

# Review of the feasibility of recycling phosphates at sewage treatment plants in the UK

## Executive Summary

Phosphorus is required by every living plant and animal cell. Deficiencies in available phosphorus in soils are a major cause of limited crop production. However, excess phosphorus can stimulate the growth of algae, which in turn reduces available oxygen concentration in water bodies leading to adverse environmental consequences.

The ACHS was asked by Defra to review the feasibility of recycling phosphates at sewage treatment plants in the UK. The review has considered:

- Technologies currently available for recovering phosphates at sewage treatment plants.
- Feasibility of adapting these technologies to UK conditions.
- Environmental Impacts from processing and use of mined versus recovered phosphate.
- Suitability of recovered phosphate to replace mined phosphate <sup>1</sup>

The following conclusions have been reached:

- The drive for sustainability coupled with the requirement to meet the targets for reduction of emissions and control of eutrophication established by the Water Framework Directive (WFD) results in the need to consider recycling of phosphates.
- Phosphate is recognised as one of the major nutrients contributing to the worldwide increase in eutrophication; closing the phosphate cycle by recycling at sewage treatment plants (STPs) is thus desirable.
- Phosphate rock / ore is a non-renewable resource and its price is likely to increase as easily mined reserves of high quality phosphate rock reduce and demand increases. It is predicted that such reserves will be depleted in approximately 100 years based on the following assumptions: (a) no new phosphate reserves will be developed; (b) phosphate recycling will be insignificant, and (c) the current rate of phosphate extraction will remain constant.
- Mined phosphate poses concerns due to levels of heavy metals (Cd and Pb) and uranium that may be present in phosphate rock. However, when fertilisers are derived from phosphate ore, the bulk of heavy metals and uranium partition into the by-products, e.g. phosphogypsum, which are the actual health hazards.
- A number of well documented adverse environmental and health issues requiring management and limitation measures are associated with the chemical processing of phosphate rocks. These include

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<sup>1</sup> In this review, mined phosphate refers to phosphate produced from phosphate rocks via chemical processes. Recovered phosphate refers to phosphate recovered from sewage treatment plants, incineration ashes and animal manure.

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serious environmental damage and operator exposure as a consequence of radiation issues, phosphogypsum stacks, heavy metal and wastewater issues and fluoride emissions.

- It should be noted that mining does not take place in the UK or in the EU, resulting in reliance on foreign sources of phosphate for agricultural productivity. Phosphate mines are primarily found in North America (e.g. United States of America, especially Florida), Africa (e.g. Morocco, Senegal, Tunisia) and Oceania (e.g. Australia, Makatea, Nauru, Ocean Island).
- A comparison of the benefits of sludge recycling and phosphate recycling would be appropriate since the products of sludge recycling have some agricultural and industrial uses. A preliminary analysis of the data submitted by the water companies to OFWAT indicates that both sludge phosphorus content and bioavailability need to be optimised to achieve truly sustainable phosphate use in agriculture.
- Direct application of treated sewage sludge to agricultural / arable land represents a cost-effective way to recycle multi-nutrients to crops. However, there are concerns about spreading potential pathogens, odour and possible sludge contaminants associated with this practice. It is preferable to treat urban sludge and agricultural waste (animal manure) differently due to the significant difference of contaminant levels. In addition, direct application rates must take into account nutrient loads, to avoid runoff or excessive build up of nutrients in the soil. Lastly, large STPs may be far from suitable arable land, thus limiting the scope to use treated sludge. However, a new initiative of transporting sludge is after sludge drying on site. Dried sludge pellets have been sold as bio-fuel or applied to land as a fertiliser in Denmark.
- There is a range of methods available for reducing phosphate in treated wastewater at STPs. Chemical removal with iron or aluminium salts is a reliable method, which precipitates the phosphorus into the sewage sludge. It is the method currently used in the UK. Biological methods for phosphate reduction also immobilise the phosphate in the sludge, however it is more difficult to achieve reliably low concentrations of phosphate in the treated wastewater. The choice between chemical and biological phosphate reduction is currently largely related to existing process and influent phosphate stability. For the majority of the UK STPs, biological phosphate removal is not an option for phosphate recovery without a process rebuild / upgrade. The economics of both processes need to be assessed on a case-by-case basis, taking into account capital and running costs. There are already several international examples on how to perform this analysis in a holistic manner such as “Wastewater Phosphorus Control and Reduction Initiative” study commissioned by the Minnesota State Legislature. The feasibility and retrofitting assessments should also take into account successful international experiences of applying the

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enhanced biological phosphorus removal (EBPR) on a large scale (e.g. in Denmark and the USA).

- Where biological phosphate removal is used, an additional step for recovery of phosphate as struvite (a phosphorus mineral) can be added. There are working examples of this technology and indications that it might be technically feasible to use it in the UK, however its economic viability will depend on costs of the technology, the exact configuration of the struvite recovery unit, the demand for struvite and the regulatory requirements imposed on the water industry.
- Struvite can provide sources of phosphorus, nitrogen and magnesium to plants and its suitability as a slow-release fertiliser was demonstrated in some pilot- and full-scale productions in Japan, Canada and Australia and a Defra-funded project, which applied synthetic struvite to potatoes. Moreover, levels of contaminants, such as cadmium and lead in phosphate recovered as struvite are significantly lower than the regulatory limit.
- Recovery and use of phosphorus as struvite also offers a number of major sustainable advantages, including natural resource protection of phosphate rocks and environmental enhancements through nutrient recovery / recycling and reduction in greenhouse gases.
- Vigilance needs to be maintained and the safety of struvite confirmed with regard to the possible contamination of the food chain because of the re-use of anthropogenic nutrients on arable land. There may be a need to monitor chemical contaminants, although pollutants that may be present in the anaerobic sludge are not transferred or only in very small amounts into the final struvite precipitation product, and therefore the likelihood of chemical contaminants (e.g. heavy metals or uranium) is small.
- Uncontrolled struvite formation can create major maintenance and operational problems in sewage treatment plants, therefore struvite recovery may offer additional economic and operational benefits.
- Except for very specific local circumstances, recovered calcium phosphate from STPs and sludge / manure incineration ashes may not currently be an attractive option for re-use at commercial levels mainly due to its cost and logistical issues. Dried sludge may be a cheaper alternative for industrial use, however phosphate recovery and greenhouse gas (GHG) emissions may need to be included for the assessment of such options.
- Iron phosphate generated from chemical phosphate removal process cannot currently be used to replace mined phosphate for most industrial uses. Furthermore, iron phosphate is likely to have relatively low bioavailability under aerobic conditions (as in soil) to plants, therefore reducing its suitability for replacing phosphate fertilisers. It is

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unclear whether iron phosphate can release phosphate in significant amounts when soil pH changes dramatically through soil process in longer term. This may be worthy of further investigation.

The following recommendations are made:

- The feasibility of reusing phosphates recovered from STPs should be investigated, given that farming and industry are currently dependent on mined phosphates, for which there are limited reserves, and these are located outside the EU.
- Life-cycle assessment and cost inventory of phosphate removal, phosphate recovery, end-use scenarios and environmental impacts should be developed as it will aid decision making on phosphate recycling for STPs that need upgrading.
- Coherent data are needed to develop a phosphate flow diagram, which can help place phosphate recycling in the context of sludge reuse.
- Advanced / enhanced treatment techniques which are used to remove “difficult” micro-pollutants to align with other regulatory or voluntary schemes, such as The Safe Sludge Matrix, should be assessed in the LCA for assessing their suitability for pre- or post- phosphate recycling versus phosphate recovery.

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## **1. Introduction**

Phosphorus is a vital element for plants and animals and an essential nutrient for crop production. It is mainly used in agriculture as a fertiliser and in animal feed. Additional beneficial uses of phosphorus include, for example, human food ingredients, detergents, pharmaceuticals and speciality chemicals. However, excess phosphorus in aquatic environments can stimulate the growth of algae, which can cause reduction in available oxygen concentration in water bodies and severely affect the diversity of the biological system and the overall quality of the water (DEFRA, 2008). More specifically, it can lead to increased cost of drinking water purification, interference with the recreational and conservation value of impoundments, loss of livestock and the possible sub-lethal effects of algal toxins on humans using eutrophic water supplies for drinking purposes (UK Environment Agency, 1998). These effects can be especially pronounced in smaller water bodies, where the phosphorus dilution is not significant. There is also a continuum of ecological responses between the extremes described above (which can be found in the UK) and the conditions where phosphorus-containing compounds are below the detection limit.

Water is vital for our health and wellbeing, for industry and for leisure. Defra's Water Strategy, Future Water, outlines the Government's vision for water policy until 2030 (DEFRA, 2008) and is focused on improving water quality in England. Moreover, following the 1991 EU Waste Water Treatment Directive that required phosphate removal in all sewage works serving more than 10,000 persons equivalent by 1998, the Water Framework Directive (2000/60/EC) (WFD) provides a significant driving force to improve the quality of water to reach 'good status' in all water bodies by 2015. The UK Technical Advisory Group has estimated that, in England, approximately 64% of rivers and around 77% of lakes are at risk of failing the proposed WFD phosphate standard for good status. Additionally, the International Conference on the Protection of the North Sea has recommended a 50% reduction in the input of phosphorus-containing compounds for a great protection of the marine environment.

There are several approaches for reducing the concentration of phosphates in the environment,

- By reducing emissions from point sources (eg. sewage works) and diffuse sources (e.g. farmland).
- By reducing the concentration of phosphorus in effluent from sewage works through a reduction in the concentration of phosphate input to the sewage (e.g. phosphate substitutions in detergents; it is however to be noted that the majority of the phosphorus arises from human waste) and/or
- By investing into the removal of phosphorus at STPs (e.g. installation of additional phosphorus removal capacity in treatment works).

However, there are numerous constraints to these approaches, both from regulatory and technical points of view, and diffuse sources complicate the efforts to control levels of phosphate in the environment. These need to be

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addressed separately, for example through the more controlled application of fertilisers.

### **2. Technologies available for recovering phosphates at sewage treatment plants**

Sewage treatment involves separation of the solid from the liquid fractions, the latter being typically discharged to the sea or fresh water bodies after undergoing various treatment stages, such as biodegradation. Due to the environmental effects of excess phosphorus, STPs seek to lower its concentration in the liquid effluent.

The most common methods for phosphorus removal are chemical precipitation and EBPR. Currently, the chemical precipitation method is used more frequently than the EBPR. Additionally, less conventional methods developed in order to improve phosphorus removal from wastewater effluents are ion exchange, reverse osmosis, chemical coagulation, electrodialysis, adsorption and use of chemical adsorbents (Horan., 1992). These methods are not currently deployed in the UK due to specific technical difficulties associated with each, especially pronounced in large-scale operations. A list of technologies for phosphorus removal and their development status were provided by Morse *et al* (1998) (Morse *et al.*, 1998).

The chemical precipitation methods consist of the addition of salts of various metal ions (such as iron and aluminium) or lime to form phosphate precipitates. The phosphorus leaves the wastewater through the removal of sludge. Chemical precipitation is a fairly reliable and common method of phosphorus removal, which can be easily installed on the existing plants, however, the following issues should be considered when upgrading the facilities: (1) the cost of ferric and aluminium salts; (2) the larger volumes of activated sludge, with decreased biodegradability and potential issues related to its disposal, such as presence of various co-contaminants (e.g. heavy metals). Although the current UK trends do not indicate a significant difficulty with sludge disposal, observed in such countries as Sweden, there is a potential for this situation to change due to public perception and concerns about contamination of soils and the food chain.

EBPR is another method of wastewater treatment. EBPR is accomplished by encouraging a preferential growth of biomass species, which accumulate and use phosphorus compounds as an energy source. As before, the end result is to partition the phosphorus to the sludge, decreasing its concentration in the liquid effluent. It is achieved by alternating cycles of anaerobic and aerobic activated sludge. Where conditions allow it to be operated successfully, for example having an existing activated sludge treatment process, the EBPR process is a relatively inexpensive modification and an environmentally sustainable method of phosphorus removal from effluent (Oehmen *et al.*, 2007). However, the reliability and stability of this process can be an issue. The EBPR process can experience process upsets, deterioration of performance and even failure, thus requiring the installation of backup systems. Factors such as high rainfall and nutrient limitations can contribute to such problems.

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These incidents can have significant impact for the large scale operations; however, it is possible to address these issues by having a combined chemical and EBPR process. This combined approach is quite promising for achieving reliable phosphorus removal. However, it might also have some limitations from a sustainability perspective, as phosphorus might be less bioavailable compared to that removed by the EBPR process. There are already several examples of the use of EBPR on a relatively large scale both in the UK and internationally, for example the STPs in the US (Durham, Oregon with flow of 76 ML/day with chemical and biological EBPR) and Denmark (5.8 ML/day, EBPR without chemical addition).

The EBPR plants increase the quantity of phosphorus held in activated sludge and also permit an option of introducing phosphorus recovery in the form of struvite. It is important to distinguish between two forms of recovered phosphorus:

- biomass, where the phosphorus is concentrated in the sludge and can be recycled by use in agriculture or recovery after incineration, and
- mineral form, such as recovery of struvite for use as a commercial fertilizer or other industrial applications.

It is also important to mention that sludge contains both organic and inorganic forms of phosphorus. Due to the high volume of material, reuse of phosphorus from sludge in agriculture is only feasible close to the STPs.

Struvite recovery relies on the addition of magnesium salts to side-streams and sludge liquors, which causes struvite precipitation. Struvite can be used as a fertiliser for various agricultural applications. However, the application of full scale struvite recovery processes is still limited, with Japan and Canada taking a lead in struvite recovery from anaerobically digested liquors. The resulting products are sold to fertiliser companies (Le Corre *et al.*, 2007). There are some technological limitations as this approach is the most viable within a certain range of phosphorus concentrations in sewage. Nevertheless, there are several positive examples of using this process in STPs. For example, Canadian company Ostara ([www.ostara.com](http://www.ostara.com)) has announced the development of an optimized struvite recovery technology, which is claimed to

- (1). offset operating costs,
- (2). prevent deterioration of plant performance,
- (3). comply with environmental regulations and
- (4). produce a high quality fertiliser product.

The fertiliser product attracts a premium price due to its slow release, high purity and high nutrient payload characteristics, which helps to offset the costs of the recovery system. The first commercial-scale Ostara nutrient removal reactor has been operating since May 2007 as part of the City of Edmonton's Gold Bar wastewater treatment plant handling wastewater requirements for 700,000 people. The Ostara reactor is extracting more than 75% of the phosphorus and 15% of the ammonia from a sludge reject water (lagoon supernatant) stream of 500,000 litres per day. It produces approximately 500 kg per day of struvite based product (called Crystal Green™), which is subsequently sold as a fertiliser. The results of this commercial operation have confirmed the advantages of the struvite recovery technology. It has also enabled the economic viability of Ostara's approach to be verified and

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appropriate operating conditions to be established. Further facilities are under development.

Another possible route of phosphorus recovery is through combustion of sewage sludge and animal manure. The ash can provide a source of dry inorganic phosphorus containing a high proportion of calcium phosphate. This can be used in the phosphorus industry by mixing with the phosphate rock before the grinding stage (Schipper *et al.*, 2001). The problem of this route of phosphorus recovery is that both sewage and manure ash contains considerable amounts of zinc and copper, and this poses a serious limitation on the recycling capacity for the phosphate industry thermo route (used as secondary raw materials). **In general**, the main requirements for using recovered phosphorus in industry are:

- Recovered phosphorus should have comparable phosphate content to that from phosphate rock (13-17.5%).
  - The amount of certain impurities should not exceed a critical value. Main impurities come from the reduction process, including Fe, Zn, Cl and Cu.
  - Recovered phosphorus should be obtainable as a dry material.
  - It should not contain large amounts of organic material or ammonium.
- It should also not interfere with the granulation and sintering process.

There are some new developments such as incineration combined with phosphorus recovery from the ashes. Phosphorus potentially can be recovered through a wet acid process and then separated from metal ions using ion exchange (Stark, 2002). Using this technology, phosphate can be collected as phosphoric acid, after regeneration with hydrochloric acid. Phosphoric acid is higher economic value material for the phosphate industry than ferric phosphate (Lundi *et al.*, 2004).

It is important to mention, however, that based on submissions from CEEP (Centre Europeen D'Etudes des Polyphosphates, a body established by the polyphosphates industry), the European Fertiliser Manufacturers Association (EFMA) and British Sulphur consultants (European Fertilizer Manufacturers Association, 2000), **there are no industrial facilities which can use recovered phosphorus in the UK**. Therefore, this route of phosphorus recovery is not as attractive as the one designed for agricultural use.

### **3. Current facilities for sewage treatment in the UK and feasibility of adapting them to recover phosphates taking into account UK conditions**

Where phosphorus removal is required, the UK water industry has primarily focused on chemical precipitation methods of treatment, spending approximately £950 million in capital on installing chemical stripping in sensitive areas. **However, the number of sewage works employing chemical precipitation is still in the minority**. A further investment of approximately £500 million will be required following the recent 2007 Urban Waste Water Treatment Directive Sensitive Area announcements (Defra, 2008).

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It is apparent that in order to achieve 'good status' for UK surface waters (to meet WFD targets) an additional investment into the UK wastewater treatment facilities is needed. EBPR and chemical (CR) methods of phosphorus removal are both feasible options of addressing this issue. However, given advantages and disadvantages of both techniques, the main question is whether to invest primarily into chemical methods, biological methods or combinations of both. The answer will have significant implications in terms of cost and sustainability. The cost will be significantly influenced by the existing process types already put in place by the UK water industries. For example, for certain ranges of wastewater compositions (expressed as BOD:P or COD:P ratios) it might not always be beneficial to introduce biological methods. Furthermore, there is a small chance of phosphorus release from sludge under anaerobic conditions, the EBPR process might need to be modified with chemical phosphorus removal, especially in the areas where treated water is discharged into sensitive eco-systems. Additionally, in areas with significant process parameters variability (e.g. the flow rate and composition changes due to heavy rainfalls), chemical methods of phosphorus removal might offer further advantages over biological methods.

Based on a study carried out by United Utilities Plc. (UUIPlc. Presentation to the ACHS, 2008), the capital expenditures of adding EBPR are higher than those for adding CR. However, the operational expenses can be higher or lower depending on the specific plant. Under certain circumstances, it is possible that EBPR might recover a portion of capital expenditures in the long-run compared to CR, but this will largely depend on the pre-existing conditions of the plant. The water industry has indicated that there are facilities in the UK, which use fixed bed sewage treatment, and these cannot be adapted to EBPR, so adoption of this technology would require significant capital investment.

An increase in phosphorus recovery in the form of sludge raises the issue of whether there is additional capacity for sludge utilisation. Currently, the principal methods of sludge recovery/disposal in the UK are application to agricultural land followed by incineration, and secondary methods include disposal to landfill, composting, and restoration (according to data reported to OFWAT by the major water treatment companies). It is possible that in the long-run sufficient agricultural land might not be available for sludge application and under such circumstances the phosphorus recovery method producing the smallest quantity of sludge (such as EBPR) would be the most sustainable. Moreover, the sludge produced by biological methods of phosphorus removal is of better quality (e.g. biologically bound phosphorus is more valuable for agricultural use than ferric phosphate).

Combustion route of sludge disposal can be also analyzed from sustainability point of view, given that dry sewage sludge can be considered as a renewable energy source. The downside of this method is a need to address the air pollution issue (e.g. from trace metal concentrations in sludge), although the Environmental Permitting Regulations and the Waste Incineration Directive requirements should ensure strict limitations of emissions to air.

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A more detailed analysis of data submitted by major UK water treatment companies and the Environment Agency to OFWAT (Appendix) reveals several important trends. The total amount of sludge produced by 10 major companies in 2005 was about 1,167 thousand tonnes of sludge on a dry weight basis. Approximately 68% of this sludge was applied in to agricultural land, with the remaining sludge being incinerated (19 %), disposed to landfill (2 %), used for land reclamation (3 %) and for other purposes (7 %). By utilizing the information on phosphorus content in sludge applied to agricultural land (which varies from 1.3 to 5.8 %, see Appendix), it is possible to aggregate the data and calculate the total phosphorus content of the sludge – 91,612 tonnes of phosphorus in sludge (in P<sub>2</sub>O<sub>5</sub> equivalent) were applied to agricultural land in 2005. This corresponds to 39 % of the phosphorus fertilisers used in the UK in 2005/06 (235,000 tonnes of P<sub>2</sub>O<sub>5</sub> equivalent in 2005/06). However, for the phosphorus to be recycled, the sludge application rates to agricultural land should take into account the phosphorus content of sludge.

If the EBPR method is chosen as a viable option, the next question is whether to introduce the struvite recovery process. It should be mentioned that struvite recovery might not work for all the EBPR processes. Several parameters will affect the viability of struvite recovery, such as flow rates, orthophosphate concentration, and magnesium concentration. Nevertheless, Parsons *et al.* (2005) tested six sewage works in the Severn Trent Water region and concluded that a significant number of wastewater treatment plants in UK have conditions favourable for introduction of struvite recovery technology. A more detailed study at Slough STP suggested that struvite recovery can achieve 97% phosphorus removal from sludge liquors and can generate revenue (Jaffer *et al.*, 2002). A subsequent pilot project at the same STP concluded that 80% of inflow phosphorus (7 m<sup>3</sup>/hour) contained in sludge liquors (amounting to 11% of total phosphorus load) can be precipitated as a relatively clean struvite (Appendix). Based on this information, Thames Water estimated that if biological nutrient removal (BNR) and struvite recovery were installed at just 7 target STW locations this would result in around 1,000 tons/year of struvite (CEEP, 2004).

The economics of the process and availability of the markets are the main uncertainty factors in implementation of struvite recovery technology in the UK. For example, the Slough laboratory scale study did not consider all the aspects of capital expenditures for the process implementation (Parsons *et al.*, 2005). At a presentation analysing the Slough pilot study, at Cranfield University in 2004, Johnson *et al.* it was suggested that the production levels were insufficient for the logistics of agricultural recycling (CEEP, 2004). This might indicate that the appropriate market for struvite utilisation still needs to be developed. Analysing the European trends Stark *et al.* (2004) concluded that economic benefits of struvite recovery are uncertain as the costs of recovery result in a much higher price than the price of phosphate rock. Given that recovered struvite is itself a finished, slow release fertiliser which can be directly used in agriculture and also provides nitrogen and magnesium, perhaps comparing its price to similar ammonium phosphate fertiliser

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products may be more appropriate than phosphate rock ore, which is an input to the fertiliser manufacturing process. Based on consultation with private companies in England and France, Jeanmarie (2001) suggested that the market value of the recovered product will not be the first motivation of the water industry to install the phosphorus recovery process. Other motivating factors, such as improved operational efficiency and reliability of sewage treatment works can however, be expected to be of decreasing significance compared to the value of the recovered fertiliser in future, given the trend of rapid price increases, which has more than doubled during 2007-2008 (IFDC, 2008).

It is to be noted that further studies are urgently needed to evaluate different municipal wastewater treatment phosphate reduction strategies and analyse the costs, level of reduction, and improvements to water quality associated with various wastewater treatment plant retrofitting strategies. Most importantly, these studies need to focus on the UK specific conditions. Although international experience might not provide all the answers to the issues above, it can help to identify some of the critical areas in this evaluation process. One powerful example is the report commissioned by the Minnesota State Legislature to develop the phosphorus control and reduction strategies (Report "Wastewater Phosphorus Control and Reduction Initiative", 2003. <http://www.meserb.org/phosphorus.htm>). This study utilised financial, technical and environmental data analysis for the 22 facilities participating in the project. Both the EBPR and chemical treatment precipitation processes were evaluated for each plant. The recommendations were based on a cost effectiveness analysis including process reliability, preliminary estimates of capital and operating cost and present worth. Several conclusions were reached in this study including the following:

- (1) EBPR has the higher capital cost and lower operation and maintenance costs. Chemical treatment has the lower capital cost and higher operation and maintenance cost;
- (2) For a given type of activated sludge system, the EBPR retrofit design and the choice of EBPR, EBPR with chemical treatment, or chemical treatment can vary depending on other site-specific factors;
- (3) Wastewater characteristics have a major impact on the feasibility and economics of an EBPR retrofit for phosphorus removal. One implication of this study, which may be relevant to the UK conditions, was that the small proportion of the EBPR facilities in the UK might not necessarily be the most cost-efficient option and the current practices should be re-evaluated using methodologies such as those described in this report.

It can be concluded that there are strong indications that the EBPR with struvite recovery can be an economically viable technology, however, further studies of the market availability and process economics specific to the UK conditions are needed to evaluate the feasibility of large-scale struvite recovery operations. If struvite recovery is indeed a feasible option, the next step is an assessment of the suitability of recovered phosphorus to replace the mined phosphorus and the impacts from the use of mined phosphorus and recovered phosphorus. These issues are addressed in the following sections.

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### **4. Assessment of the environmental and health impacts from processing and use of mined versus recovered phosphate**

This section reviews the impacts from the chemical processing of mined phosphorus from phosphate rocks, and use of recovered phosphorus in the form of struvite. Available examples are drawn with information or data in the context of environmental and subsequent human health impacts of using recovered versus mined phosphate.

#### **4.1 Impact from processing and use of mined phosphate**

##### **4.1.1 Radiation hazard**

Phosphorus deposits throughout the world contain uranium and thorium as a natural constituent of the rock / ore. When the ore is handled during beneficiation (e.g. the process in which phosphate rock is separated from clay and sand) the radioactivity concentrations in the rock that goes on for further processing is very similar to the concentration in the original ore that was mined (FIPR, 2003). At the chemical processing plant, rock is reacted with acids and filtered. It is here, during the production of phosphoric acid and granulated fertilisers that the different radioactive elements may be separated and concentrated, especially uranium and radium, in particular, heavy metals and radioactivity partition in the processing by-products (e.g. phosphogypsum). Radioactivity may also become embedded in equipment or form scale precipitates on pipes or other objects. Radium-bearing scale, in particular, can build up to an extent where radiation levels on site are of concern (FIPR, 2003).

Processing and waste handling in the phosphate industry is associated with radiation levels of concern for workers and the public (Schmidts & Krüpper, 1995); the main source of occupational exposure results from chronic inhalation of particulates containing radioactive material and/or potentially toxic chemicals (Khater *et al.*, 2004). Human exposure to these constituents in these emissions has been associated with adverse carcinogenic respiratory, nervous system, dermal, developmental and/or reproductive health effects (US EPA, 1995). Studies on activity and ambient radiation background levels around phosphate mines in Africa (Tanzania) have shown that high concentrations of radium-226 are observed in phosphate rock, waste rock, wild leaf vegetation, edible leaf vegetation, surface water and chicken feed relative to selected sites (Banzi *et al.*, 2000). These findings suggest a radiation health risk particularly when the samples are ingested and/or inhaled, because the internal exposure may give rise to an effective dose exceeding 20mSv which is the annual limit of intake of natural radionuclides recommended by the International Commission on Radiological Protection (ICRP).

The mining and processing of the phosphorus ore consequently redistribute radionuclides throughout the environment and introduce them into phosphoric

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acid and phosphogypsum. Phosphoric acid is the starting material for the fertilisers triple superphosphate (TSP), single superphosphate (SSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), NPK fertilisers and di-calcium phosphate (DCP) (Saueia *et al.*, 2005). Concentrations of naturally occurring radionuclides in the surrounding environment at the locations of this industry e.g. mines, phosphorus fertiliser factory and phosphorus export platforms have recently been studied (Othman & Al-Masri, 2007). Air particulates, soil, water, biota and plant samples were collected and analysed. The results showed that the distribution and enhancement of natural radionuclides in the surrounding environment in these three locations are mainly due to fallout of phosphate dust generated during loading and processing of phosphate ore. The extent of contamination was related to climate conditions. Radon gas and its daughters generated from phosphorus ores were found to be the main source of enhanced concentrations of Po-210 and Pb-210 in soil and leafy plants.

### **4.1.2. Phosphogypsum – a specific radiation hazard**

In phosphorus fertiliser manufacture, sulphuric acid is used directly (e.g. wet route) to produce SSP or the intermediate phosphoric acid, which will be used in TSP and ammonium phosphate production. The principal environmental impact identified with SSP production is the large quantity of phosphogypsum generated as a by-product (Silva & Kulay, 2003). Like natural gypsum, phosphogypsum is calcium sulphate, a relatively innocuous compound that is used for various purposes. Unlike natural gypsum, however, the phosphogypsum is slightly radioactive. The source of the gypsum's radioactivity is the presence of uranium, and uranium's various decay products (i.e. radium), in raw phosphorus ore. While uranium, and its decay-products, naturally occur in phosphorus ore, their concentrations in the gypsum waste, after the extraction of soluble phosphate, are up to 60 times greater (FIPR, 2005). One of the main concerns with gypsum stacks centres around the fact that radium-226 breaks down into radon gas. When radon gas is formed, it can become airborne, leading to potentially elevated exposures downwind of the stacks. Some concerns have been raised that cancer rates downwind of the stacks may be elevated although no conclusive evidence has been presented (US News and World Report, 1995).

### **4.1.3 Heavy metals and wastewater issues**

Process water is the water used in the chemical process, which converts mined phosphate into phosphoric acid, used to make fertilisers and as a feedstock for the chemical industry (FIPR, 2003). In mining operations, this wastewater accumulates on top of gypsum piles and is highly acidic (pH of about 1 to 2 due to a dilute mixture of phosphoric, sulphuric and fluosilicic acids), with high levels of toxic contaminants, including fluoride, arsenic, cadmium, chromium, lead, mercury, radionuclides and the various decay-products of uranium. This combination of acidity and toxicity poses an environmental risk and if leaked into the environment (for example following heavy rains, spills or if a plant is abandoned or closed before a stack is

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drained), can cause considerable damage to waterways and fish populations (FIPR, 2003).

### **4.1.4 Fluoride emissions**

Raw phosphorus ore contains high concentrations of fluoride, usually between 20,000 to 40,000 parts per million (equivalents to 2 to 4% of the ore) (Connett, 2003). When this ore is processed into water-soluble phosphate (via the addition of sulphuric acid), the fluoride content of the ore is vaporised into the air, forming highly toxic gaseous compounds (hydrogen fluoride and silicon tetrafluoride) (US EPA, 1995). When inhaled many fluoride salts react with water (moist lung tissue) and break down into hydrofluoric acid. The acute reaction of hydrofluoric acid with lung surface may result in the hydrofluoric acid puncturing the lung parenchymal tissue leading to primary pulmonary oedema. Pulmonary oedema develops as a result of damage to the capillary endothelium in the alveolar wall, which subsequently leads to leakage of protein rich fluid into the alveolar spaces (US EPA, 1995). The adverse environmental and health effects from fluoride gases emitted from phosphate industries have been well documented (Connett, 2003) and include serious environmental damage and poisoning of domestic animals caused by fluorine in smoke, gas, or dust. Today fluorine recovery is increasingly necessary because of stringent environmental restrictions, which require drastic reductions in the quantities of volatile and toxic fluorine compounds emitted into the waste gases.

The silicofluorides, as obtained from the current pollution control devices, contain a wide variety of impurities present in the process water including arsenic, lead, and possibly radionuclides (FIPR, 2003). These silicofluorides are widely used in the production of chemical compounds and in the treatment of public drinking water. While these impurities occur at low levels, especially after water dilution, concern has been expressed that their purposeful addition directly violates public EPA health goals (Connett, 2003). For instance, the EPA's Maximum Contaminant Level (MCL) Goal for arsenic, a known human carcinogen, is 0 parts per billion. However, according to the National Sanitation Foundation, the current MCL for arsenic is 10 ppb and the addition of silicofluorides to the water supply will add, on average, about 0.12 ppb, and as much as 0.6 ppb, arsenic to the water (NSF Factsheet on Fluoridation Chemicals<sup>2</sup>

### **4.1.5. Increase soil heavy metal**

Phosphorus mineral fertilisers contain levels of heavy metals associated with the phosphate rock. Consequently, there is potential for soil contamination due to the presence of heavy metals in the ore, although there are limits to the amount of contaminants that can be present in fertilisers. For example, there has been concern that phosphorus fertiliser introduces cadmium into the food chain by increase of soil heavy metals. In 1972 the World Health Organisation issued some provisional limits on Cd intake by man. Despite the fact that they

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<sup>2</sup> [http://www.nsf.org/business/water\\_distribution/pdf/NSF\\_Fact\\_Sheet.pdf](http://www.nsf.org/business/water_distribution/pdf/NSF_Fact_Sheet.pdf)

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account for only a minor fraction of the total cadmium input to agricultural soils, mineral phosphorus fertilisers have been the main target of restrictive measures in the European Union (EU). A first draft of an EEC Directive was elaborated in 1982 to limit the content of cadmium and other undesirable elements in industrial wastes. The Directive was published in 1983, and required reductions of the amounts of cadmium spread with the phosphogypsum, (formed as a waste in phosphoric acid production). A Cd risk assessment is available on the ORATS database.<sup>3</sup>

### 4.2 Impact from use of recovered phosphate

#### 4.2.1 Struvite recovery - sustainability advantages

Struvite recovery as the principal route of phosphorus recovery in STPs in combination with EBPR offers major sustainability advantages (CEEP, 2008). These include;

##### *i) Natural resource protection and environmental enhancement:*

- Typically, a 75% recovery of phosphorus in sludge liquors for recycling, and simultaneous recovery of approximately 15% of nitrogen have been demonstrated using struvite recovery, which is positive for receiving waters.
- A reduction of phosphate rock mining by 1.6% (Shu *et al.*, 2006) is achievable if struvite were to be recovered from wastewater treatment plants worldwide resulting in 0.63 million tons of phosphorus (as P<sub>2</sub>O<sub>5</sub>) harvested annually. In addition, the phosphorus in the sludge is more readily available because no chemical stripping is used. The quantities of struvite that might be recovered if all STPs in the UK greater than 200,000 population, using activated sludge process and discharging to freshwaters were converted, has been estimated to approximately 3250 tonnes/year as phosphorus (Howard Brett, Thames Water, pers. comm.). The Canadian company Ostara claims that 500 kg/day production can be recovered from a 700,000 population sewage treatment plant using optimised struvite recovery technology. Thus, taking the UK population as 60 million, this puts an upper theoretical limit of over 40 tonnes/day or over 15,000 tonnes/year of recovered struvite (not as phosphate) (Howard Brett, Thames Water, pers. comm.) – this represents over 4,000 tonnes of phosphate fertiliser measured in P<sub>2</sub>O<sub>5</sub> equivalent, which is close to 2% of the phosphorus fertiliser used in the UK in 2005/06 (Agricultural Industries Confederation, 2007). It should however be noted that not all the population is connected to STPs.
- The levels of heavy metals in sewage-precipitated phosphorus are much lower than commercial phosphorus fertilisers (CEEP, 2008). A significant benefit is therefore the reduction in spreading of heavy

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<sup>3</sup> <http://ecb.jrc.it/esis/index.php?PGM=ora>

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metals and other contaminants in phosphate rock, via mineral fertilisers, to agricultural land and so the ecosystem.

- Struvite production and mineral use is a very simple, robust method, which does not require special equipment or working conditions. The materials needed are added in small amounts – magnesium is added as dolomite (magnesium-calcium carbonate), which is found worldwide and is not a scarce resource.

### *ii) Climate Change impacts:*

The results from pilot trials show that struvite production results in reductions of over 50% in sulphur dioxide, carbon monoxide and nitrous oxide emissions and 80% lower green house gas (GHG) emissions on a carbon dioxide equivalent (CO<sub>2</sub>E) basis when replacing traditional fertilisers. This results from the fact that conventional fertiliser manufacturing processes are energy intensive, involving mining, long transport distances, thermal processes, and in some cases direct combustion of fossil fuels for product manufacture (e.g. ureas production). In contrast, the struvite recovery facility operates on a total installed electrical capacity of approximately 25 HP, and uses waste heat from biogas combustion for product drying<sup>4</sup>.

Using struvite precipitation together with biological phosphorus removal produces up to 20% less sewage sludge than chemical phosphate removal (Howard Brett, Thames Water, pers. comm.).

### **4.2.2 Potential impact on human health**

One problem associated with phosphorus recovery is the re-use of anthropogenic nutrients on agricultural or arable land. A Code of Practice has been produced with tighter zinc and cadmium standards following recommendations from an independent scientific committee, which considered soil fertility. In order to increase confidence in the practice of sewage sludge application to agricultural land, a non-statutory 'Safe Sludge Matrix' (SSM) (Safe Sludge Matrix, 1998) was agreed between Water UK and the British Retail Consortium in 1998. This contains minimum acceptable levels of treatment for sewage sludge, which currently can be applied to certain crops. It is reasonable to assume that the same good practice should also apply to recovered phosphorus, e.g. struvite, when the main use is as fertilisers applied to agricultural land. DEFRA<sup>5</sup> contributed to a large-scale long-term (start 1994 and ongoing) research project, which investigates the impacts of soil fertility when sewage sludge, which contains very high levels of metals is applied to agricultural land. The research focussed on copper, zinc and cadmium. Analysis has shown that cadmium does not seem to pose risks but further work is required to draw any conclusions about copper and zinc.

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<sup>4</sup> <http://www.cepis.ops-oms.org/bvsaar/cdlodos/pdf/valuefromwaste575.pdf>

<sup>5</sup> <http://randd.defra.gov.uk/default.aspx?menu=menu&module=more&location=no>

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Although struvite itself does not pose contamination issues and recovered struvite can be rinsed before use, there are possible concerns attached to the agricultural use of any sewage-recovered product and it needs to be confirmed that recovered struvite does not contain traces of chemical or pathogen contaminants (CEEP, 2004). The analysis carried out to date in a significant number of pilot and full scale struvite recovery trials from sewage (von Munch & Barr, 2001; Ueno & Fuji, 2001; FIPR, 2005; Nakamura *et al.*, 2006; Forrest *et al.*, 2008; Britten, 2008; Fattah, 2005; Matsumiya *et al.*, 2000) show that the struvite has low heavy metal levels and low levels of organics which appear to indicate no identified risk with the spreading of recovered struvite on arable land.

To date, there remains very little information on the health impact of using recovered struvite. Therefore, the precautionary principle requires that vigilance must be maintained and the safety of struvite confirmed with respect to possible contamination of the food chain.

### **4.2.3 Potential impact on environmental health**

To date, no studies appear to be available on the environmental impacts of struvite.

Although there are issues associated with direct application of sewage sludge to land (for further information see part 5 of this review), struvite should not add to eutrophication problems e.g. build up of nutrients and potential diffuse pollution of nutrients. The concerns about heavy metal contamination of soil, such as the effects of zinc on soil microorganisms would not apply since the levels of heavy metals in struvite (e.g. the struvite structure does not accommodate e.g. heavy metals or uranium) are much lower than those found in rock phosphate.

## **5. Assessment of the suitability of recovered phosphate to replace mined phosphate**

This section provides a qualitative assessment on the extent to which recovered phosphorus from different routes can be used to replace mined phosphorus in fertiliser manufacture and other industries. International and UK examples are used together in the context of regulatory and economical implications. Manufacturing potential, sustainable production and consumption are also considered. Life-cycle assessment (LCA), including process efficiency, sustainable benefits, energy consumption and environmental (including climate change) impacts may be useful in providing quantitative benefit analysis when a sewage facility requires upgrading in the UK. There are examples of similar LCA carried out in other countries, e.g. Murray *et al.* (2008) developed an array of productive end-use options for treated sewage sludge, such as use as fertilisers.

Using recovered phosphorus to replace mined phosphorus will eventually depend on cost of recovered phosphorus (taking into account sewage work

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operational cost savings and capital investments) and relevant regulatory requirements. There are still difficulties on how to evaluate the economic benefit of using recovered phosphate due to various types of wastewater treatment facilities in the UK and industrial willingness to accept the products. If / when recovered phosphorus can be produced cost-effectively in large scales and if further restrictions are imposed on direct sludge application to landfills and agricultural land, recovered phosphorus should become much more attractive for use in fertiliser and other industries than mined phosphorus.

### **5.1 Regulatory Background Relevant to UK**

There are different regulatory requirements for phosphorus recycling for different industries, for example, the WFD (EC, 2000) for the water industry, the Fertilisers Regulation (Defra, 2007a) for the fertiliser industry, the Food and Cleaning products regulations for other industries that use phosphorus, the Sludge Regulations (Ridley *et al.*, 1989) and Safe Sludge Matrix (ADAS, 2001) for the water and agricultural industries. Other relevant regulations and voluntary measures are summarised (Defra, 2007b) and aimed to protect wild life and human health resulted from point or diffuse emissions to the environment. Some countries (e.g. Sweden) have policies in place to require phosphorus to be recovered and recycled, because direct agricultural sewage sludge re-use is increasingly limited. There is also a drive to reduce the amount of waste applied to landfill.

Excessive phosphorus released into water bodies from STPs may cause eutrophication, such as algal blooms, which reduce light penetration and available oxygen to the water body. As a result, WFD may require P reduction from sewage waters before releasing to fresh waters to meet the desired limit at < 1 mg/L. In UK conditions, chemical P-removal can achieve less than 0.5 mg/L phosphorus in treated effluents, however effluent after biological P reduction alone can sometimes exceed 1 mg/L P. Therefore chemical P removal or combined bio-P and chemical P removal are preferred by UK water industries. According to a presentation provided by the Water Industry to the ACHS in June 2008, 55 out of 64 large STPs (i.e. > 200,000 population equivalent) adopted activated sludge treatment in the UK, representing the maximum numbers that can be converted to bio-P reduction. However more than half of the large STPs with activated sludge treatment in the UK discharge into coastal waters, where WFD limits of nutrients do not apply. In addition, only Thames Water and SevernTrent Water, of the UK water industries, have not installed EBPR plants.

#### **5.1.1 Sludge recycling versus phosphate recycling**

Direct application of treated sewage sludge to agricultural land is currently considered a cost-effective way to introduce multi-nutrients, e.g. N and P to crops and may be counted as one route of phosphate recycling. Indeed, 60-70% of treated sludge is applied to agricultural land (Defra advice on use of

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sludge), using ~0.8% of the total UK agricultural land <sup>6</sup>. Although there may be advantages to soil fertility and structure from regular application of sludge, there are concerns on sludge safety, e.g. potential pathogens, odour, acidifying / eutrophying inputs and possible sludge contaminants, including heavy metals, PBT chemicals, endocrine disruptors and pharmaceuticals, etc associated with direct sludge recycling (Ridley *et al.*, 1989; ADAS, 2001; Defra, 2007b; Langenkamp *et al.*, 2001). It follows that there is a need for investigation into greater contaminant removal, for example of heavy metals (EU, 2000) and some organic pollutants (Langenkamp *et al.* 2001), in order to produce a less hazardous material that can safely be applied to arable land. As a result, heavy metal contents have reduced over the years in treated sludge in the UK. However, apart from all these, the principal limitation for application rates of sludge to agricultural land seems to be the nutrient load of nitrogen, in respect of which there is an advisory limit on application of nitrogen and phosphorus per hectare (ACHS communication with Thames Water). This is in place too because of the concern that agricultural runoff is a diffuse source for elevated phosphorus concentrations in surface waters (e.g. Deasy *et al.*, 2008). Therefore, control of nutrients from agricultural runoff has been implemented through legislation (Withers & Lord, 2002). Sewage sludge phosphate is more soluble and available than struvite, therefore more likely to undergo runoff and contribute to eutrophication. In addition, agricultural reuse of sludge biosolids is also limited by logistics, i.e. lack of available land reasonably close to large STPs in towns and cities. Finally it is uncertain whether iron and aluminium phosphate precipitated from chemical phosphate-removal plants should be counted as effective recycling of phosphorus due to its low availability to plants. A usable form of phosphate fertiliser will need to take into account farmers' concerns on bioavailable phosphate content. Eventually LCA assessment may provide an option for decision making on whether to adopt sludge recycling or phosphate recycling.

Spreading treated sewage sludge on landfills for disposal is a different issue and is currently regulated by waste regulations, which results in additional expense. This practice may be beyond plant needs and has little nutrient recycling benefit. In the UK, landfilling of batches of sludge only occurs when there is no suitable beneficial use due to contaminants, and is typically around 1% (Thames Water communication to ACHS). Incineration is applied in larger STPs in the UK and represents 17-19% of the total use. If there are no appropriate alternatives for re-use, the incinerated ash is subsequently landfilled. Other applications of sewage sludge include land restoration, composting, industrial crops and forestry.

There do not appear to be guidelines in the UK relating to whether recovered phosphate (e.g. struvite) is classified as a waste or a re-usable material in EU. Following the publication of the new waste framework Directive in November 2008 it may be that the probable status of struvite as a waste will change once it has been through a protocol procedure. However, transposition of the Directive is not due until December 2010. Regulatory clarification could have a significant impact on using recovered phosphate as fertilisers. For example,

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<sup>6</sup> [http://randd.defra.gov.uk/Document.aspx?Document=SP0130\\_6505\\_FRP.pdf](http://randd.defra.gov.uk/Document.aspx?Document=SP0130_6505_FRP.pdf)

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if struvite is considered a waste, it will limit its use as a fertiliser. Waste is not included in the current EU Regulation REACH (EC, 2006). However when recovered phosphate turns into usable materials, it may be covered by REACH since it is seen as manufacturing a product that is subsequently placed on the market. There is a regulation exemption in REACH Article 2.7(d) for substances that have been recovered in the Community, but such substances still need to be registered. This may have further implications on the use of recovered phosphate to replace mined phosphate in the EU.

Overall, the regulatory challenges for phosphorus recycling are complex, involving various industries, established commercial interests, dependence on manufactured fertilisers, change of mindset in nutrient use and environmental sustainability. Although some of the phosphorus is already recycled through application of treated sewage sludge to agricultural land in the UK, there may still be a general need to close the loop of the nutrient cycle by phosphorus recovery for reuse in other industries and as a replacement to mined fertilisers (Green Alliance, 2007).

### 5.2 Mined phosphate

Phosphorus occurs almost exclusively in nature as orthophosphate ( $\text{PO}_4^{3-}$ ) (EU FOREGS). It is currently sourced predominantly from phosphate rocks and there is no substitute for phosphate in nature (USGS, 2005). Phosphate rock is bound to calcium as apatite ( $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ ), which also contains fluoride, chloride, hydroxyl or carbonate ions at a variable degree. Mined phosphorus is produced from phosphate rock that typically has a  $\text{P}_2\text{O}_5$  content of 30-40% (equivalent to 13-17.5% phosphorus content) and iron of 0.4-1%. Usually phosphorus fertilisers processed from phosphate rocks are water-soluble. Approximately 40 million tons of phosphate rock ( $\text{P}_2\text{O}_5$  equivalent) is mined annually, of which 80-90% is used in fertilisers (CEEP, 2008). Around the world there is augmentation on production of fertilisers containing phosphorus with an increasing demand for phosphate rock by 1.5% each year (Steen, 1998). There are an estimated 7 billion tons of phosphorus ( $\text{P}_2\text{O}_5$  equivalent) in phosphate rocks as remaining reserves (Özden *et al.*, 2007). The high quality portion of the phosphate rock is predicted to be largely depleted in ~100 years at the current rate of exploitation (Isherwood, 2000; Steen, 1998) if mined phosphate other than apatite cannot be developed for industrial uses. The reserve depletion could potentially occur in less than 100 years if the world demand for phosphate fertiliser rises due to increasing demands of food and energy crop productions. For example, phosphate ore prices increased dramatically in the past year (Oelkers *et al.* 2008) although they fell back in late 2008. Also, as the best reserves are progressively consumed, the phosphate content of remaining rock will be lower and the comparative heavy metal content will be higher, posing increasing difficulties for use in fertilisers without purification.

The majority of the phosphate industry (including detergent and fertiliser industries) uses phosphate rock as a raw material to generate phosphoric acid via either a dry or wet process (Rehmm *et al.*, 2002). The process starts

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from a thermo route to produce elemental phosphorus, which is burned in the air to generate  $P_2O_5$ .  $P_2O_5$  is then reacted with water to form pure phosphoric acid.

The thermal process starts with a granulation step for the phosphate rock, calcium apatite ( $Ca_5(PO_4)_3OH$ ), where a binder (clay) is added as a slurry on a rotating disc, together with ground rock to produce pellets. Reducing agents are then added to the dried pellets with pebbles ( $SiO_2$ ) and the mixture is heated to  $1500^\circ C$  in a furnace. At the elevated temperature, phosphorus is reduced to  $P_4$ . Trace amounts of iron are also reduced to form ferrophosphorus with roughly 75% Fe and 25% P, which is sold as a steel additive. Calcium oxide left in the furnace can be combined with  $SiO_2$  to form a liquid slag, which is then cooled, crushed and used for road construction.

The dry-acid process involves treating rock phosphate in an electric furnace and produces a very pure and expensive white phosphoric acid that can also be used by the food and chemical industries. The wet process involves adding sulphuric acid to the phosphate rock and produces green or black phosphorus acid with gypsum as a by-product, which may contain high-levels of impurities from the phosphate rock. The phosphoric acid is then used to acidulate the phosphate rock to produce triple superphosphate (TSP) - a common form of phosphate fertiliser with 100% water solubility. Diammonium phosphate (another form of phosphate fertiliser) can be produced by neutralising phosphoric acid with ammonia. Air emission of sulphur dioxide, acid mist or particulates that contains heavy metals such as cadmium, mercury and lead are the most significant environmental issues for these manufacturing processes. Therefore, emission through both air and effluent of these manufacturing plants is regulated (EPA, 2002; IPPC BAT-BREFs<sup>7</sup>).

The main issues associated with mined phosphorus are:

- Phosphate rock often contains significant amounts of heavy metals, such as cadmium and lead that can be toxic to the environment and indirectly to human health.
- Due to relatively high water solubility, the phosphorus fertilisers currently processed from mined phosphate have limitations for certain applications, such as in forestry and turf that require slow- or phased- release of phosphate fertiliser.
- As described in detail in part 4, there are associated environmental issues from manufacturing emissions and by-products (gypsum).

### **5.3 Recovered phosphate**

There are a number of possible routes for the re-use of recovered phosphorus that include re-use as a raw material (in substitution for mined phosphate rock) in the phosphorus industry or re-use directly as a fertiliser (without further processing other than packaging and conditioning).

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<sup>7</sup> <http://eippcb.jrc.ec.europa.eu/pages/FActivities.htm>

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Currently phosphorus can only be recovered from sludge with biological processes (e.g. EBPR) because the commonly used chemical precipitation of phosphorus involves addition of iron salts, therefore produces a product that cannot currently be recycled for industrial use (see section 2 for a description of the technologies for phosphorus removal). Sludge contamination with heavy metals has been reducing over the years. Heavy metals are unlikely to remain in the soluble form of supernatant streams that are used for struvite recovery, therefore a combination of biological phosphate removal followed by struvite precipitation will not retain heavy metals in the recovered struvite; i.e. these pollutants present in the anaerobic sludge are not transferred or only in very small amounts into the final struvite precipitation product (Heinzman & Engel, 2003). As a result, levels of cadmium and lead in phosphate recovered as struvite are significantly lower than the regulatory limit (Heinzman & Engel, 2003; Nakamura *et al.*, 2006; Forrest *et al.*, 2008; Britten & Ahren, 2008; Münch & Barr 2001) or those in mined phosphate rock, therefore are unlikely to be an issue for fertiliser applications. The only limitation is the variation that the recovered phosphate products need to have reasonable phosphate content and limited water content to be used for the phosphorus and fertiliser industries.

The most promising form of phosphorus recovered from STPs is struvite for use as a fertiliser. More than 90% of dissolved phosphorus and 50-80% of total phosphorus can be recovered from anaerobic digester supernatant as struvite (Shu *et al.*, 2006). Struvite recovered from sewage works is generally less water-soluble than commercial phosphate fertilisers and can be used most effectively as marketable slow-release P fertiliser. It has been successfully applied to turf, tree seedlings, ornamental plants and vegetables. Crops that are most responsive to phosphate include cereals, oil seed rape and linseed, peas and beans, and potatoes. Defra has recently funded a project to compare synthesised struvite and manufactured phosphate (triple super-phosphate, TSP) as fertilisers for potatoes under field conditions in UK (de-Bashan & Bashan, 2007). Results suggest that the yields were similar for plots fertilised with struvite and TSP at soil phosphorus concentrations recommended for the crop (up to soil P index 4), however at higher phosphorus levels, a slight (non significant) depression in yield for some plots applied with struvite was observed. This yield reduction might be due to an observed reduction of the potassium (K) content of plants observed on these plots, possibly due to antagonism between K and the Mg present in struvite (Hammond, personal communication). It should be noted that the source of struvite used for these trials was chemically synthesised rather than recovered struvite, which may have different properties, such as availability of elements.

Struvite is not suitable for use as a secondary raw material for the phosphorus industry. However, another re-usable form of recovered phosphorus from STPs is calcium phosphate, which can be used as a secondary material for the phosphorus industry. Calcium phosphate precipitation has been extensively researched since the 1970s (Valsami-Jones, 2001). It requires more chemical input (CO<sub>2</sub> stripping by acid, and then alkali addition) and has higher cost (reactor and energy consumption) than struvite precipitation.

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Recovered calcium phosphate is also less valuable than struvite as a multiple source of nutrient and a slow-release fertiliser. There is a range of calcium phosphate with different solubility; some of which might release phosphate at similar rate as struvite and others would release phosphate much slower than struvite (Valsami-Jones communication to ACHS). Calcium phosphate can be used as a secondary raw material for the phosphate industry, but this is only profitable if there is a site nearby (CEEP, 2008). A source of dry phosphorus containing a high proportion of calcium phosphate is obtained from combustion of sewage sludge and animal manure.

Magnesium, aluminium or iron phosphates obtained from phosphorus chemical removal cannot be used in detergent manufacture. One of the main functions of phosphates in detergents is to remove metal ions such as calcium, magnesium and iron, therefore adding these metal ions to detergents is counter-productive and such compounds have no useful role in detergents (John Pickup, Pers. Comm.). Some authors suggested ferric phosphate may release some phosphate to crops in pot and field trials (CEEP, 2001). One interpretation is that solubility (as a function of bioavailability) of phosphate may depend on soil pH (Oelkers & Valsami-Jones 2008). However it is generally considered that iron phosphate produced from chemical phosphorus removal at STPs cannot be used for any industrial purposes currently (CEEP Communication to ACHS). It may be possible to develop biological processes for recovering a useful phosphorus product from iron phosphate / iron containing sludge by using sulfur reducing bacteria (Suschka, 2001). However, the possible processes (e.g. Krepro process in Sweden) for recovering a useful form of phosphate from chemical phosphorus removal are likely to be complex and expensive and the recovered iron phosphate could not be sold to farmers as a fertiliser.

A large variety of phosphorus-containing wet and dry materials result from the treatment of industrial and food industry waste streams. Struvite from such waste streams may be able to increase production and improve logistics of marketing sewage-recovered struvite. However, the main limitation for this route of recovery is the difficulty in transportation of these wastes under the current waste legislation.

There have been emerging initiatives for recycling phosphate, e.g. drying sludge after anaerobic digestion at the STPs to produce dried sludge pellets that can be sold as bio-fuel or applied to land as a fertiliser (Hansen J. A. communication to ACHS). Volume and weight reduction can be significant compared to treated sewage sludge, i.e. a factor of 5 as an example (change from 19 to 95%). Once the sludge is dried, it is cheap and easy to transport. This may provide a new scenario of sludge recycling, however cost, phosphate recovery and GHG emission are parameters to be included in the LCA when this option is assessed.

### **5.4 Benefits and limitations of using recovered versus mined phosphate**

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### 5.4.1 Benefits of using recovered phosphate (Shu *et al.*, 2006)

The main benefits of using recovered phosphorus, in particular as struvite are related to sustainable production and consumption (de-Bashan & Bashan, 2007). They are in the areas of:

- Reduction of contamination levels of heavy metals (e.g. Cd) in recovered phosphate from STPs.
- Reducing operating cost for maintenance of water treatment pipes for biological treatment plants by alleviating the chances of unwanted struvite deposits in anaerobic digestion, post digestion processes and return lines.<sup>8</sup>
- Savings on chemicals and sludge handling associated with iron and aluminium dosing.<sup>8</sup> Currently, iron and aluminium phosphates have limited industrial applications. In the UK, use of ferric salts for phosphate precipitation at STPs requires a consent and use of aluminium salts is not allowed.
- Reducing the volume of sludge produced and increasing the proportion applied to agricultural land.
- Ensuring sustainable consumption and production i.e. reduce the reliance of agricultural production on use of natural phosphate rock resources that may be depleted in 100 years.
- Co-precipitation of other nutrients, e.g. nitrogen and magnesium for use as complex fertilisers.

Although the theoretical potential of using recovered phosphorus is much larger when considering phosphate recycling as fertilisers (Gaterell *et al.*, 2000), it is arguable that realistic use of recovered phosphorus in the UK is much less optimistic because only a small proportion of the total phosphate load (40,000 tonnes) can be recovered for industrial use and there are no facilities to recover struvite for use as fertilisers. Profitability of using recovered phosphorus is dependent on the process used for phosphorus recovery, chemical costs (e.g. magnesium hydroxide), struvite sales prices and reactor efficiency achieved, etc. It also relates to the costs of phosphorus removal vs. phosphorus recovery, therefore there will be variations in different STPs dependent upon their existing technologies. An example is a pilot-scale struvite recovery reactor located at Oxley Creek municipal wastewater treatment plant in Brisbane, Australia that showed profitability between US\$ 8,600/year losses through to US\$ 98,000/year profit (Munch & Barr, 2001).

Benefits of struvite recovery can be significantly improved if a waste material from the magnesium industry can be used as a magnesium source. Magnesium hydroxide purchase costs are then avoided and overall resource recycling is further improved. This has been successfully experimented at laboratory scale in Spain (Quintana *et al.*, 2008). The existence of such possible secondary Mg sources should be investigated in the UK.

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<sup>8</sup> These may need to be assessed quantitatively by LCA and consider other issues, such as difficulties for recovering phosphate from digesters and thickening plants and capital investment of converting STPs to EBPR in the UK (see 5.4.2).

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## 5.4.2 Limitations for using recovered phosphate

### 1. Transportation and waste legislation

Although there are examples of “waste” phosphate being exported from UK and used as a secondary material by Thermphos in Netherlands, reclassification as a recovered material would result in less stringent requirements for handling and use, and facilitate its reuse. In addition, transportation over long distance can lead to considerable GHG emissions.

### 2. Variation of phosphorus and water content from different waste streams

Current phosphorus recovery techniques generate materials with different phosphorus content and sometimes they are not comparable to phosphate rock, i.e. 13-17.5% P. Water content is also a problem limiting recovered phosphate to be used in the phosphorus industry as secondary materials (Heinzman & Engel, 2003).

### 3. Cost effective production and competitive pricing

Although experiences in several countries have demonstrated struvite is a marketable fertiliser, further development and more examples will be needed to demonstrate the competitiveness of recovered phosphate to be used in other industries and encourage uptake. Furthermore, there are capital and operating costs of converting or adapting existing UK wastewater treatments to EBPR. Commercial use of recovered phosphate will relate to the drivers of pricing and toughened regulations.

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## APPENDIX:

### Total sludge production (tonnes dry solids) and use (%) in 2005 (2007 EA Report to OFWAT, data refers to 2005)

Water Company	Total Sludge	Agricultural land	Incineration	Landfill	Composted	Cement Manufacture	Land reclamation	Forestry	industrial crops	Other
Anglian	170119.86	94.58	-	0.02	-	-	5.40	-	-	-
Northumbrian & Essex & Suffolk	20766.00	3.50	-	3.50	-	87.90	-	-	-	5.11
Severn Trent	207825.00	76.57	15.13	8.22	-	-	-	0.07	-	-
Southern	1612.00	50.00	-	50.00	-	-	-	-	-	-
South West	62366.30	98.11	-	1.89	-	-	-	-	-	-
Thames United	189510.00	49.05	47.74	-	1.31	-	1.81	-	0.09	-
Utilities	223425.00	74.81	19.30	-	-	-	5.89	-	-	-
Welsh Water	85353.31	94.30	-	0.77	2.47	-	2.47	-	-	-
Wessex	71399.38	92.47	4.02	-	2.45	-	-	-	-	1.06
Yorkshire & York	134800.63	5.19	42.28	3.56	1.63	-	7.40	-	-	39.93
<b>Total</b>	<b>1167177.48</b>									

### Aggregated sludge use (%) for all water companies in 2005 (2007 EA Report to OFWAT, data refers to 2005)

Agricultural land (%)	Incineration (%)	Landfill (%)	Composted (%)	Cement Manufacture (%)	Land reclamation (%)	Forestry (%)	industrial crops (%)	Other (%)
68.23	19.27	2.17	0.73	1.56	3.24	0.01	0.01	4.77

### Calculation of phosphate flows in sewage sludge applied to land, based on data published by OFWAT (from EA Report 2007, data refers to 2005)

Water Company	Total Sludge applied to agricultural land <sup>1</sup>	Phosphorus content, g/kg	Total phosphorus <sup>1</sup>	Land Used (ha)	Phosphorus application rate (Kg/ha)
Anglian	160.900	48.600	7819.74	25823	302.8
Northumbrian & Essex & Suffolk	44.147	58.000	2560.53	6610	387.4
Severn Trent	159.136	72.000	11457.79	26009	440.5
Southern	110.615	31.574	3492.56	14068	248.3
South West	61.189	13.489	825.38	7817	105.6
Thames United	153.940	28.240	4347.26	22943	189.5
Utilities	167.131	21.879	3656.66	19699	185.6
Welsh Water	80.489	18.900	1521.24	11452	132.8
Wessex	66.020	43.988	2904.09	6950	417.8
Yorkshire & York	36.088	38700	1396.60	4638	301.1
<b>Total</b>	<b>1039.655</b>	<b>-</b>	<b>39981.85</b>	<b>146009</b>	<b>273.8</b>

<sup>1</sup> thousand tons dry solids

Total phosphorus in sewage sludge applied to land in 2007, in P<sub>2</sub>O<sub>5</sub> equivalent, is approximately 39,981\*2.2914 = 91,612 tonnes.

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## Mass balance of phosphorus ammonia and magnesium at Slough STW (Jaffer et al., 2004)

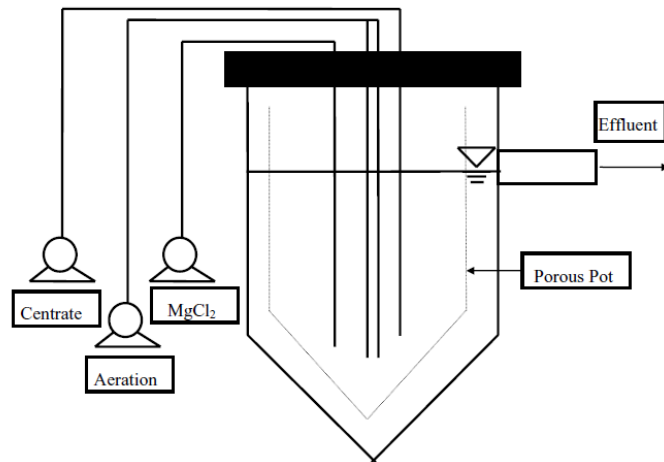


Fig. 1. Schematic of pilot plant.

