P (€0.5–18 per total population per year) and €2.6–7.5 per kg P (€1.6–3 per total population per year), respectively. These data do not include the Mephrec process and do not take into account possible operational savings or revenue from recovered phosphorus (Petzet and Cornel, 2013). For the recovery technologies evaluated in the P-REX project, the annual recovery costs ranged from €0 to €15 per capita. Processes based on leaching of sludge had the highest annual cost per capita (€5–15), while processes based on precipitation from sludge liquor/sludge and recovery from existing undiluted SSA had a similar cost range of €0–5 per capita. In the case of recovery from ash, an additional cost of up to €3 per capita per year would be necessary for installation of mono-incineration in place of co-incineration or direct application of sludge in agriculture. In Europe, the yearly cost of wastewater treatment is in the range €40–140 per capita (P-REX, 2015d).

3.5 Conclusions

In summary, the phosphorus recovery processes identified:

- are based on three main types of technology: (1) crystallisation and precipitation, (2) wet chemical and (3) thermochemical technologies;
- can be integrated at various stages in the wastewater treatment process to recover phosphorus from the liquid phase, sewage sludge or SSA;
- are in various stages of development from lab or pilot demonstration phase to commercially available.

For the installation of the technology to be cost effective, large quantities of phosphorus would have to be available for recovery. Phosphorus recovery technologies are usually based in or near WWTPs that have PE levels of >100,000 or are attached to industrial (food, pharmaceutical, etc.) locations that have very high phosphorus outputs. Approaches based on the precipitation of phosphorus from sludge liquor are considered to be simple and technically feasible and can be applied on a small scale at individual WWTPs producing marketable struvite. However, their application is generally limited to WWTPs with EBPR and the

phosphorus recovery potential is low (approximately 30–40% of WWTP influent) (Sartorius *et al.*, 2012; Egle *et al.*, 2015). EBPR is currently used in only approximately 10% of European WWTPs (P-REX, 2015d) and in only a small number of WWTPs in Ireland (Irish Water, 2016). The cost of installing or retrofitting the equipment for EBPR is generally greater than that for installing chemical phosphorus removal (approximately €460,000 for chemical phosphorus removal vs €2.8m for EBPR based on a 65,000 PE WWTP that must have a phosphorus effluent level of lower than 1 mg/L). The CAPEX costs include installation of tanks or retrofitting existing tanks as well as installation of mixing and recycle pumping equipment. However, OPEX costs of EBPR systems are lower (approximately €18,000 per year) than for chemical phosphorus removal systems (€500,000 per year based on a 65,000 PE WWTP). Cost savings result primarily from the reduced chemical and sludge handling costs (Minnesota Pollution Control Agency, 2006; Menninga *et al.*, 2014). EBPR is, however, less reliable than chemical phosphorus removal and can have other associated costs (maintenance due to struvite formation). Precipitation/crystallisation recovery technologies would then require further investment. The Pearl plant in Slough (approximately 300,000 PE) cost approximately £2m to build (ESPP, 2013).

A higher phosphorus recovery potential (up to approximately 90%) can be achieved from sewage sludge/sludge ash using wet chemical and thermal processes. These processes can generally be carried out on sludge from chemical phosphorus removal and also give the opportunity to potentially have centralised locations to which sludge from other wastewater treatment plants

can be transported for phosphorus recovery. These are complex, multi-step processes requiring large amounts of chemicals and/or energy with large investment and operational costs that may not be economic on a small scale (Desmidt *et al.*, 2015). Furthermore, these types of processes are not as far along in their technical development, and the risk of technology lock-in needs to be considered. In the survey of experts in phosphorus recovery reported by Sartorius *et al.* (2012), 53% of the experts considered that the precipitation of phosphates from the liquid phase represents the most important route for phosphorus recycling and the less costly approaches were preferred, even at the expense of lower yields. In countries already incinerating sewage sludge, phosphorus recovery from ash becomes more attractive, as the cost of incineration is not attributed to phosphorus recovery. This is evident in the Sartorius survey, with 61% of the experts considering phosphorus recovery from ash the best alternative if sewage sludge is incinerated. This approach is generally considered to be the most promising for phosphorus recovery, as, in addition to the high recovery potential, SSA of appropriate composition can be used directly as raw material in the fertiliser industry or in the electro-thermal production of phosphorus, as outlined in Chapter 4 (Petzet and Cornel, 2013). Recovering phosphorus from SSA is, however, very expensive in terms of CAPEX, with plants that can process 20,000 tonnes of ash estimated to cost approximately €15 million (minimum price). A mono-incinerator with the capacity to incinerate 100,000 tonnes sludge every year would cost €50m. The building of the EcoPhos facility in Dunkirk required an investment of €60m (Nord France Invest, 2015).

4 Global Demand for Phosphorus and Potential Market for Recycled Phosphorus

4.1 Background and Aims

The global demand for phosphorus is increasing mainly because of a growing population and a shift towards meat- and dairy-based diets. Recovered phosphorus should be of satisfactory quality and purity to, at least partially, replace phosphate rock, the supply of which is vulnerable to future phosphate scarcity, volatile pricing and geopolitical tensions, as outlined in section 1.3. The productive use of recovered phosphorus will contribute to ensuring global food security, maintaining water quality and re-establishing a circular economy, while also facilitating the large-scale commercialisation of phosphate recovery. To achieve this, the recovered phosphorus must match the needs and requirements of potential users, either as an end product or as raw material for existing industries. As outlined in Chapter 3 and Table 3.1, products from the phosphorus recovery technologies described include mainly struvite, calcium phosphate and calcined phosphates. Struvite may be used directly as a fertiliser or undergo further processing to produce fertiliser. Recovered calcium phosphate is similar in composition to phosphate rock and in a suitable physical form is acceptable to the phosphate industry, while calcined phosphates can be used as a fertiliser (Desmidt *et al.*, 2015). A further possibility for phosphorus reuse is the incorporation of SSA to replace some of the phosphate rock in the process used to produce fertiliser or elementary (white) phosphorus. Furthermore, the EcoPhos process (section 3.3.2.3) can use alternative phosphorus sources, including SSA, to produce various products including phosphoric acid (fertiliser, food or electronic grade), animal feed phosphates and fertilisers (EcoPhos, 2015b). This chapter focuses on the market potential of recovered phosphorus. The main industry sectors currently using phosphorus are profiled and, in each case, current and future phosphorus demand, associated technical, quality and regulatory requirements (where applicable) and the potential for incorporating recycled phosphorus are examined. Information on pricing structure is also provided where available. The main focus is on the use of recycled phosphorus in the fertiliser industry, as this represents the major market for recycled phosphorus

and several recovered phosphorus products are of direct use in this sector, as outlined above. Other markets discussed include the animal feed phosphate industry and, to a lesser extent, sectors accounting for minor proportions of overall phosphorus consumption, such as the food and detergent industries and various technical applications.

4.2 Global Phosphate Rock Market

Society is currently dependent on the processing of phosphate rock to produce phosphorus compounds for use in various applications, most notably the production of fertiliser for food production (Withers *et al.*, 2015b). World phosphate rock production is shown in Figure 4.1(a). World production in 2013 equates to 58.9 million tonnes (Mt) phosphorus pentoxide (P_2O_5) (IFA, 2015a). Production, import and consumption of phosphate rock in the EU-28 during the same period is shown in Figure 4.2(b), which also highlights the dependence of Europe on imported phosphorus. In the USA, phosphate rock production was 31.2Mt (8.9Mt P_2O_5) in 2013, with consumption increasing 3% from 2012 to 31.3Mt. (USGS, 2015b). In 2014, an estimated 27.1Mt of marketable phosphate rock was produced valued at US\$2.4 billion f.o.b. mine (USGS, 2015a). The average unit value of phosphate rock sold or used by producers in the USA in 2013 was \$90.72 per tonne while an average unit value of \$120.72 per tonne was determined for imported phosphate rock (USGS, 2015b).

It is projected that global phosphate rock supply will increase to 255Mt per year in 2019 (Heffer and Prud'homme, 2015). The global demand for phosphate rock is increasing because of the growing world population (which is predicted to reach 9–10 billion by 2050) and associated food requirements, major producers of phosphate rock becoming importers and a growing market for biofuel crops (Ridder *et al.*, 2012; Cordell and White, 2014). Mew (2016) expects phosphate rock prices to remain within the range \$110–160 per tonne for some time. Variations in market supply/demand dynamics affect the market price of phosphate rock. Price hikes were observed in 1975 and in 2008, with

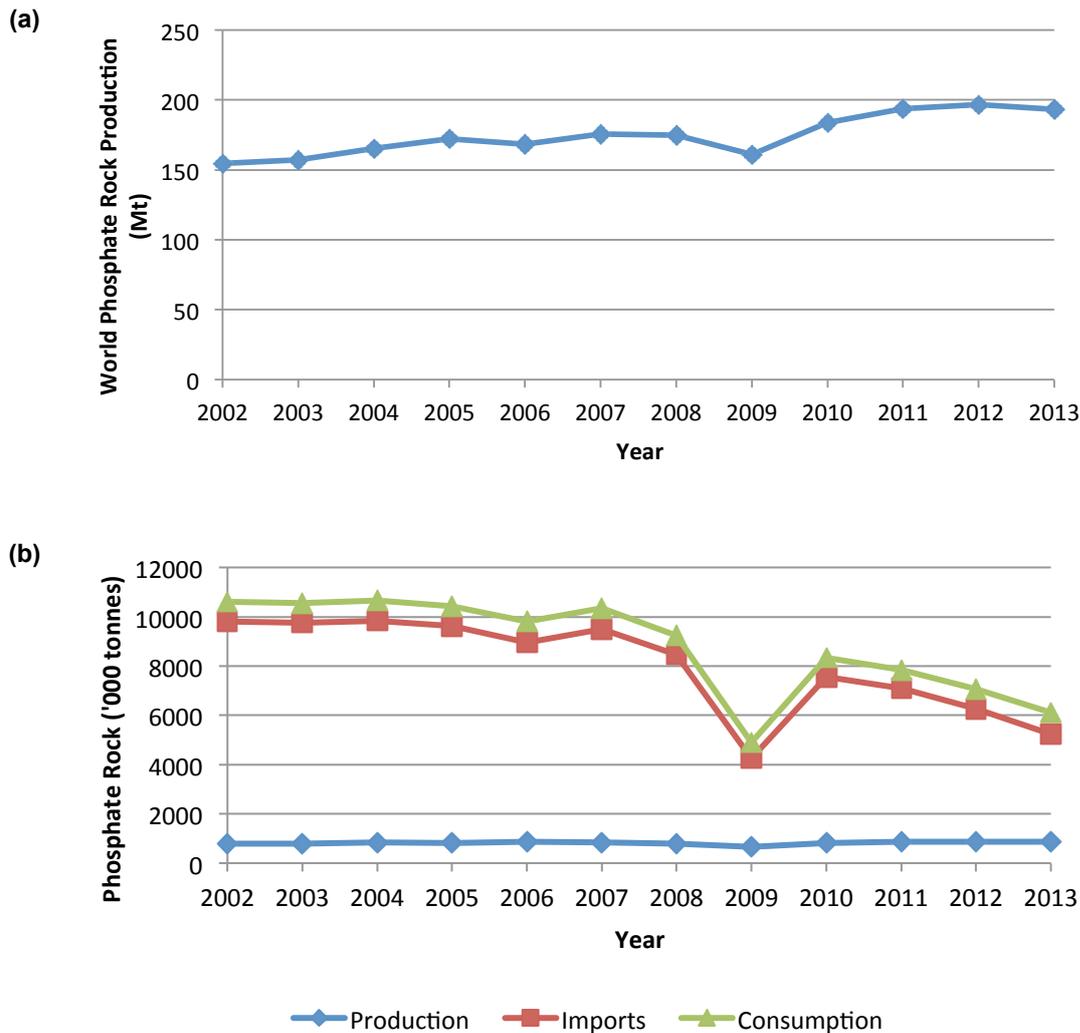


Figure 4.1. (a) World phosphate rock production during the period 2002–2013; (b) production, import and consumption of phosphate rock in EU-28 during the period 2002–2013. Data from IFA (2015a).

market price jumps of six- to eightfold. High phosphate rock prices result in higher prices for phosphorus fertilisers, causing farmers, where possible, to reduce phosphorus application for one or more seasons and rely on the phosphorus sink in the soil without affecting crop yield. This reduces demand for phosphorus fertiliser and phosphate rock, reducing prices to lower levels before they reach a plateau phase, typically higher than before the price hike (Mew, 2016).

4.3 Industrial Uses of Phosphate Rock

It is generally reported that approximately 80–90% of phosphate rock is used as fertiliser in agriculture, 5–7% for animal feed additives, 1–3% for food additives and the remainder in various industrial applications, for

example detergents, cleaning agents, toothpastes, flame retardants, metal coatings, ceramics, leather, anti-freeze and anti-corrosion agents, medicines, paint ingredients and matches (Cordell and White, 2014; Heckenmuller *et al.*, 2014; Reijnders, 2014; Desmidt *et al.*, 2015). Reijnders (2014) reported that approximately 22Mt P is added to the world economy annually from mined fossil phosphate resources, of which approximately 18Mt P is currently used in phosphate fertiliser, approximately 1.3Mt P in feed additives, approximately 0.9–1.1Mt in detergents, approximately 1.2Mt in pesticides and other industrial uses and approximately 0.2Mt in food additives. The mineral phosphorus demand of Europe (1.55 Mt P/a) is divided between fertiliser (65%), feed additives (16%), detergents and soaps (13%) and others (6%) (P-REX, 2015d). Markets and Markets (2015a) project the phosphorus and derivatives market

to register a compound annual growth rate (CAGR) of 3.5% between 2015 and 2020 and to have a market size of US\$75.9 billion by 2020 (from US\$61.9 billion in 2014).

The production of 85% of phosphates is based on the conversion of phosphate rock into phosphoric acid (Figure 4.2). There are two processes for the production of phosphoric acid: the wet acid process and the thermal (furnace) process. The majority of phosphoric acid production (>90%) is via the wet acid process. During this process the rock phosphate (tricalcium phosphate, TCP) is reacted with acid, usually sulphuric acid, producing phosphoric acid. The thermal process involves the production of elemental phosphorus from phosphate rock, coke and silica in an electrical resistance furnace, which is then oxidised and hydrated to produce the acid (IFC, 2007; Walters, 2011). The thermal process produces a very pure and more expensive phosphoric acid used primarily in non-fertiliser applications (IFC, 2007) and use of this process is decreasing because of high energy costs and progress of purification techniques (Walters, 2011; JDCPhosphate, 2015). Phosphoric acid from the wet process can be further purified to produce technical-grade acid (TGA) and food-grade acid (FGA) via solvent extraction technology (Walters, 2011).

An alternative method for producing phosphoric acid, the improved hard process (IHP), has been developed by US-based JDCPhosphate, Inc. It is claimed that the IHP can process lower quality phosphate rock reserves and various phosphate waste materials (including those of low phosphorus concentration). The process produces phosphoric acid at a lower cost than the wet process (Walters, 2011) and a demonstration plant has been constructed to validate the process and move towards commercialisation. The phosphate rock is combined with green petroleum coke, sand (silica) and clay to form 3/8-inch balls using conventional equipment, which are fed to a ported rotary kiln, where phosphorus in the ball is reduced and oxidised to P_4O_{10} gas, which is subsequently cooled and absorbed in water, producing 70% phosphoric acid, while the spent balls (mostly calcium silicate) can be used as a construction aggregate (JDCPhosphates, 2015).

Approximately 90% of phosphoric acid (80% in the EU-27) is used to produce fertiliser as outlined below and a small amount is purified further for use in other applications (Gilmour, 2013; Dikov *et al.*, 2014a). In 2013, global phosphoric acid production amounted to 42Mt P_2O_5 (Figure 4.3), while phosphoric acid production and consumption in the EU-28 were 1.27Mt and

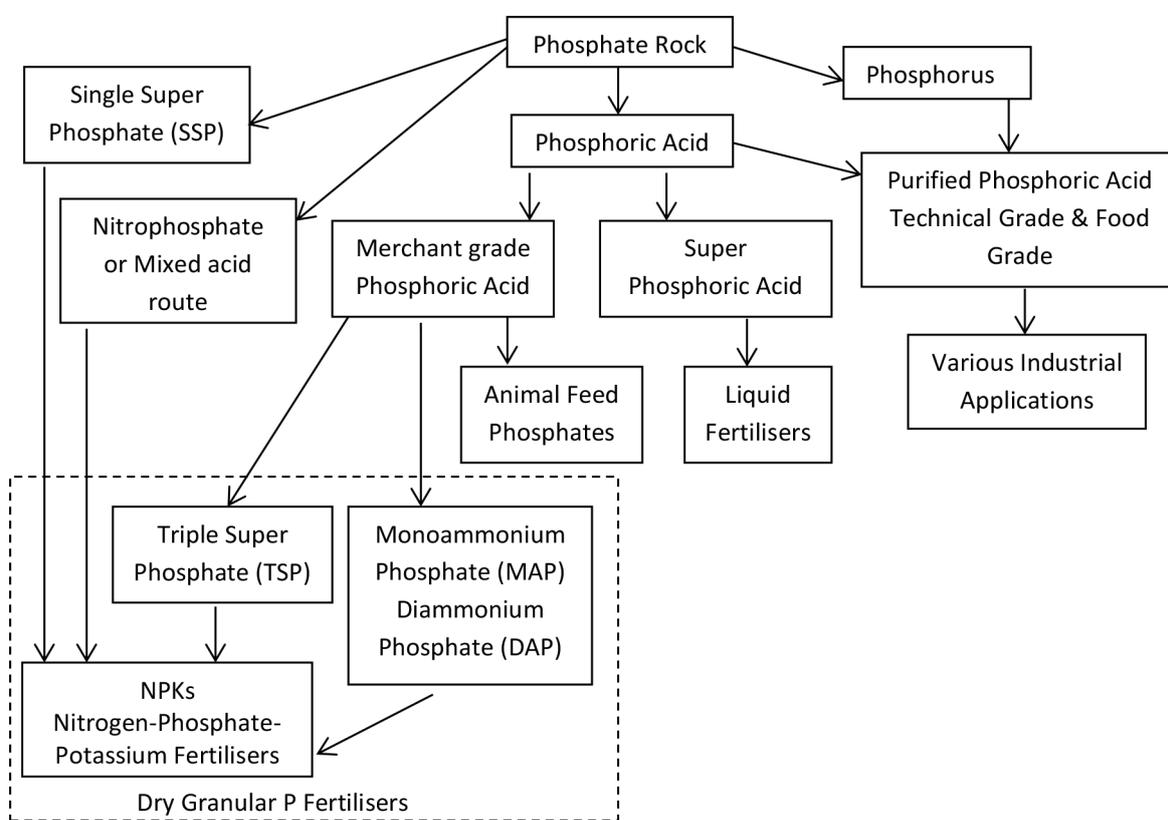


Figure 4.2. The production of products for use in various industrial applications from phosphate rock.

1.88Mt, respectively. In 2013, East Asia and North America were the largest producers and consumers of phosphoric acid (IFA, 2015a). The United States produces approximately 12Mt phosphoric acid per year (USGS, 1999) of which 8.22Mt P_2O_5 was for agricultural use in 2013 (USGS, 2015b). A global phosphoric acid demand of 48.3Mt P_2O_5 has been estimated for 2019, with demand forecast to grow at an annual rate of 2.4% compared with 2014 (Heffer and Prud'homme, 2015).

4.4 The Fertiliser Industry

4.4.1 Overview

Phosphorus is an essential plant macronutrient, accounting for approximately 0.2% of a plant's dry weight, and is a vital component of nucleic acids, phospholipids and ATP. It has a role in enzyme reactions and regulation of metabolic pathways and is essential for cell growth, fruit formation and seed development (Schachtman *et al.*, 1998; Cordell and White 2014). In agricultural systems, the application of phosphorus, identified as a limiting nutrient in 1840, is necessary to replace the phosphorus removed from the soil in crops. Historically, this was achieved using bones, guano, manure and human excreta until after the First World War when synthetic fertilisers were used to improve yields (Cordell and White, 2014). Today, the focus of the fertiliser industry is to provide the three major plant nutrients (nitrogen, phosphorus and potassium) in a form available to plants. Application of phosphate fertilisers is associated with increased crop yield and quality and

greater agricultural productivity and is considered critical for adequate food supply and food security for a growing global population (Heckenmuller *et al.*, 2014). Commercial phosphorus fertilisers are $\geq 90\%$ water-soluble and, upon their dissolving in soil, orthophosphate is available for plant uptake while polyphosphates are readily converted to orthophosphate for uptake (IPNI, 2010).

4.4.2 Production of phosphate fertilisers

Phosphate rock is mainly extracted via open pit mining techniques (IPNI, 2010). The grade of phosphate ore ranges from 2 to 35% phosphorus pentoxide (P_2O_5), with lower-grade sedimentary ore ($<26\%$ P_2O_5) now being recovered and processed thanks to advances in technology, which can increase the amount of saleable phosphate concentrate (IFA, 2015b). Beneficiation of the phosphate rock ore is undertaken to remove sand, clay, carbonates, organics, iron oxide and other materials and increases the phosphate content to 27–40% P_2O_5 (IPNI, 2010; IFA, 2015b). Other important factors include a low free-carbonate content (to prevent excess acid consumption during phosphoric acid production), $<5\%$ Fe_2O_3 , Al_2O_3 and MgO (to prevent formation of intermediate products) and <500 ppm Cl^- (to avoid corrosion of equipment) (IPNI, 2010).

There are three main routes for converting phosphate rock into fertiliser products/intermediates: production of phosphoric acid, single superphosphate (SSP) or nitrophosphates (Figure 4.2). As outlined above, phosphoric

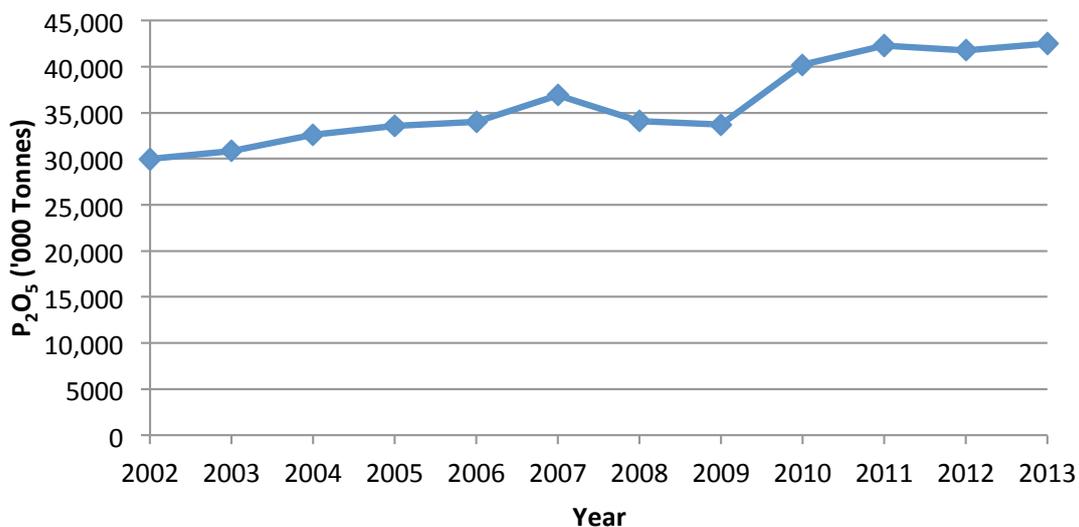


Figure 4.3. World phosphoric acid production during the period 2002–2013 (including merchant grade and super phosphoric acid grade). Data from IFA (2015a).

acid is a key intermediate which is further processed to produce different phosphate fertilisers. Phosphoric acid for fertiliser production is produced mainly by the wet acid process, which requires high-grade beneficiated ore (>28% P_2O_5 with low impurities). During this process, the rock phosphate (TCP) is reacted with acid, usually sulphuric acid, producing phosphoric acid. Phosphogypsum (calcium sulphate) is produced as a by-product (IPNI, 2010). Dihydrate and hemihydrate processes produce 28% P_2O_5 and 42% P_2O_5 phosphoric acid, respectively (Walters, 2011). Commercial phosphoric acid is concentrated to 52–54% P_2O_5 (merchant grade acid) while that used to produce fertiliser may be less concentrated (UNEP, 1998). In 1998, it was reported that phosphoric acid is used as the main intermediate in 70% of global phosphate fertiliser production (UNEP, 1998). Phosphoric acid is used to manufacture the three main phosphate fertiliser products, triple superphosphate (TSP), diammonium phosphate (DAP) and monoammonium phosphate (MAP), details of which are shown in Table 4.1.

TSP, a high-concentration phosphate fertiliser, is produced by the reaction of phosphoric acid with phosphate rock. DAP and MAP are produced by addition of ammonia to the phosphoric acid (IPNI, 2010). DAP is produced by reacting 2 moles ammonia with 1 mole phosphoric acid, while MAP is produced by reacting 1 mole ammonia with 1 mole phosphoric acid and can be produced using lower quality phosphate rock than DAP (IPNI, 2010). TSP, DAP and MAP may be used directly as a fertiliser or used to produce multi-nutrient fertilisers such as NPK fertiliser, as described below. Phosphoric acid may also be concentrated further to superphosphoric acid (68–70% P_2O_5), which can be

used as a feedstock to produce liquid polyphosphate fertilisers such as ammonium polyphosphate produced by reaction of superphosphoric acid, ammonia and water (IPNI, 2010). Single or normal superphosphate is produced by the reaction of finely ground phosphate rock with sulphuric acid (IFC, 2007; IPNI, 2010) so that most of the phosphate is converted to the water-soluble mono-calcium form (UNEP, 1998). SSP can be used directly as a fertiliser or as a feedstock for the production of NPK fertiliser (IPNI, 2010). SSP is highly water soluble and is a source of the secondary nutrients sulphur and calcium (IFA, 2015c).

Multi-nutrient fertilisers are produced by dry mixing/blending of previously manufactured components and/or by chemical reaction. Chemically compounded multi-nutrient fertilisers of various formulations, for example for NPK, NP or PK, are produced by the nitrophosphate or mixed acid route. The nitrophosphate route uses nitric acid to digest phosphate rock, with subsequent separation of the calcium ions as calcium nitrate (which is of use as a fertiliser). The resulting nitrophosphoric acid solution is neutralised with ammonia and mixed with potassium/magnesium salts, sulphate and/or micro-nutrients to give the desired final formulation. In the mixed acid route, phosphoric, nitric and sulphuric acids are mixed to produce multi-nutrient formulations. In the mixed acid process with phosphate rock digestion, the phosphate rock is initially digested with nitric acid prior to the addition of phosphoric, sulphuric and nitric acids. The acid slurry is ammoniated and, before, during or after neutralisation, components such as ammonium phosphates, superphosphates, ammonium sulphate and potassium- and magnesium-containing compounds are added (UNEP, 1998; EFMA, 2000).

Table 4.1. Composition of common commercial phosphate-containing fertilisers (data from IFA, 2015c)

Product		Nutrients as % of product				
		N	P_2O_5	K_2O	S	MgO
SSP or OSP	Single superphosphate (ordinary or normal superphosphate)	0	16–20	0	12	0
TSP	Triple superphosphate	0	46	0	0	0
DAP	Diammonium phosphate	18	46	0	0	0
MAP	Monoammonium phosphate	11	52	0	0	0
Complex fertilisers	NPK fertilisers	5–25	5–25	5–25	^a	^a
	NP fertilisers	15–25	15–25	0	^a	0
	PK fertilisers	0	7–30	10–30	^a	^a

^aSome with S and/or Mg and/or micronutrients.

4.4.3 Current and projected demand for phosphate fertiliser

Phosphate fertilisers account for 25% of global fertiliser production and 10% of European production (Fertilisers Europe, 2015a). Global and EU-28 production of the three main phosphate fertilisers is shown in Figure 4.4. In 2013, East Asia and North America produced the largest amounts of MAP and DAP, while East Asia consumed the largest amount. Africa and Latin America accounted for the greatest production and consumption of TSP in 2013, respectively (IFA, 2015a). The EU produces 3% and consumes 7% of global phosphate

fertilisers (Fertilisers Europe, 2015a). DAP is the most consumed phosphorus fertiliser globally because of its high phosphorus and nitrogen content, with DAP/ MAP accounting for 56% of the global phosphorus fertiliser market in 2010/2011, relative to 20%, 10%, 6% and 9% for NPK, SSP, TSP and others, respectively (Yara, 2014). In the USA, production of DAP and MAP amounted to 10.2Mt in 2013 (USGS, 2015b). In 2008, an average of 19kg of phosphorus per hectare was applied in the EU-27, with national averages ranging from 6 kg P per hectare (Bulgaria) to 50 kg P per hectare (Malta) and an input of 22kg P per hectare reported for Ireland (Dikov *et al.*, 2014b). In 2013, consumption

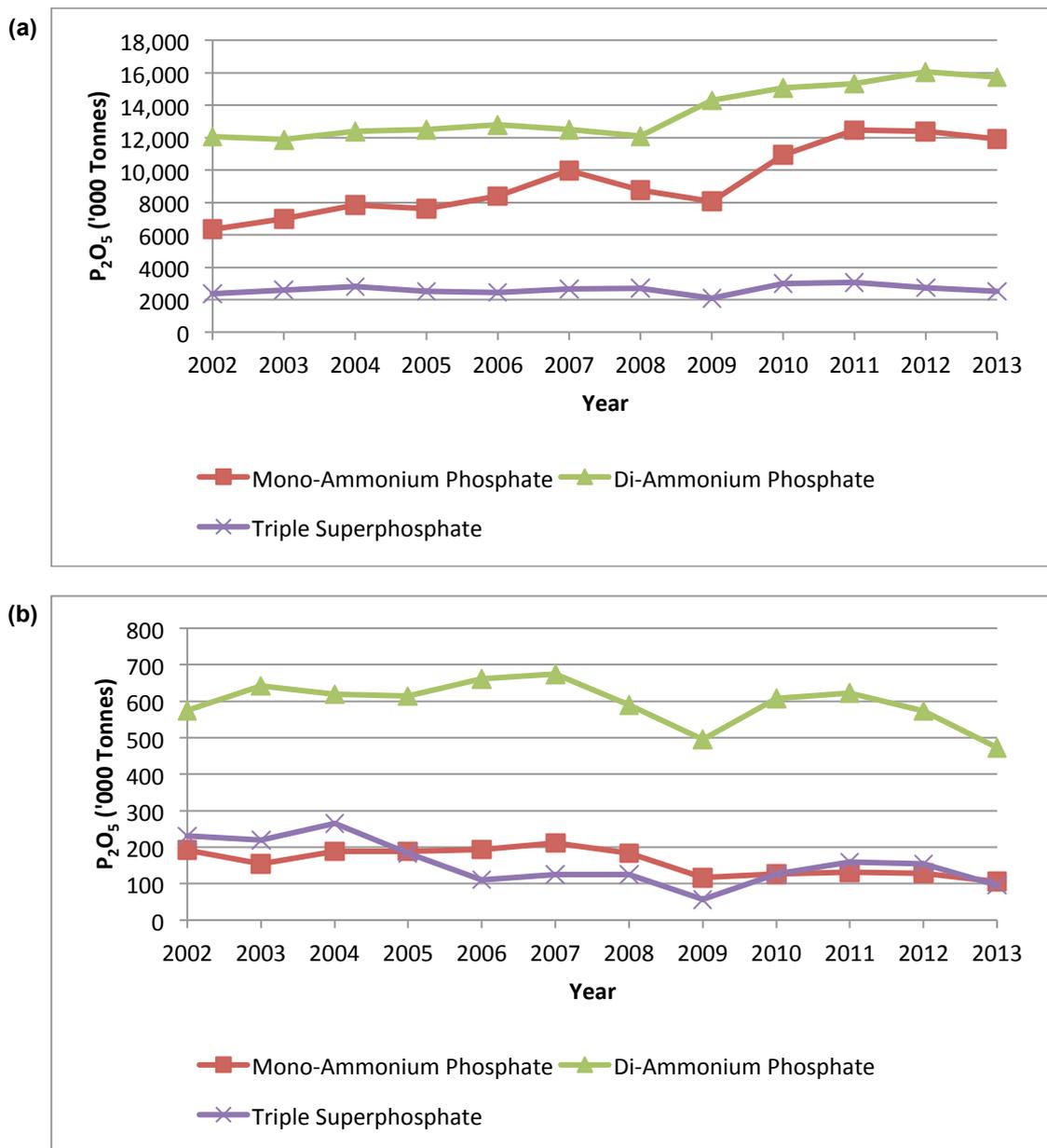


Figure 4.4. (a) World and (b) EU-28 production of phosphate fertilisers monoammonium phosphate, diammonium phosphate and triple superphosphate during the period 2002 to 2013. Data from IFA (2015a).

of phosphate fertilisers (P_2O_5 total nutrients) in Ireland amounted to 104,264 tonnes, while the import, export and production amounted to 105,315, 1051 and 0 tonnes, respectively (FAOSTAT, 2016). Global fertiliser phosphate demand is expected to grow 1.8% per year from 41.1 Mt P_2O_5 (average 2012/2013 to 2014/2015) to 45.7 Mt P_2O_5 in 2019/2020 (Heffer and Prud'homme, 2015). Fertilisers Europe *Forecast of food, farming and fertiliser use in the European Union 2013–2023* reports that, from 2010 to 2013, fertiliser containing an average of 2.5 million tonnes of phosphate was applied to 133.5 million hectares of farmland per year and expects annual phosphate consumption to reach 2.6 million tonnes by the 2022/2023 season, with a 6.7% increase in phosphate consumption (Fertilisers Europe, 2015b).

4.4.4 Use of recycled phosphorus products in the fertiliser industry

4.4.4.1 European legislation governing technical phosphorus recovery and recycling as fertiliser

Various EU laws and directives govern the production, marketing and use of phosphorus recovered from sewage sludge, sludge water or mono-incinerated sludge ash and are of relevance to WWTPs, the fertiliser industry and other phosphorus recyclers, such as external sludge/ash management companies and start-up companies (Hukari *et al.*, 2016). The main focus of this legislation is protection of human health and the environment. Legislation relevant to recovery and recycling processes is as follows, with exact requirements depending on national legislation and regional authorities:

- Environmental Impact Directive (EIA), Directive 2011/92/EU (EU, 2011);
- Industrial Emissions Directive (IED), Directive 2010/75/EU (EU, 2010);
- Waste Framework Directive (WFD), Directive 2008/98/EC (EC, 2008a);
- Shipment of Waste Regulation (1013/2006 EC) (EC, 2006a) (if waste for process comes from outside the country).

Under the EIA and IED, operators must provide relevant process information to authorities, which grant an operation permit, possibly with conditions (Hukari *et al.*, 2016).

Classification of the recycled phosphorus as “waste” or “product” and the application of relevant legal obligations is determined by whether or not it meets the end of waste (EoW) criteria (Article 6) of the WFD, as decided by national or regional-level authorities. A material may, therefore, have a different status, for example “waste” or “product”, in different countries. While product status is a pre-requisite for large recyclers aiming at national or international fertiliser markets, selling recovered phosphorus locally under waste status may be more desirable for small-scale recyclers, such as WWTPs, to avoid lengthy and costly registration processes (Hukari *et al.*, 2016). Product, however, is more favourable than waste status in terms of marketability and potential sales revenues. If the recycled phosphorus is determined to have waste status, WFD and Shipment of Waste regulations, as above, apply. If it is classified as product, the following legislation applies:

- Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC 1907/2006) (EC, 2006b):
 - requires registration with the European Chemicals Agency (ECHA) of chemical substances (>1 tonne per year) manufactured in or imported into Europe;
 - in some cases, nutrients recovered from waste can be exempt from registration (Article 2(7)d) (Hukari *et al.*, 2016);
- Classification, Labelling and Packaging of Substances and Mixtures (CLP/GHS) Regulation (EC 1272/2008) (EC, 2008b);
- Mutual Recognition Regulation (EC 764/2008) (EC, 2008c):
 - allows free trade between Member States in materials which have received product status in a Member State, unless considered detrimental to human health or the environment by the receiving state.

Placement of fertiliser products on the EU market is governed by the Fertilisers Regulation (Regulation EC 2003/2003) (EC, 2003). This is currently being revised to include, in addition to mineral fertilisers, authorisation of organic and recovered fertilisers, subject to annexing specific criteria for each category. The current Fertilisers Regulation requires conformance to quality standards and declaration of nutrient type, minimum concentration and solubility. Complying fertilisers are referred to as “EU fertilisers” and can be marketed throughout the EU.

Proposal of a new fertiliser as an EU fertiliser requires submission of technical documentation (including REACH registration details and hazard classification, information on the effects on health, environment and safety, agronomic data, details of methods of analysis and results and proposal for inclusion in Annex I to Regulation 2033/2003) to the relevant authorities in a Member State. National legislations are usually also in place in Member States and compliance with national regulations allows non-EU fertilisers to be put on the national market with market access in other Member States according to the Mutual Recognition Regulation. Relevant legislation in Ireland includes the Fertilisers, Feedingstuffs and Mineral Act 1955, Statutory Instrument 248/1978 “Marketing of fertilisers and liming materials not covered under EU regulations” and Statutory Instrument 384/2005 transposing Regulation (EC) 2003/2003 on EC Fertilisers (DAFM, 2015). Some national regulations, for example in Germany and Switzerland, include provisions for recycled fertilisers (Hukari *et al.*, 2016). The revision of the EU Fertiliser Regulation 2003/2003, currently under discussion, will facilitate the market of inorganic recovered phosphate products (struvite, phosphates from sewage sludge, incineration ash) with criteria for eligible input materials, treatment process, safety and quality requirements (ESPP, 2015a). Current EU regulation does not include maximum concentrations for impurities, and relevant limits are defined by national laws. Revision of the EU

Fertiliser Regulation includes proposals for maximum levels of contaminants, with some of those under discussion shown in Table 4.2 along with current Member State limits. The recent Circular Economy Package confirms that “The Commission will propose a revised EU regulation on fertilisers, so as to facilitate recognition of organic and waste-based fertilisers in the single market and thus support the role of bio-nutrients in the circular economy”. Key aspects to develop bio-nutrient and material recycling, identified during the associated public consultation, included improving quality, information, reliability and standards of recycled materials, addressing the cost differential with primary materials and regulatory obstacles and gaps at regional, national and EU levels (ESPP, 2016).

Regulations (EC) 834/2007 (EC, 2007) and (EC) 889/2008 (EC, 2008d) are relevant to organic farming, a potential niche market for recycled phosphorus fertilisers derived from sewage sludge, as outlined below.

4.4.4.2 Quality requirements

Recovered phosphorus-containing materials must be of satisfactory quality in terms of phosphorus content, plant bioavailability and contaminant concentration for acceptance by the fertiliser industry. The phosphorus content, water solubility, plant-available phosphorus and heavy metal composition of recycled phosphorus products (Table 4.3) vary between products and

Table 4.2. Maximum levels of contaminants in fertilisers proposed for the revised EU Fertiliser Regulation and those specified in current Member State regulations. The former also includes proposals for limit values for polyaromatic hydrocarbons, *Salmonella* spp., *E. coli*, viable weed seeds and macroscopic impurities (ESPP, 2015b; Hukari *et al.*, 2016)

Contaminant	Maximum contaminant level (mg/kg dry matter, unless otherwise stated)		
	Proposed for new EU Fertilisers Regulation		Current regulations in Member States for fertilisers
	Inorganic fertilisers	Organic fertilisers	
Cadmium (Cd) products <5% P ₂ O ₅	3	1.5	
Cadmium (Cd) products >5% P ₂ O ₅	60 mg/kg P ₂ O ₅ ^a		20–60 mg/kg P ₂ O ₅
Chromium ^{VI} (Cr ^{VI})	2	0.5	2
Mercury (Hg)	2	1	1–2
Nickel (Ni)	120	50	50–120
Lead (Pb)	150	120	150–200
Arsenic (As)	60		10–60
Copper (Cu)		200	
Zinc (Zn)		600	

^aMember States may enact lower limits of 20 or 40 mg/kg Cd

Table 4.3. Characteristics of selected final products from phosphorus recovery technologies and raw phosphate; data from Egle et al. (2015)

Approach	g/kg total solids			mg/kg total solids							
	P	N	Ca	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
<i>Aqueous phase</i>											
Ostara Pearl	122	50	–	1	0.5	2.1	67	–	8.7	–	29
DHV crystalactor	133	0	240	0.9	0.4	2.1	2.3	<0.1	7.6	2.1	37
Airprex	100	50	61	–	0.25	–	25.5	<0.1	3.6	6.5	50
<i>Sewage sludge</i>											
Seaborne	120	23	129	–	0.1	1.5	11.5	<0.1	17.6	0.5	24
Mephrec	35	0	~300	–	0.2	68	123	<0.1	13	2.5	11
<i>Sewage sludge ash</i>											
AshDec	85	0	100	10.6	0.1	90	57	<0.1	0.9	12.3	389
Leachphos	135	0	170	–	1.0	25	600	0.5	15	12.5	1500
SSA untreated	50–100	0	100	8–20	1–6	6–120	240–600	<0.1	34–80	40–290	1.0–1.3
Raw phosphate	90–170	0	–	7–26	2–92	25–640	1–23	<0.1	17–37	1.5–17	204–382

production processes. The use of struvite as a fertiliser is well studied relative to other recycled phosphorus products and is considered to be as effective as commercially available phosphate fertilisers in most studies (Tarayre et al., 2016). In general, SSA products are considered of little use for direct utilisation as phosphorus fertiliser in agriculture because of their poor phosphorus bioavailability and high heavy metal content and, with the possible exception of very acidic soils, require further treatment to produce marketable fertiliser products (Franz, 2008; Dikov et al., 2014b; Herzel et al., 2016).

The struvite from controlled precipitation systems, for example PHOSPAQ and ANPHOS, has a sand-like structure, may not be homogeneous and may be contaminated with organic substances, while that from controlled crystallisation systems, for example Pearl, Phosnix and NuReSys, is clean, easy to dry and suitable for use directly as a fertiliser or for mixing with other fertilisers (Desmidt et al., 2015). The low solubility of struvite (1–5% in water), in contrast to conventional fertilisers, may be environmentally beneficial, as the high solubility of the latter may result in high phosphorus concentration in land runoff if rainfall occurs soon after application, potentially contributing to eutrophication. Furthermore, high solubility results in a high concentration of phosphorus in soil solution during early crop growth, which subsequently becomes adsorbed and immobilised on soil particles, limiting the phosphorus supply to crops in later stages of growth. The less soluble struvite, as a slow-release fertiliser, potentially

provides phosphorus to the crop over a longer period and its effectiveness as a phosphorus source for plants has been observed in several lab studies (Talboys et al., 2016). In a lab-based study to determine the potential of struvite in a sustainable phosphorus fertiliser management strategy for arable crops, it was concluded that applying mixes of struvite and DAP to spring wheat could potentially result in optimal early and late season phosphorus supply and uptake, and enhance the overall efficiency of phosphorus use (Talboys et al., 2016). It was also reported that plants exuding large amounts of organic acids, for example buckwheat, achieve more effective uptake of phosphorus from struvite due to the effect of these acids on the rate of dissolution of struvite phosphorus (Talboys et al., 2016).

As part of the EU FP7-funded project P-Rex, the quality of struvite from three different recovery processes and three SSA materials (Leachphos calcium phosphate, AshDec and Mephrec slag) was compared with the quality requirements of the fertiliser sector (Dikov et al., 2014b). It was reported that the phosphorus concentrations of the three struvite products (10–14%) and Leachphos calcium phosphate (12%) was comparable to that of phosphorus rock (13–17%), while the product from AshDec process and Mephrec slag had concentrations of 6% and 4%, respectively, all of which are less than the conventional fertiliser TSP (23%). Assessment of plant bioavailability, as judged by neutral ammonium citrate solubility, indicated poor solubility in the case of Mephrec slag while good solubility

(≥80%) was observed for the other recycled materials. Phosphorus plant availability, as assessed in pot tests, was good with the exception of some struvite (limited) and Mephrec (poor). The recycled materials satisfied the heavy metal legal requirements as specified by German legislation. Struvite, Leachphos and AshDec were better than SSA and some types of sewage sludge in terms of plant availability and conformance to heavy metal legal requirements. Possible fertiliser recommendations have been proposed by P-REX for recycled products including:

- thermochemically treated ash (AshDec) for use on loamy, alkaline soils (less suitable for acidic sandy sites);
- chemically treated ash (Leachphos) on acidic soils;
- thermo-metallurgic treatment (Mephrec) possibly as a slow-release fertiliser.

Upon determination of the phosphorus fertilising effect of various phosphorus recycling products (including a H₂SO₄-digested SSA, four thermochemically treated SSAs and struvite) on five different crops, Vogel *et al.* (2015) reported plant phosphorus uptakes of 90.6–119% relative to TSP and concluded that struvite and treated SSAs are suitable for providing phosphorus for crop cultivation, with struvite the most favourable, followed by Mg-SSAs, Ca-SSAs and H₂SO₄-digested SSA. Positive effects of struvite, thermochemically treated SSAs and H₂SO₄-digested SSAs have also been reported in other studies as described by Vogel *et al.* (2015).

While the use of SSA in the production of fertiliser requires levels of heavy metals in the final product to satisfy regulatory requirements, other elements, such as Cu and Zn, are not currently specified in fertiliser regulations, and also need to be considered, with good-quality ash of high phosphorus and low heavy metal concentration desirable. Furthermore, the Fe/Al concentration of the SSA/phosphate rock mixture should be <2%, which may require alternative precipitants or improved biological phosphorus removal (Egle *et al.*, 2015).

The ESPP has proposed EU Fertiliser Regulation criteria for recovered struvite (which define struvite and conditions under which it could be authorised as a fertiliser) (ESPP, 2015c), as well as criteria for the use of ashes as a fertiliser/fertiliser raw material (ESPP, 2015d). Proposed criteria for struvite (magnesium

ammonium phosphate) consider its use as a fertiliser (directly or subsequent to conditioning or mixing with other nutrient products) or as a raw material/ingredient for fertiliser production, and it is recommended that the same criteria be used in both cases. Recovery of struvite should be undertaken in an installation/system specifically designed to generate struvite. Within the ESPP criteria, purity requirements are described as follows:

- water content (no limit);
- struvite content: acceptable purity range:
 - 10.0–13.9% phosphorus, measured as total phosphorus;
 - 13.1–18.1% MgO, measured as MgO;
 - 4.6–6.3% nitrogen, measured as total nitrogen;
- total organic content (TOC):
 - should not exceed the expected revised EU Fertiliser Regulation limit for inorganic fertilisers (2% of dry matter).

Struvite should comply with contaminant criteria as specified for all products in the revised Fertiliser Regulation, including proposed inorganic contaminants, shown in Table 4.2. Physical quality and general safety criteria should comply with those for inorganic fertilisers in the revised regulation. Additional labelling requirements are proposed for struvite, including water content, nutrient content (% soluble phosphorus), organic carbon content (if >0.1% TOC) and respirable dust (if >10% of particles have diameter <100 µm).

ESPP criteria for the use of ash as a fertiliser (ESPP, 2015d) require it to satisfy the Fertiliser Regulation safety and agronomic efficacy criteria for the category in which it is marketed, while, if it is used as a raw material in a fertiliser production process, such criteria are applied to the finished product and not the raw material. Criteria for mineral contaminants are as above, with possible inclusion of specific limits for Cu and Zn, combustion-specific contaminants, dioxins and furans and polyaromatic hydrocarbons (PAHs). Given the poor plant availability of ash phosphorus, the ESPP recommends that the Fertiliser Regulation recognise ashes as raw materials for fertiliser production as a default and as fertilisers (for direct use) only if there is evidence of agronomic efficacy and that a minimum percentage of phosphorus plant availability should be required for direct use as a phosphorus fertiliser.

4.4.4.3 Market entry of recycled phosphorus

Producers of recycled phosphorus may sell the resulting products to wholesalers, retailers and/or customers as finished fertiliser products or to fertiliser producers as feedstock/raw material for acidulation or phosphoric acid production, granulation or blending. In terms of raw material, fertiliser producers can use SSA, meat and bone meal ash or recycled intermediates free from organic matter in the wet chemical process (Hukari *et al.*, 2016). The recycled product may be sold to the fertiliser producer as waste or product. Selling as waste (at a lower market price) is associated with lower technology costs and reduced requirements for REACH registration, quality control etc. and is likely to be favourable for small recyclers. Larger recyclers, with the advantage of economy of scale, are likely to favour product status, with associated higher market prices (Dikov *et al.*, 2014a). In terms of the end-user, while agriculture and horticulture represent the main fertiliser market, similar products, sold in smaller packages and with higher margins, are of interest to the gardening and landscaping sector (Dikov *et al.*, 2014a). This may be a potential target market for smaller recyclers/fertiliser producers. Organic farming (accounting for 4.7% of EU agricultural land; Dikov *et al.*, 2014a) may also be a potential niche market for recycled phosphorus fertilisers derived from sewage sludge. In general, land-spreading of sewage sludge is currently prohibited in organic farming because of potential contamination with harmful substances (Wollmann and Moller, 2015). Recycled fertiliser, while currently not approved for this application (Dikov *et al.*, 2014a), reduces the risk of soil contamination (Wollmann and Moller, 2015) and, in some cases, satisfies organic farming principles as a “renewable source enabling closing of the nutrient loop and non-water soluble” (Hukari *et al.*, 2016). The slow-release nature of some recycled phosphorus fertilisers, allowing release of phosphorus to the soil over time, is also desirable for this sector (Dikov *et al.*, 2015b). The suitability of recycled phosphorus products for this sector, along with associated sustainability criteria and philosophical requirements, are still being considered by organic farming associations and approval is likely to be time-consuming and would require changes to the EU legislation on organic farming (Hukari *et al.*, 2016). As part of the P-REX project, the “eMarket” was set up to facilitate market development of secondary nutrients by supporting matchmaking between suppliers of recovered nutrients and potential end-users. The eMarket is

non-commercial and is available on the website of the ESPP at <http://e-market.phosphorusplatform.eu/>

4.4.4.4 Current status

Full-scale phosphorus recovery installations are operational in some European countries (the Netherlands, Belgium, Germany, Austria), North America and Asia (Japan), where their implementation has been driven mainly by national regulations governing the use of sludge in agriculture, environmental protection, recycling targets and, in the case of Japan, high sludge disposal costs (Desmidt *et al.*, 2015). Switzerland has become the first country to make phosphorus recovery and recycling from sewage sludge and slaughterhouse waste obligatory, with the introduction of a new regulation on 1 January 2016 with a transition period of 10 years. Specific details, including required efficiency of the recovery process and required fertiliser plant availability, will be defined (ESPP, 2016). Approximately 2000–3000 tonnes of struvite are currently produced in Europe each year from municipal sewage (EC, 2015a). Currently, struvite is not recognised as a fertiliser in Europe and, without special acknowledgement by the national government as fertiliser, struvite is considered as waste with implications for distribution for use in agriculture (Desmidt *et al.*, 2015).

A market study undertaken as part of the P-REX project (Dikov *et al.*, 2014a) covering Bulgaria, the Czech Republic, Germany, Spain and Switzerland, looked at the potential use of recycled phosphorus by fertiliser producers. While there was little interest in phosphorus recycling in Bulgaria, in the Czech Republic Lovochemie is interested in using struvite and would consider ash (phosphorus content approximately 17%), while FOSFA is interested in recycled product and recycling technologies. In Germany, ICL (discussed below) is interested in ash-based secondary phosphate products, while two other companies expanding their product range were also interested in secondary phosphates. In Spain, provision of secondary phosphorus at a comparable price and adaptation of legislation were seen as challenges, while price was also a factor in Switzerland, as well as availability in granular, ready to use form. The P-REX project identified 76 sites processing phosphorus-containing fertiliser in the EU-27, of which five sites (in Germany, the Netherlands, France and the UK) are currently using or are very interested in using recycled phosphorus and a further 13 sites are interested pending

availability of larger amounts or quality changes (Dikov *et al.*, 2014a).

ICL Fertilisers, with production units in the Netherlands, Germany and Israel, has undertaken extensive research including plant-scale tests on the use of secondary phosphates (including struvite, SSA, meat and bone meal ash and calcium phosphates) in fertiliser production (Langeveld, 2015). Promising results have been observed with only minor modifications to the current production facilities required (Langeveld and ten Wolde, 2013). Moreover, the use of secondary phosphates for fertiliser production may reduce phosphate and fluorine emissions compared with the use of phosphate rock (Langeveld and ten Wolde, 2013). Issues under investigation include the possible presence of contaminants such as pathogens and pharmaceuticals in struvite (Langeveld and ten Wolde, 2013). In 2011, ICL and the Dutch authorities committed to replace 15% phosphate rock with secondary phosphates by 2015 and up to 100% in 2025. ICL aims to use 25–30 kilotonnes secondary phosphate by 2015 (ESPP, 2015b; Langeveld, 2015). John Hatcher & Co Ltd (UK) sells fertiliser containing incinerated poultry litter (FibroPhos) and is interested in using additional recycled phosphorus in its products (Dikov *et al.*, 2014a; Hatcher Fertilisers, 2015). The direct use of SSA as a partial substitute for phosphate rock in the fertiliser industry offers the advantage of using existing infrastructure and technologies and selling to existing markets (Egle *et al.*, 2015). More recent developments include the Dutch companies HVC and SNB and EcoPhos (Belgium) signing a contract in 2015 for EcoPhos to use approximately 60,000 tonnes/year of SSA from the Netherlands as a raw material for phosphorus recycling using a wet chemical process to produce DCP for use in fertilisers or animal feed (EcoPhos, 2015b; ESPP, 2015e).

The following are some examples of successful market entry of recovered phosphorus products in the fertiliser industry:

- The struvite from Pearl technology (Crystal Green) is certified as fertiliser in the United States and the UK (Desmidt *et al.*, 2015). Crystal Green contains 28% available phosphorus and is sparingly water soluble, providing phosphorus, nitrogen and magnesium in a slow-release granule which dissolves in response to organic acids produced by the plant during root growth. The low water solubility

of Crystal Green distinguishes it from conventional phosphorus fertilisers, which are highly water soluble. Crystal Green has been successful on high-value agricultural crops, turfgrass, golf and horticulture applications, including container or field-grown nursery stock. Crystal Green may be produced in different sizes (100–240 size guide number), is dust free and may be combined with other fertiliser components (Crystal Green, 2015). In January 2016, the signing of a licensing agreement between the British company ACWA and Ostara Nutrient Recovery was announced, under which ACWA will offer nutrient recovery technology in the UK while Ostara will manage the sale and marketing of the resulting Crystal Green fertiliser (Waste and Wastewater International, 2016).

- AirPrex struvite is mainly sold directly to the fertiliser industry for additional processing or to farmers for direct use (P-REX, 2015d). Berlin Wasserbetriebe distributes struvite from the Airprex process as a mineral fertiliser under the name “Berliner Pflanze” within Berlin and the Brandenburg region and it is sold as compound fertiliser containing nitrogen, phosphorus and magnesium under German and European fertiliser regulations. It is recommended for flowering plants (Schitkowsky, 2015) and is the first AirPrex product with official fertiliser approval and REACH registration (P-REX, 2015e).
- The struvite from NuReSys (BioSTRU) is certified as fertiliser in Belgium (Desmidt *et al.*, 2015) and its use as a start-up fertiliser for maize (ESPP, 2015e), as a soil conditioner and in wine growing has been reported (Desmidt *et al.*, 2015).
- Struvite from the ANPHOS and PHOSPAQ processes is exported to Germany for use as a raw material in the production of fertilisers or for mixing with other fertilisers to achieve desirable nutrient content.
- In Japan, struvite from the Phosnix process is used as a raw material by the fertiliser industry, with the resulting fertiliser used for growing rice, vegetables and flowers (Desmidt *et al.*, 2015).
- The PhosKraft fertiliser product (calcined phosphorus) from the AshDec process is licensed in Austria and Germany (Desmidt *et al.*, 2015) and it has been reported that Lonza has produced NPK granule fertilisers using recovered phosphates from AshDec of sewage sludge incineration ash (ESPP, 2014).

4.5 Animal Feed Phosphates

4.5.1 Overview

Phosphorus is an essential nutrient for all animals and, after calcium, is the most abundant element in the body, where approximately 80% of phosphorus is found in the skeleton (IPNI, 1999; Hoffmann *et al.*, 2009; Kebreab *et al.*, 2012). Phosphorus is required for the development and maintenance of the skeleton and plays a role in a variety of physiological processes (Poulsen 2000; Humer and Zebeli, 2015). Phosphorus deficiency results in reductions in appetite, feed efficiency and weight gain, has a negative effect on fertility, milk yield and composition in ruminants and is associated with reduced growth and bone abnormalities in pigs and with skeletal problems and reduced egg yield and eggshell quality in poultry (IPNI, 1999; Poulsen, 2000; Humer and Zebeli, 2015). Plants used as animal feed contain phosphorus, much of which (up to 80%) is in the form of phytate (Poulsen, 2000). While phytate can be utilised by ruminants thanks to microbial activity in the rumen, it is not sufficient to meet the animal's requirements, and supplementation with more readily available inorganic phosphate is necessary for optimal animal growth, performance and welfare. Phytate is poorly available to monogastric animals (pigs and poultry) and, while its digestibility can be improved by adding the enzyme phytase to animal feed, supplemental inorganic phosphate is also required to satisfy nutritional requirements (Humer and Zebeli, 2015; Kebreab *et al.*, 2015). Inorganic phosphates are highly digestible and

phosphates may be incorporated into complete feed or used as mineral supplements. The most commonly used feed phosphates are MCP and DCP, while others include TCP as well as magnesium, calcium-sodium, calcium-magnesium, ammonium and sodium phosphates (IFP, 2016). Details of selected animal feed phosphates are shown in Table 4.4.

Important criteria for feed phosphates used in animal nutrition include:

- high phosphorus availability/digestibility:
 - determined via bone measurements and balance trials;
- in vitro solubility >95% in both 2% citric acid and alkaline ammonium citrate:
 - indication of good availability/digestibility;
 - solubility in alkaline ammonium citrate determines presence of TCP, which is less favourable for monogastric animals;
- known phosphorus and calcium content and calcium to phosphorus ratio:
 - necessary to calculate dietary inclusion levels;
- acceptable level of impurities:
 - arsenic, cadmium, lead, fluorine and mercury;
 - presence and level regulated by EU legislation (section 4.5.4);
- application-relevant physical properties:
 - for example, particle size and density appropriate for intended use (for example in compound feed, mineral supplements, lick block etc.) to allow ease of handling and uniform dispersion.

Table 4.4. Composition of selected animal feed phosphates (Wzorek and Kowalski, 2001; IFP, 2016)

Product	P content		Ca (minimum content)	Ca:P
	%	g/kg	g/kg	
Dicalcium phosphate (DCP) ^a	17–21	180–200	210	<1.15:1
Monocalcium phosphate (MCP) ^a	22.7	210–220 minimum	150	<0.8:1
Tricalcium phosphate (TCP) ^b	20	Up to 180 minimum	350	1.9:1
Crude defluorinated phosphate (DFP) ^c	18	140	220	
Tricalcium phosphate with sodium addition (DFP CaNaP)		180–185	320–330 (40–50 g/kg Na)	1.9:1
Monodicalcium phosphate (MDCP) ^a	21	40–60% MCP, 25–40% DCP plus non-calcium phosphates		

^a>95% solubility in citric acid and ammonium citrate.

^b<95% solubility in citric acid and ammonium citrate.

^c>95% solubility in citric acid and < 95% solubility in ammonium citrate.

4.5.2 Production of animal feed phosphates

Calcium phosphates for animal feed are generally produced from phosphate rock, which is first digested with sulphuric acid to produce phosphoric acid (wet process, as described in section 4.3). Purification (often by solvent extraction) and defluorination is undertaken to reduce the content of heavy metal compounds and fluorine to permissible levels (Hoffmann, 2007). Calcium phosphates are obtained by neutralisation of the phosphoric acid with calcium compounds (calcium oxide, hydroxide or carbonate) under controlled conditions (Hoffmann, 2007; Hoffmann *et al.*, 2011). For example, Aliphos DCP is produced in the Netherlands using this approach, while Aliphos Monocal (MCP) is produced by reaction of DCP with purified and defluorinated feed-grade phosphoric acid (Aliphos, 2016).

In Tessenderlo's phosphate plant in Ham, Belgium (which closed down in 2014 for sustainability reasons), the production of feed-grade phosphates used HCl from the sulphate production process. Phosphate rock was purified using the hydrochloric acid dissolution method, resulting in the formation of a MCP solution and, following counter-current purification, DCP crystals were precipitated, filtered and dried. The DCP obtained had a crystalline structure (unique to the HCl production process) reported to be nutritionally beneficial and was also used to produce monocalcium phosphate (All About Feed, 2003). A complex of MCP and DCP (monocalcium phosphate; MDCP) can be produced by reacting DCP with defluorinated and purified feed grade phosphoric acid (Aliphos, 2016). In animal feed phosphate production, transformation into biologically unavailable forms of phosphorus, such as pyro- and meta-phosphate, must be prevented during the production process (IFP, 2016).

4.5.3 Current and projected demand for animal feed phosphates

Inorganic feed phosphates are used by the animal feed industry and producers of feed and mineral supplements, pet food and premixes. Global consumption, estimated at 7.7 million tons 41% P_2O_5 in 2012, is projected to increase to 8.5 million tons in 2017 (Feedinfo News Service, 2013). MCP and DCP accounted for 91.7% of global feed-grade calcium phosphate consumption in 2012, with TCP accounting for 8.3%. Increased use of MDCP is expected to replace DCP

(IHS, 2013). The largest market for feed phosphates in 2014 was Asia-Pacific, followed by North America and Europe, with China accounting for 23.5% of world consumption (Markets and Markets, 2015). An increase in consumption has been observed in developing countries, which has been attributed to increased wealth and dietary changes towards increased meat consumption (Feedinfo News Service, 2013; IHS, 2013). In contrast, consumption of feed phosphates has been declining in developed countries because of cost, more efficient use of feed phosphate (driven mainly by pollution concerns and associated regulation) and the growing use of phytase to increase phytate-phosphorus bioavailability, which is reported to save >7kg DCP per tonne of feed (EUFETEC, 2013; IHS, 2013). A report on the feed phosphate market by the market research firm Markets and Markets projects the market for feed phosphates to reach US\$5.8 billion by 2020, with a compound annual growth rate of approximately 3% from 2015 to 2020 (Markets and Markets, 2015b).

4.5.4 Relevant European legislation

In Europe, phosphates are considered as feed material by law (as opposed to feed additives) in accordance with Regulation EC 68/2013 (Catalogue of feed materials) (EU, 2013). Rules relevant to the marketing of feed materials and compound feed are established in Regulation (EC) No 767/2009 on the placing on the market and use of feed (EC, 2009). Among the objectives of this regulation are to ensure feed safety and, therefore, protection of public health, to provide sufficient information for users and consumers and to ensure transparency and traceability. Feed materials may be marketed without pre-market approval assuming they are safe and genuine and do not have a direct negative effect on animal welfare or the environment (FEFANA, 2016). Labelling requirements are described and information relating to the composition or claimed properties of the feed material must be available to competent authorities (FEFANA, 2016). Directive 2002/32/EC on undesirable substances in animal feed (EC, 2002) sets down controls including maximum permitted levels of various contaminants in feed including heavy metals (Table 4.5). Cefic (the European Chemical Industry Council) awards a Quality Feed Phosphate symbol to products guaranteed to be of high quality and nutritional value and meeting EU regulations for impurities. Continuing compliance is monitored by random

Table 4.5. Maximum levels of undesirable substances allowed in products intended for animal feed as laid down in Annex I of Directive 2002/32/EC (EC, 2002; IFP, 2016)

Undesirable substance	Maximum content in mg/kg (ppm) relative to a feedingstuff with a moisture content of 12%
Fluorine	2000
Cadmium	10
Arsenic	10
Mercury	0.1
Lead	15

sampling and testing (IFP, 2016). Regulation (EC) No 1831/2003 on Feed Hygiene specifies minimum hygienic requirements with which operators along the feed chain must comply (FEFAC, 2014a). The European Feed Manufacturers' Guide (EFMC) (FEFAC, 2014b) is considered a practical tool for the implementation of the hygiene and hazard analysis and critical control points (HACCP) requirements of this regulation. National guides to good practice have also been established, for example "GMP+ certification" in the Netherlands and QS certification in Germany, adhered to by TIMAB Phosphates.

4.5.5 Use of recycled phosphorus – current status

As part of the EU FP7-funded project P-Rex, the quality of struvite from three different recovery processes and three SSA materials (Leachphos calcium phosphate, AshDec and Mephrec slag) was compared with the quality requirements of the feed industry in terms of impurities (Dikov *et al.*, 2014b). It was reported that the recycled products were not suitable to be used for this application and production process adjustments would be necessary to reduce the concentrations of aluminium, calcium, magnesium and iron, as well as arsenic, in some cases.

EcoPhos, a Belgian company, is involved in the phosphate industry both as a producer of animal feed phosphate and as a technology provider, with the developed technology based on using alternative sources of phosphate including low-grade phosphate rock and fly ashes from incineration of sewage sludge (EcoPhos, 2015b). EcoPhos is currently building a €60

million facility in Dunkirk, France (as outlined in section 4.4.4.4), with a reported second phase to include a production line for the transformation of approximately 60 kt ashes into feed phosphate per year. The plant will have the capacity to produce up to 220 kt DCP per year, partially based on SSAs, and is the first industrial plant in Europe processing these ashes. One of the business models of EcoPhos is to sell its technology and supply basic engineering to the phosphate production sector. Patented technologies have been developed for (1) producing DCP and/or phosphoric acid from various phosphate sources including secondary phosphates; (2) purifying phosphoric acid to produce various grades, including technical, feed, food and electronic grades; and (3) preparing phosphate specialities from various raw materials. The processes have been developed as modular units that can be combined for various raw material/product combinations.

4.6 Other Uses

4.6.1 Food industry

Adequate dietary levels of phosphorus, while essential, are normally consumed in modern diets and, therefore, food phosphates are generally used not as a dietary additive but rather to improve food products (Cefic, 2016). A range of phosphate compounds with different properties are used for numerous technological purposes in a range of foodstuffs, for example to maintain flavour and food quality, to provide buffering capacity, to improve shelf life, as leavening agents in baking, for stabilisation of texture, as a support for calcium, magnesium and iron mineral enrichments (EFSA, 2013; Cefic, 2016) and to prevent bacterial growth in bottled soft drinks (Desmidt *et al.*, 2015). Several phosphate-containing food additives (E 338–341; E 343; E 450–452) are permitted in the EU and are included in the list of additives established by Regulation (EC) No 1333/2008 (EC, 2008e). Phosphates are added to food at low levels with maximum permitted levels, as defined in Regulation EU No 1129/2011, in the range 1000–50,000 mg/kg food (EFSA, 2013). Phosphates are included in the planned re-evaluation of food additives under Regulation EU No 257/2010 due for completion in December 2018 (EFSA, 2013). Approximately 100,000 tonnes of food phosphates (approximately 25,000 tonnes P) are used in Europe (EU 25) per year. Food phosphates are produced from purified phosphoric acid.

4.6.2 Detergent industry

Phosphate, in the form of sodium tripolyphosphate (STPP) is added to detergents as a builder to reduce water hardness by binding to calcium and magnesium ions, which would otherwise decrease surfactant activity, and is also added to enhance cleaning by loosening dirt, breaking it into small particles and keeping it in suspension in the wash water, preventing reattachment to the cleaned material (Richards *et al.*, 2015). Environmental concerns in relation to the contribution of detergent products containing STPP to eutrophication has led to many regions in Western Europe, USA, Canada and Japan regulating their use. Regulation (EU) No 259/2012 (EU, 2012) addresses the need to reduce the use of phosphates in consumer laundry and dishwasher detergents and sets a limitation of 0.3g on the total phosphorus content in the standard dosage in consumer automatic dishwasher detergents from January 2017, while a limitation of 0.5g has been applied for laundry detergents since June 2013. Alternative substances are available to replace phosphates in this application, and stringent regulations, together with the development of phosphate-free detergents, will significantly reduce the demand for STPP. Several countries in Western Europe and North America have already phased out the use of STPP in detergents (Nielsen, 2012).

4.6.3 Additional technical uses

As outlined in section 4.3, phosphates are used in various other applications, which represent only a small fraction of total consumption ($\leq 5\%$) (Desmidt *et al.*, 2015). These include, for example, flame retardants, lithium-ion batteries and pharmaceuticals.

Flame retardants, of various composition, are used to prevent combustion and slow down spreading of fire. Phosphorus flame retardants (PFRs) accounted for 20% of flame retardant consumption in Europe in 2006 and may be divided into three main groups: inorganic (red phosphorus, ammonium polyphosphate), organic (organophosphate esters, phosphonates and phosphinates) and halogen-containing [Tris(chloropropyl) phosphate (TCPP) and Tris(2-chloroethyl)phosphate (TCEP)]. Phosphorus flame retardants may be reactive, which are chemically bound to a polymer molecule, or additive, which are mixed into the polymer material by physical means. They are used, for example, in plastics,

polyurethane foams, thermosets, coatings and textiles (van der Veen and de Boer, 2012; pinfa, 2016).

Lithium iron phosphate (LiFePO_4) is of use as a cathode electrode material for lithium-ion batteries used in electric vehicles, electric bikes and power tools and is associated with low cost, non-toxicity and low environmental impact, as well as good cycle stability and thermal stability (Satyavani *et al.*, 2016).

Phosphorus compounds, in particular phosphonates, are used in pharmaceutical drugs because of their antifungal, antibacterial, anticancer and analgesic properties, and their potential as antioxidants and anti-diabetics has been reported (Kamel, 2015).

4.6.4 Use of recovered phosphorus in the production of white phosphorus

Recovered phosphorus, including SSA and calcium phosphate, may be used to replace some of the phosphate rock in the process used to produce elementary (white) phosphorus. Thermphos International in Vlissingen, the Netherlands, a former producer of phosphorus chemicals and the only white phosphorus producer in Europe, supplied high-end markets (chemical and food industry) and incorporated SSAs and recovered calcium phosphate in its existing production process (Desmidt *et al.*, 2015; P-REX, 2015d). Although Thermphos was declared bankrupt in 2012 (for reasons unrelated to phosphorus recycling), its use of recovered phosphorus is described here for information purposes and to highlight the potential use of recovered phosphates as a complementary raw material to phosphate rock in such a process. As Thermphos was the only producer of elementary phosphorus in Europe, the availability of this option for phosphorus recycling in the future is uncertain (Petzet and Cornel, 2013).

Thermphos produced elemental phosphorus via the thermal route (section 4.3), as opposed to producing phosphoric acid by the wet-acid process as undertaken at other phosphate/fertiliser sites (CEEP, 2001). The process involved an initial granulation step where ground phosphate rock is added with a binder (clay) on a rotating disc to produce pellets, which are dried and sintered at 800°C prior to mixing with cokes (reducing agent) and pebbles (SiO_2 , for slag formation) and feeding to a furnace at 1500°C . Under these conditions, phosphate is reduced to P_4 , which is condensed after leaving the furnace as a gas. The remaining calcium

oxide in the furnace combines with the SiO₂ to form liquid slag, which is used, for example, in road construction. Another slag, ferrophosphorus (25% P), is also formed from iron (present as an impurity in the rock), and is used as a steel additive (CEEP, 2001; Schipper *et al.*, 2004; Egle *et al.*, 2015). For phosphate recycling, the material is mixed with the phosphate rock prior to the grinding stage. Important criteria in this process include phosphate content, water content and level of impurities, with a molar ratio of Fe/P <0.3 required. The high iron content (up to 10%) of SSA is undesirable because of excessive production of ferrophosphorus but can be reduced by replacing the ferric chloride used in the phosphate precipitation step in WWTPs with calcium or aluminium. The high zinc and copper content of sewage ash can also be a problem, with concentrations of <0.1 and <0.5g/kg ash required, respectively. In WWTPs with EBPR, phosphate precipitation of liquid side streams using Al or Ca could produce phosphates suitable for this process with low Cu and Zn content (CEEP, 2001). The calcium phosphate from the Crystalactor process meets quality requirements and was successfully used as a raw material by Thermphos (Desmidt *et al.*, 2015). Selective phosphate recovery at WWTPs with biological phosphate removal, using the Phostrip process, also produces a very pure calcium phosphate with acceptable impurity levels. Struvite is not a suitable substitute for phosphate rock in the electrothermal process due to its ammonia content, as nitrogen is associated with emission or gas scrubbing problems in the sintering stage (Schipper *et al.*, 2004; Desmidt *et al.*, 2015).

The use of SSAs by Thermphos was associated with reduced operational costs due to the ash having a lower price than phosphate rock, while sewage sludge incinerators benefited from the ash, previously a waste and cost factor, being considered an asset (P-REX, 2015d). While there is no producer of elementary phosphorus in Europe since the closure of Thermphos, a European-funded project, RecoPhos, has developed a bench-scale reactor to recover thermal phosphorus from SSA. The thermochemical RecoPhos process based on the fractioned extraction of phosphorus and heavy metals from the ash at high temperatures under reducing conditions can run entirely on SSA and has a simple design without pelletising/sintering (RecoPhos, 2016).

Elementary phosphorus can be used a raw material to produce high-quality phosphoric acid and other

phosphorus compounds for use in various industrial applications outside the fertiliser industry including flame retardants, crop protection agents, food additives, lubricating oil additives and water treatment additives (Desmidt *et al.*, 2015; EcoPhos, 2015b). In the context of these applications and the use of recycled phosphorus, it is noteworthy that the EcoPhos process (section 3.3.2.3) is also capable of producing technical-, food- and electronic-grade phosphoric acid from various raw materials.

4.7 Market Value of Recycled Phosphorus

As part of the P-REX project, the estimated price range of recycled mineral phosphorus-containing materials was compared with the price range of relevant market segments (fertiliser, feed and technical use) (Table 4.6). Sewage sludge and SSA were considered to have a negative market value. The offered/estimated prices for the recycled phosphorus products (€300–1700) were reported to be in line with those of the fertiliser market, while it was recognised that higher prices could potentially be obtained for recycled products meeting the requirements of the feed and more technical market segments.

Desmidt *et al.* (2015) reported prices for phosphate rock ranging from €200 to €260 per tonne P in March 2007 and from €830 to €1120 per tonne P in March 2012 compared with fertiliser prices in the USA in 2012 of €1900 per tonne P and €3300 per tonne P for DAP and superphosphate, respectively. In terms of

Table 4.6. Market price estimations of phosphorus used in different markets and recycled phosphorus products from P-REX project (Dikov *et al.*, 2014b)

Market segment	Price (€/t P)
Phosphate rock	500
Triple superphosphate	1400
Feed phosphate (DCP)	2000
Other non-food uses	2000–3000
<i>Recycled phosphorus materials</i>	
Struvite	300–1000 (niche markets up to 6000)
Calcium phosphate 14% phosphorus	850–1100
Calcium phosphate 16% phosphorus	1200–1600
Mephprac slag	700–1700

inorganic fertilisers in Ireland, the cost of a mean kg of phosphorus was €203 in 2011 (Healy *et al.*, 2015). When the value of struvite was calculated based on its individual components using fertiliser prices from March 2012, a value of €684 per tonne struvite (€2600/t P) was obtained. The market value of struvite from the NuReSys process ranges from €380 to €460 per tonne P (€100–120 per tonne struvite) (Desmidt *et al.*, 2015), while AirPrex struvite is being sold at approximately €100 per tonne (P-REX, 2015d). The sales price of the Berliner Pflanze struvite fertiliser depends on package size, with smaller packages having higher sales prices (€2.50/kg) (Schitkowsky, 2015). Molinos-Senante *et al.* (2011) report market price estimates for struvite ranging from €188 to €763 per tonne. Donatello *et al.* (2010) highlight the higher revenues that could be achieved by targeting non-fertiliser markets using 85% phosphoric acid (for example technical, food, beverage and electronic markets), with prices of 85% phosphoric acid ranging from US\$750 to \$2000 per tonne in the period 2007–2009.

In addition to the market value of the recovered phosphorus, determination of economic feasibility should also consider the associated environmental benefits, as well as potential cost savings, for example reduced

waste disposal and phosphorus removal chemical costs, and operational benefits, which, depending on the process, may include improved sludge dewatering properties, improved nutrient removal performance, avoidance of unwanted phosphorus precipitation and pipeline clogging/incrustations etc. (ESPP, 2015e, Desmidt *et al.*, 2015; Tarayre *et al.*, 2016).

4.8 Conclusions

Phosphorus recovered from municipal waste can be used directly as a fertiliser, for further processing to produce fertiliser or as a raw material substitution for mined phosphate rock in certain processes. Selection of a phosphorus recovery technology should include the identification of an outlet for the recovered phosphorus and also associated requirements, such as quality, physical characteristics and logistics. Technology selection should include any regulatory requirements that should be considered so that the recovered phosphorus is compatible with the requirements of the target market. While market entry of recycled phosphorus products is currently possible, legal, societal and economic barriers exist which need to be overcome to facilitate further market development and acceptance of recycled phosphorus, as outlined in Chapter 5.

5 Conclusions and Recommendations

There is a global need to promote more efficient use of phosphorus and also its recovery and reuse. Municipal wastewater represents a major source of poorly exploited phosphorus. Current wastewater treatment approaches are driven by water pollution concerns and are “treatment orientated” with emphasis on phosphorus removal to meet discharge requirements as opposed to recovery and recycling. A recovery-focused approach viewing phosphorus as a resource as opposed to a pollutant needs to be adopted. Numerous technologies have been developed to recover phosphorus from wastewater. In addition to reducing effluent phosphorus to acceptable levels and preventing eutrophication of receiving waters, such technologies offer the potential to produce marketable phosphorus products reducing the requirement for phosphate rock, providing a revenue stream and addressing contamination concerns associated with conventional recycling by the direct application of treated sludge onto agricultural land. Recovery of phosphorus from wastewater also has the potential to create jobs and promote economic growth. It is expected that phosphorus recovery will become an established process in industrialised countries over the next 20 years for economic reasons (Sartorius *et al.*, 2012). The number of phosphorus recovery technologies operating at full or demonstration scale in Europe increased from 2 in 1998 to 22 in 2014 (Hukari *et al.*, 2016). Although several recovery technologies are technically feasible at industrial scale, widespread implementation has not been achieved to date, which can be attributed, at least in part, to the lack of an economic incentive as well as legal, societal and market barriers (Desmidt *et al.*, 2015; P-REX, 2015d).

5.1 Conclusions

5.1.1 Implementation of phosphorus recovery

- International strategies and policy support are necessary to motivate and establish phosphorus recovery. In a survey of 197 experts from 30 countries reported by Sartorius *et al.* (2012), 68% believe that additional political measures are necessary to establish phosphorus recycling. Measures proposed by P-REX to establish extensive phosphorus

recovery in Europe include European phosphorus recovery targets in combination with a European road map and definition of “Best Available Technologies” for phosphorus recovery and recycling, as well as obligatory national or regional action plans for phosphorus recovery in line with European goals (P-REX, 2015d).

- A clearly defined and reliable policy framework is necessary for investment in phosphorus recycling (EC, 2015b). Although current European legislation enables phosphorus-recycling efforts, a review of the relevant European legislation by Hukari *et al.* (2016) highlights a number of challenges. These include fragmented legislation and decision-making, differing interpretations of legislation (and hence exact requirements for recovery) within Member States, initial classification of recovered phosphorus as waste with associated handling obligations as opposed to the product status of imported phosphate rock, national authority-dependent approval of the “End of Waste” status, meaning a material may have product status in one country but not in another, and lengthy REACH authorisation processes. Such challenges support the use of phosphate rock over recovered phosphorus. Clearer guidelines to assist with interpretation of existing legislation in relation to phosphorus recycling are required in addition to clarification and harmonisation of current legislation, more consistent implementation, an end to contradictory national interpretations and clearer EU-wide end-of-waste criteria (EC, 2015b; P-REX, 2015d; Hukari *et al.*, 2016).
- National and EU-wide mechanisms to ensure fair distribution of recovery costs (for example fertiliser mixing quotas, recovery obligations, subsidies) and financing of demonstration projects have also been proposed (P-REX, 2015d; Hukari *et al.*, 2016) to help establish phosphorus recovery and recycling, force market entry of the resulting products and encourage the fertiliser industry and other players to invest and/or enter into long-term agreements with secondary phosphorus producers. However, such mechanisms need to be developed with careful consideration to avoid unwanted side effects.

5.1.2 Phosphorus recovery technologies

- Numerous technologies have been developed for recovering phosphorus from municipal wastewater which differ significantly in terms of their scale, cost, performance and state of development. Selection of the most appropriate means of phosphorus recovery for a given country is strongly influenced by national context, regulations and drivers as well as existing infrastructure. Phosphorus recovery rate, economic efficiency and environmental impact are important considerations. Furthermore, an outlet for the recovered phosphorus needs to be identified and associated requirements such as quality, physical characteristics and logistics need to be considered so that the phosphorus recovered using the technology selected is compatible with the requirements of the target market. The objectives and needs of the WWTP also need to be satisfied.
- Approaches based on the precipitation of phosphorus from sludge liquor are considered to be simple and technically feasible and can be applied on a small scale at individual WWTPs, producing marketable struvite. However, their application is generally limited to WWTPs with EBPR and the phosphorus recovery potential is low (approximately 30–40% of WWTP influent) (Sartorius *et al.*, 2012; Egle *et al.*, 2015). A higher phosphorus recovery potential (up to approximately 90%) can be achieved from sewage sludge/sludge ash using wet chemical and thermal processes. These are complex, multi-step processes requiring large amounts of chemicals and/or energy with large investment and operational costs that may not be economic on a small scale (Desmidt *et al.*, 2015). Furthermore, these types of processes are not as far along in their technical development and the risk of technology lock-in needs to be considered. In the survey of experts in phosphorus recovery reported by Sartorius *et al.* (2012), 53% considered that the precipitation of phosphates from the liquid phase represents the most important route for phosphorus recycling and the less costly approaches were preferred even at the expense of lower yields. In countries already incinerating sewage sludge, phosphorus recovery from ash becomes more attractive, as the cost of incineration is not attributed to phosphorus recovery. This is evident in the Sartorius survey, with 61% of the

experts consulted considering phosphorus recovery from ash the best alternative if sewage sludge is incinerated. This approach is generally considered to be the most promising for phosphorus recovery as, in addition to the high recovery potential, SSA of appropriate composition can be used directly as raw material in the fertiliser industry or in the electro-thermal production of phosphorus, as outlined in Chapter 4 (Petzet and Cornel, 2013).

5.1.3 Phosphorus recovery in an Irish context

- The potential for implementing phosphorus recovery in Ireland is currently limited by the lack of existing infrastructure. Approaches based on the precipitation of phosphorus from sludge liquor are generally limited to WWTPs with EBPR, which is currently used in only approximately 10% of European WWTPs (P-REX, 2015d) and only a small number of WWTPs in Ireland. Furthermore, mono-incineration of sewage sludge, a prerequisite for phosphorus recovery from ash, is currently not undertaken.
- Currently, the dominant use of sewage sludge in Ireland is as a fertiliser or soil enhancer on agricultural land. While landspreading of treated sludge is a simple and straightforward method of phosphorus recycling, this approach may need to be reconsidered in the future because of concerns in relation to contamination with pathogens, heavy metals and toxic organic compounds, as well as the plant availability of sewage sludge phosphorus (Tarayre *et al.*, 2016). Incineration, as an alternative sludge outlet, would create further possibilities for phosphorus recovery and potentially allow maximum utilisation of phosphorus from wastewater. Incineration of sewage sludge and subsequent recovery of phosphorus from ash would not involve major changes at WWTP level (except possibly for the precipitant, as outlined in section 4.6.4) and could be developed as an independent operation by an external company at a central location to which sewage sludge could be transported, providing the advantage of economy of scale.
- An additional challenge to implementing phosphorus recovery in Ireland is the absence of an obvious market for the recovered phosphorus. The fertiliser market in Europe is highly consolidated, with five to seven producers accounting for more

than 80% of the volume (Hukari *et al.*, 2016). Although several fertiliser companies have a presence in Ireland (including Gouldings, Grassland AGRO, Nitrofert, Target, Grassland Fertilisers and Yara), phosphorus fertilisers are imported into Ireland for blending into finished products, with no manufacture of phosphate fertiliser undertaken here (Fertilizer Association of Ireland, 2 February 2016, personal communication). The possibilities for future use of recovered phosphorus by the fertiliser industry in Ireland may, therefore, be limited and detailed investigation with relevant players is essential to explore possibilities and associated requirements prior to selecting appropriate recovery technologies. While recovered struvite could potentially be marketed directly as a fertiliser, developing a niche market for this product is likely to require significant effort, and scale of production is limited by the lack of EBPR in Ireland. To our knowledge, there are currently no other industries involved in phosphorus processing or potential users of significant quantities of recovered phosphorus in Ireland. Should incineration facilities be developed, as outlined above, various possibilities could be investigated including for example the potential export of SSA for phosphorus recovery in countries with existing industrial outlets for the recovered phosphorus.

5.2 Recommendations

- Developments in international strategies and policy in relation to phosphorus recovery should be monitored in terms of their implications for implementing phosphorus recovery in Ireland.
- Selection of the most appropriate phosphorus recovery technology/technologies for implementation should include an up-to-date review of the phosphorus recovery technologies described in Chapter 3 (including the technologies shown in Table 3.1) to identify those successfully introduced and operating in other regions since completion of this project.
- Long-term national strategies in relation to wastewater treatment and sludge management should consider the implications for potential phosphorus recovery. If incineration of sludge becomes necessary in the future as an alternative outlet to agriculture, mono-incineration should be considered to facilitate potential phosphorus recovery.
- Identification of available outlets for the recovered phosphorus should be undertaken as part of selecting a phosphorus recovery technology for implementation. Establishment and implementation of phosphorus recovery should involve close co-ordination between relevant stakeholders (WWTPs, users of recycled phosphorus etc.) policymakers and government.

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Abbreviations

AER	Annual Environmental Report
CAPEX	Capital expenditure
CSTR	Continuous stirred-tank reactor
DAP	Diammonium phosphate
DCP	Dicalcium phosphate
EBPR	Enhanced biological phosphorus removal
EPA	Environmental Protection Agency
EIA	Environmental Impact Directive
ESPP	European Sustainable Phosphorus Platform
FP7	Seventh Framework Programme
HAP	Hydroxyapatite
IEX	Ion exchange
IED	Industrial Emissions Directive
IHP	Improved hard process
MAP	Monoammonium phosphate
MCP	Monocalcium phosphate
MDCP	Monodicalcium phosphate
Mt	Megatonne
NP	Nitrogen-phosphate
NPK	Nitrogen-phosphate-potassium
OPEX	Operating expenditure
PAO	Phosphorus-accumulating organism
PE	Population equivalent
PHB	Polyhydroxybutyrate
PK	Phosphate-potassium
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SSA	Sewage sludge ash
SSP	Single superphosphate
STPP	Sodium tripolyphosphate
TCP	Tricalcium phosphate
TOC	Total organic content
TRL	Technology readiness level
TSP	Triple superphosphate
VFA	Volatile fatty acid
WAS	Waste activated sludge
WASSTRIP	Waste Activated Sludge Stripping to Remove Internal Phosphorus
WFD	Waste Framework Directive
WWTP	Wastewater treatment plant

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaoil a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaoil a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gclóíonn leis na córais sin.

Eolas: Soláthraimid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírthe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.

Tacaíocht: Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaoil atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaoil inbhuanaithe.

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaoil:

- saoráidí dramhaíola (*m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistriúcháin dramhaíola*);
- gníomhaíochtaí tionsclaíoch ar scála mór (*m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta*);
- an diantalmhaíocht (*m.sh. muca, éanlaith*);
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe (*OGM*);
- foinsí radaíochta ianúcháin (*m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíoch*);
- áiseanna móra stórála peitрил;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce poiblí, a mhaoirsiú.
 - Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhírú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúcháin.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídionn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaoil.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uisce idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéal uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaoil

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil (*m.sh. tuairisciú tréimhsiúil ar staid Chomhshaoil na hÉireann agus Tuarascálacha ar Tháscairí*).

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainnaint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeraíde, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaoil in Éirinn (*m.sh. mórphleananna forbartha*).

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéal radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a forbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar forbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaoil ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaoil (*m.sh. Timpeall an Tí, léarscáileanna radóin*).
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a forbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair inní agus le comhairle a chur ar an mBord.

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Identifying Pressures

Phosphorus is essential for all life and the depletion of global phosphorus deposits; widening supply-demand gap and security of supply risks have economic, social and environmental implications especially in relation to food production and security for a growing population. Phosphorus cannot be produced synthetically and has no substitute in food production. Almost all of the phosphorus consumed in food by the global population enters the wastewater sector. Municipal wastewater therefore represents a major point source to recover phosphorus and re-establish a circular economy. This research identified and evaluated technologies available for phosphorus recovery from municipal wastewater which could be implemented to generate marketable recycled phosphorus products in an Irish context. This research also examined the current phosphorus market, potential outlets for recovered phosphorus and the associated quality and regulatory requirements.

Informing Policy

The findings from this research indicate that establishing phosphorus recovery will require close coordination between relevant stakeholders (WWTPs, users of recovered phosphorus, etc.), policy makers and government to overcome existing legal, societal and market barriers.

The findings highlight the absence of an existing market for recovered phosphorus in Ireland as well as the need for clarification and harmonisation of existing legislation in relation to the marketing and use of recycled phosphorus products and may inform regulations/directives in relation to, for example, waste/product status of recovered phosphorus, standards and quality requirements for recovered phosphorus and authorisation of secondary phosphorus products. The research undertaken concludes that large-scale implementation of phosphorus recovery is likely to require international strategies and policy support. This research is of relevance to the Circular Economy Package adopted by the European Commission in 2015. One of the key action areas is secondary raw materials and the research undertaken is in line with the objectives in this area, which include increasing the use of recycled nutrients. The research undertaken may also inform the required key actions around EU regulation on fertilisers, quality standards for secondary raw materials, waste legislation and cross-border transfers of waste.

Developing Solutions

Outputs from this research include a database of municipal WWTPs (detailing phosphorus influent and effluent levels, capacity and details of any phosphorus treatment currently undertaken), a Table of Phosphorus Recovery Technologies (detailing 28 technologies identified) and a review of the potential market for recovered phosphorus (detailing potential outlets and associated quality and regulatory requirements). These outputs will contribute towards facilitating knowledge-based decision making in relation to the potential implementation of phosphorus recovery from municipal waste in the future in terms of, for example, selection of the most appropriate technology and geographical location(s) for phosphorus recovery and identification of a target market(s) for the recovered phosphorus. The research shows that numerous technologies in various stages of development are available for the recovery of phosphorus from wastewater targeting the liquid phase, sewage sludge or mono-incinerated sewage sludge ash. The evaluated approaches differ significantly in terms of their scale, cost and performance. This research concludes that selection of the most suitable phosphorus recovery technology/technologies for implementation is currently limited by the lack of existing infrastructure in relation to biological phosphorus removal and sludge mono-incineration facilities, which are prerequisites for several of the technologies identified.

