

# Evaluation of Local and National Effects of Recovering Phosphorus at Wastewater Treatment Plants: Lessons Learned from the UK

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## Abstract

P recovery from wastewater treatment plants (WWTPs) as struvite fertiliser is a recognised method of improving P use efficiency and reducing P losses into the environment. The main driver for P recovery from the water industry viewpoint is the reduction in the nuisance of struvite clogging inside pumps and pipes. Struvite recovery leads to an average P recovery rate of  $72\pm 7\%$  from centrifuge centrate, with  $8.8\pm 0.7\%$  total P and  $20.5\pm 3.2\%$   $\text{PO}_4\text{-P}$  removed from the WWTP influent as struvite. This reduces the potential for struvite precipitation, moderates P loads on biological nutrient removal processes and lowers P concentration in the final effluent. Totalling revenue from sale of struvite and operational site savings, P recovery becomes an attractive option for water companies. The implementation of P recovery technologies to produce struvite fertiliser in all UK WWTPs could produce a national P fertiliser source of  $7.05\pm 2.01$  kt P/year. In addition, sludge produced at WWTPs could be diverted to advanced energy recovery (AER) processes and P recovered from AER residues; up to  $21.71\pm 0.95$  kt P/year could be recovered in this way in the UK. Combining the two methods of P recovery, UK imports of P fertiliser could be reduced by  $36.2\pm 1.1\%$ . P recovery on a large scale has the further benefit of protecting against eutrophication by reducing P emissions to water bodies by  $21.7\pm 1.9\%$ . The protection of the environment and reduction in reliance on imported P are major national motivations to legislate P recovery from waste.

**Keywords:** phosphorus recovery; phosphorus efficiency; struvite; wastewater treatment plants

## 1. Introduction

Phosphorus (P) is an essential nutrient for all living organisms, while phosphate rock is a non-renewable resource (Ashley et al., 2011). As the human population booms and dietary expectations change in the developing world, P fertiliser use will increase dramatically. The global P cycle is a “leaky” inefficient supply chain: P is lost through erosion, leaching, and crop and post-harvest distribution losses (Clift and Shaw, 2011). While phosphate production may be non-critical, the current reliance on mined phosphate rock is economically, environmentally, and socially unsustainable (Scholz et al., 2014). The scarcity of phosphate rock can be considered an economic issue (Scholz et al., 2014). In a report of critical raw materials, phosphate rock was ranked as 20<sup>th</sup> in an index of price volatility (Oakdene Hollins and Fraunhofer ISI, 2013). The volatility of P prices results from many factors, including “bubbles” in financial markets, imbalances of supply and demand, and geopolitical effects (Scholz et al., 2014).

39 China, Morocco, and USA account for 70% of the world's phosphate rock supply (INRA, 2014). Less than 1% of  
40 phosphate rock supply in the EU arises from within the EU (Oakdene Hollins and Fraunhofer ISI, 2013).  
41 Approximately 6 million tonnes of phosphate rock was imported to the EU from 2002 to 2012 (INRA, 2014).  
42 However, this figure varies over time; for example in 2009 P imports declined to 4 million tonnes (European  
43 Commission, 2013; INRA, 2014).

44 Since records began in 1983, application rates of phosphate fertiliser on crops and grassland in the UK have  
45 generally been in decline. A dip in application rates of 15kg phosphate/ha was experienced in 2009, but  
46 application rates have plateaued since 2009 at 18kg/ha phosphate (Figure 1) (DEFRA, 2014). There is a  
47 constant need for phosphate fertiliser, despite occasional decreases resulting from high phosphate rock prices.  
48 Fertiliser P imports accounted for 56% of total UK P imports in 2009; a total of 138kt P was imported through  
49 detergents, crops, animal feed, animal products, processed food, industrial applications and P dosing in water  
50 treatment (Cooper and Carliell-Marquet, 2012). Approximately 25% of the P in wastewater arises from  
51 detergents, but this declined due to the reduction of phosphates in most laundry detergents (Richards et al.,  
52 2015).

53 P recovery from waste streams can help alleviate reliance on imported P and reduce vulnerability to  
54 fluctuating prices. Globally, P in digested food amounts to 3.6 Mt P/year (Scholz and Wellmer, 2015). Much of  
55 this digested P is discharged to wastewater treatment plants (WWTPs), making them ideal point sources for P  
56 recovery (Cooper and Carliell-Marquet, 2012; Maaß et al., 2014; Mo and Zhang, 2013).

57 P in wastewaters is primarily generated from human sources, cleaning products and industry (Environment  
58 Agency, 2012). Human excretions contribute at least 75% of the P entering WWTPs, providing a perpetual  
59 source of P even if P were removed entirely from detergents (Scholz et al., 2014). Since the implementation of  
60 the EC Urban Waste Water Treatment Directive (UWWTD) 97/271, many European WWTPs must meet P  
61 and/or N discharge consents. Due to these stringent targets, biological and chemical processes have been  
62 developed to remove nutrients from wastewater (Doyle and Parsons, 2002).

63 The biological nutrient removal (BNR) system has become an established technology in WWTPs to remove P  
64 and control eutrophication (Hu et al., 2012). As a result of removing nutrients from wastewater, waste sludge  
65 contains greater concentrations of P, N, and Mg (Doyle and Parsons, 2002). When found in combination, these  
66 elements can result in the formation of struvite deposits primarily in WWTPs operating BNR (Doyle and  
67 Parsons, 2002). Struvite is a white crystalline substance composed of Mg, NH<sub>4</sub>, and PO<sub>4</sub> in equi-molar  
68 concentrations and forms by the reaction in Equation 1 (Doyle and Parsons, 2002).

69 **Equation 1:**  $Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6(H_2O)$

70 Currently, struvite is seen as a nuisance in BNR WWTPs because it forms a hard deposit inside pipes, pumps,  
71 and centrifuges. Struvite formation reduces internal pipe diameters and increases the energy required to  
72 pump sludge through the network, while removing deposits significantly increases maintenance effort and  
73 hence cost (Doyle and Parsons, 2002). One such site affected by nuisance struvite formation is Slough WWTP -  
74 owned and operated by Thames Water; a privatised water utility based in the South of England. Originally,  
75 Slough WWTP treated wastewater by a BNR process with wasted activated sludge being anaerobically digested  
76 (Jaffer and Pearce, 2004). Anaerobic digestion of BNR sludge releases high concentrations of Mg and PO<sub>4</sub>-P;  
77 coupled with high concentrations of NH<sub>4</sub> in wastewater, this results in struvite formation (Jaffer et al., 2002).  
78 This became a problem at Slough WWTP within six months of BNR plant commissioning: the pipeline between  
79 the digested sludge holding tank and centrifuge became restricted to such an extent that it was no longer  
80 possible to transfer sludge to the centrifuge for dewatering (Jaffer et al., 2002). To suppress soluble PO<sub>4</sub>-P  
81 release, FeCl<sub>2</sub> was injected immediately prior to the aeration phase of BNR process to reduce nuisance struvite  
82 formation, aid compliance with regulatory discharge consents and to suppress on-site odours. Fe ions in

83 solution react with soluble PO<sub>4</sub>-P producing insoluble metal phosphates which precipitate into the sludge,  
84 thereby reducing struvite formation in the digester (Crutchik and Garrido, 2012; De-Bashan and Bashan, 2004).  
85 Due to the problems caused by BNR, WWTPs frequently become reliant on chemical P removal as a simple and  
86 reliable method of P removal with struvite suppression, despite its cost.

87 Rather than Fe dosing, a more expedient method to reduce struvite formation in BNR WWTPs is to recover P  
88 as struvite fertiliser. This reduces the quantities of P recycled through the WWTP, diminishing the potential for  
89 struvite to clog pumps and pipes (Jeanmaire and Evans, 2001). Struvite is an effective slow-release P, N, and  
90 Mg fertiliser; P and N are primary nutrients for plants while Mg is an important secondary nutrient (Tucker,  
91 1999). Using slow release fertilisers improves the efficiency of P use in agriculture (De-Bashan and Bashan,  
92 2004). Due to the uncertainty over the future of P and P fertilisers, increasing P efficiency is a requirement  
93 (Scholz et al., 2014).

94 While the chemistry of struvite precipitation is well known, there is little published information describing the  
95 impacts of full scale P recovery on BNR WWTPs and indeed the potential impact of P recovery via struvite on  
96 the national P budget. This paper addresses both these gaps, starting from the local effects of P recovery using  
97 the Ostara Nutrient Recovery system at Slough WWTP. This is achieved by presenting two mass balances  
98 showing different scenarios: scenario one in which no P recovery occurs (business as usual), and scenario two  
99 in which an average P recovery of 72±7% is achieved. Operational and financial benefits of P recovery are  
100 described. The subsequent effects of P recovery on the national UK P budget are then discussed.

101

## 102 **2. Materials and Methods**

### 103 *2.1 Slough WWTP Study Area*

104 Slough WWTP serves a population equivalent (PE) of 238,000, a significant proportion of this PE being food  
105 and confectionary producers located in the area. Slough WWTP accepts up to 10 tonnes of imported sludge  
106 per day from smaller satellite WWTPs. Slough WWTP is similar to many other BNR sites across the UK and  
107 Europe that have problems of struvite precipitation which could be resolved by recovering P. A process flow  
108 diagram detailing data for the Slough WWTP is presented in Figure 2 and Table A - Supplementary Data. When  
109 the P recovery system is not operational, centrifuge centrate (Flow P) joins Flow S directly. When operating,  
110 centrate (Flow P) enters the P recovery system, where it is separated into struvite fertiliser (Flow Q) and  
111 effluent from P recovery (Flow R).

112

### 113 *2.2 Sample Collection and Mass Balance Calculations*

114 Slough WWTP was sampled for approximately 18 months prior to the installation of the Ostara Nutrient  
115 Recovery system to provide baseline data to create a mass balance of the WWTP without P recovery. To obtain  
116 the data, 24 hour composite samples were taken using auto-samplers at three sampling points (crude sewage  
117 Flow B, settled sewage Flow C, and final effluent Flow H - see Figure 2), supplemented by 'grab' samples at  
118 other points. Samples were sent to UKAS 17025 accredited Thames Water Laboratories for analysis of total  
119 phosphorus (P), phosphate (PO<sub>4</sub>-P), and suspended solids (SS). Total P measures all forms of P, i.e. dissolved  
120 and particulate, whereas PO<sub>4</sub>-P measures the filterable, soluble P fraction, i.e. the form taken up directly by  
121 plants cells (Murphy, 2007). The reporting of both total P and soluble PO<sub>4</sub>-P is important as PO<sub>4</sub>-P is  
122 bioavailable for recovery using the Ostara Nutrient recovery system. Recovery rates of such technologies refer  
123 to PO<sub>4</sub>-P recovery rather than total P. Due to the complex chemistry of P and its interactions with other  
124 elements found in WWTPs, particularly Ca and Fe, PO<sub>4</sub>-P and total P are distinct and independent. Averages

125 and standard deviations for each parameter at each sampling point were calculated. Equations 2 and 3 were  
126 used to calculate total P and (PO<sub>4</sub>-P) in kg/day as depicted in the mass balances, where M<sub>n</sub> is mass flow in  
127 kg/day, Q<sub>n</sub> is volume flow in m<sup>3</sup>/day and C<sub>n</sub> is concentration in mg/l.

128 **Equation 2:** Liquid streams:  $M_n = (C_n \times Q_n) / 1000$ , where C<sub>n</sub> = mg/l

129 **Equation 3:** Sludge streams:  $M_n = C_n \times Q_n \times 10$ , where C<sub>n</sub> = %

130 Mass flows were calculated across each unit process using equations 4, 5, and 6. Mass balances for each unit  
131 process were calculated separately (see Figure 3), before combining unit processes to create a full WWTP mass  
132 balance. The mass balance for scenario one (no P recovery) was calculated using this method; that for scenario  
133 two (P recovery) was based upon scenario one calculations with the inclusion of the P recovery system and  
134 associated changes in flows. Crude sewage influent and imported sludge characteristics were assumed to  
135 remain constant between the scenarios. Mass balances were calculated using Excel; values arising from Excel  
136 calculations were input to STAN 2.5 (subSTance flow ANalysis software version 2.5.1103) to create Sankey  
137 diagrams depicting mass flows.

138 **Equation 4:**  $M_1 = M_2 + M_3$

139 **Equation 5:**  $M_n = Q_n \times C_n$

140 **Equation 6:**  $[Q_1 \times C_1] = [Q_2 \times C_2] + [Q_3 \times C_3]$

141 In scenario one, centrate is recycled directly back to the head of the WWTP at Flow R. In scenario two, total P  
142 and PO<sub>4</sub>-P concentrations in centrate (Flow P) are reduced by P recovery (Flow Q) before centrate is returned  
143 to the head of works (Flow R). The Ostara nutrient recovery system is designed to recover struvite from  
144 influent PO<sub>4</sub>-P concentrations >100mg/l. The scenario two mass balance was calculated using PO<sub>4</sub>-P  
145 concentrations >100mg/l and corresponding total P concentrations. Struvite recovery averaged 71.6±7.4% at  
146 PO<sub>4</sub>-P concentrations >100mg/l. Table 1 displays influent (Flow P) and effluent (Flow R) P concentrations as  
147 measured at the P recovery system. These concentrations were input into the models to calculate total P and  
148 PO<sub>4</sub>-P flows.

149

### 150 *2.3 UK Substance Flow Analysis Model*

151 The Substance Flow Analysis (SFA) models presented in this research focus on flows entering and exiting UK  
152 WWTPs. The SFA model of Cooper and Carliell-Marquet (2012) was used to produce scenarios depicting effects  
153 of P recovery at WWTPs on UK P flows. Their SFA was based on flows of P through the UK in 2009; hence each  
154 scenario investigated in this paper is based on this year. Flows from Cooper and Carliell-Marquet's SFA were  
155 calculated as a percentage of previous flows and input into the Excel models. Using this method, changes to  
156 individual flows cascade throughout the SFA model equations, resulting in a recalculated model. Five different  
157 P recovery scenarios are presented, with degrees of recovery varying from none to "best case scenario".  
158 Imports of food, feed and non-food commodities were assumed to remain constant across the scenarios. It  
159 was also assumed that total fertiliser applied to agricultural land remains constant at 72.0 kt P/year. Table B in  
160 Supplementary Data details the effects across all flows and stocks.

161

## 162 **3. Results and Discussion**

### 163 *3.1 Necessity for P Recovery in Slough WWTP*

164 Figures 4 and 5 depict P movement and accumulation in the WWTP network when the P recovery system is  
165 not operating (scenario one). Mass balances in Figures 4 and 5 show that  $23.2\pm 4.5\%$  of the total P and  
166  $24.2\pm 7.5\%$  of the  $\text{PO}_4\text{-P}$  entering the head of the works (Flow B - refer to Figure 2) was due to P in the return  
167 stream comprising dewatering liquors from three sludge treatment processes (Flow S). These estimates are  
168 compatible with those of Jaffer et al. (2002), who quote 26% of the total P as recycle streams, and Evans  
169 (2009) who reports that sludge dewatering liquors contribute 20% to influent total P. Accumulated P is  
170 recycled in the WWTP requiring retreatment and removal along with the influent P. The accumulated excess P,  
171 and more specifically  $\text{PO}_4\text{-P}$ , exacerbates struvite formation in pumps and pipes. Figures 4 and 5 indicate that  
172  $42.1\pm 11.8\%$  total P and  $78.6\pm 1.6\%$   $\text{PO}_4\text{-P}$  in the return stream (Flow S) originates from centrate liquors (Flow  
173 R). Due to the high proportion of centrate in return liquors, the centrate stream is recognised as an ideal point  
174 for P recovery to reduce struvite precipitation in WWTPs (Jaffer and Pearce, 2004).

175

### 176 *3.2 Effect of $72\pm 2\%$ P Recovery in Slough WWTP*

177 Scenario 2 (Figures 6 and 7) depicts the reduction in total P and  $\text{PO}_4\text{-P}$  achieved by producing struvite fertiliser  
178 from centrifuge centrate in Slough WWTP. Table 2 details for comparison the changes achieved in selected  
179 flows as a result of P recovery. Operating the P recovery system at average  $71.6\pm 7.4\%$  recovery transfers  
180  $8.8\pm 0.7\%$  of the total P and  $20.5\pm 3.2\%$  of the  $\text{PO}_4\text{-P}$  from the influent (Flow A) to the struvite fertiliser product.  
181 Removal of total P and  $\text{PO}_4\text{-P}$  as struvite reduces the flow of P in the centrate component (Flow R) of the  
182 recycle stream (Flow S) by  $56.9\pm 2.5\%$  total P and  $45.5\pm 2.1\%$   $\text{PO}_4\text{-P}$ . As a result, the contribution of the recycle  
183 stream (Flow S) to Flow B reduces from  $23.2\pm 4.5\%$  to  $19.2\pm 2.6\%$  total P and from  $24.2\pm 7.5\%$  to  $19.5\pm 4.3\%$   $\text{PO}_4\text{-P}$ .  
184 Thus P recycling reduces the P load across each process as seen in Figures 6 and 7, reducing the potential for  
185 struvite precipitation. A decrease in P load to the BNR process is also achieved, with total P reduced by  
186  $4.9\pm 2.6\%$  and  $\text{PO}_4\text{-P}$  by  $23.7\pm 1.7\%$ . This reduction in P load increases the  $\text{BOD}_5/\text{P}$  ratio; providing the BNR  
187 process with additional buffer capacity to remove P biologically and meet final effluent discharge consents  
188 (Jeanmaire and Evans, 2001). Final effluent (Flow H) total P is reduced by  $3.7\pm 3.3\%$  with  $\text{PO}_4\text{-P}$  reduced by  
189  $23.5\pm 2.6\%$ .

190 On one occasion during operation with P recovery, 87% recovery was achieved in Slough WWTP. On this day,  
191 influent concentrations to the P recovery system were 127.2 mg/l total P and 118.2 mg/l  $\text{PO}_4\text{-P}$ , while effluent  
192 concentrations were 32.5 mg/l total P and 15.3 mg/l  $\text{PO}_4\text{-P}$ . At 87% recovery,  $11.6\pm 1.4\%$  total P and  $19.6\pm 1.6\%$   
193  $\text{PO}_4\text{-P}$  was removed from WWTP influent into struvite fertiliser. Reducing  $\text{FeCl}_2$  solution dosing increased P  
194 concentrations onsite with total P and  $\text{PO}_4\text{-P}$  exceeding 200mg/l and 190mg/l, respectively. Had P recovery  
195 been possible with these concentrations on this date, 90% P recovery would have been achieved,  
196 corresponding to recovery of approximately 20% total P and 45%  $\text{PO}_4\text{-P}$  as struvite. Each of the benefits  
197 described in the previous paragraph would be amplified, increasing the attractiveness of P recovery in WWTPs.

198 At maximum P recovery of 90%, 0.5 tonnes of struvite fertiliser can be produced per day. Over one year this  
199 equates to 185 tonnes of struvite fertiliser. At an indicative price of £100/tonne, this leads to revenue of  
200 approximately £20K/year. Maaß et al., (2014) reported struvite sales amounting to 4% of total benefits  
201 achieved by P recovery, equating to approximately €40K/year. However, the research was conducted on a  
202 much larger WWTP with PE of 1.2 million. This revenue stream combined with other site specific savings  
203 provides substantial drivers for P recovery from WWTPs.

204

### 205 *3.3 Cost savings associated with P Recovery*

206 Figure 8 summarises the costs, savings and revenue associated with P recovery, as subsequently described. For  
207 P recovery to operate more efficiently, injection of FeCl<sub>2</sub> solution was gradually decreased. In 2012, 1352  
208 tonnes FeCl<sub>2</sub> solution was injected; at £58/tonne FeCl<sub>2</sub> solution, this represents a cost of £78K. Since 2012,  
209 chemical dosing has reduced steadily with 1006 tonnes FeCl<sub>2</sub> solution used in 2013, 440 tonnes in 2014 and an  
210 estimate of 330 tonnes to be used in 2015. Compared to 2012, over £59K has been saved on chemical dosing  
211 in 2015. According to Thames Water Asset Standards (2013), 1mg/l Fe is required to reduce odours,  
212 corresponding to 616 kg FeCl<sub>2</sub> solution/day (225 tonnes FeCl<sub>2</sub> solution/year). If this represents the minimum  
213 possible injection rate, FeCl<sub>2</sub> solution dosing can be reduced by a further 105 tonnes, corresponding to  
214 additional savings of £6K. The total potential savings on chemical dosing compared to 2012 amount to £65K.

215 Reducing FeCl<sub>2</sub> dosing to the minimum of 1mg/l required for odour removal also results in a reduction of  
216 16.5% in sludge cake production, based on calculated mass balances. On average, 3966 tonnes of sludge cake  
217 are produced each year at Slough WWTP. For each tonne of sludge cake produced, water companies must pay  
218 £20.50/tonne for loading, hauling, stockpiling, and spreading of sludge to agricultural land. A reduction of  
219 16.5% would reduce sludge handling costs by over £13K.

220 P recovery itself results in further reductions in sludge cake mass (Maaß et al., 2014). The water content of the  
221 sludge matrix is decreased as the dewatering characteristics of sludge are improved (Maaß et al., 2014). P  
222 removal as struvite reduces sludge mass by approximately 178.85 tonnes/year at Slough WWTP, representing  
223 cost savings of £3.6K.

224 Along with savings quantified in this research, recovery of P as struvite can lead to other chemical and  
225 maintenance savings. Savings at Slough WWTP include polymer costs of ~£10.6K, centrifuge anti-scaling  
226 chemicals ~£10.5K, and operating expenses for pump and pipe rehabilitation of ~£10K. Unquantified savings  
227 include reduced operator labour/maintenance costs required to remove struvite from clogged pumps and  
228 pipework and energy savings achieved as a result of unclogged pumps and pipes. Total cost savings at Slough  
229 WWTP amount to approximately £113K. The savings are much larger than the £20K revenue from sale of  
230 struvite fertiliser, but together they represent a significant driver for P recovery. Maaß et al. (2014) report that  
231 reduced use of flocculating agents contributed 51% (i.e. €500K) of the benefits achieved by recovering P from  
232 their research WWTP. For comparison, reduction of FeCl<sub>2</sub> solution dosing provides 57.7% of the total savings at  
233 Slough WWTP.

234 Thames Water must pay for electricity utilised by the Ostara P recovery system to produce struvite, estimated  
235 at £24K for 2015. MgCl chemical costs are covered by Ostara but Thames Water pay for other chemicals, e.g.  
236 NaOH and CO<sub>2</sub> for pH correction, amounting to £12K expected costs for 2015. Annual maintenance costs for  
237 the Ostara system amount to approximately £54K. In total, the gains to be made from P recovery aggregate to  
238 £133K pa (savings + revenue) while the costs amount to approximately £90K, but this comparison does not  
239 allow for the unquantified electricity and maintenance costs resulting from nuisance struvite precipitation.

240

### 241 *3.4 Reduction in Sludge Cake Total P*

242 Sewage sludge production is increasing in the UK due to increased population, sewerage connections and  
243 enhanced treatment (Charlton et al., 2012). Therefore more agricultural land must be found on which to apply  
244 sludge cake. P-vulnerable zones are becoming more prevalent due to historical P contained in the land bank,  
245 limiting the land on which sludge cake can be applied (Jeanmaire and Evans, 2001). England and Wales have no  
246 legislation as yet concerning P application to land; the only regulation affecting this is indirect, arising from N  
247 restrictions under the Nitrates Directive. When sludge application is limited by N, excess of P in soils can  
248 become an issue (Amery and Schoumans, 2014). Agriculture is estimated to be responsible for 30-50% of the P  
249 pollution contributing to environmental and water quality problems (Kay et al., 2012). In 2013 there was a P

250 surplus of 7.2 kg/ha on managed agricultural land in the UK, an increase of 3% compared to 2012 (DEFRA,  
251 2014).

252 Surplus P in agricultural land can be more effectively managed by removing P from WWTPs as struvite  
253 fertiliser. P recovery from centrifuge centrate causes a reduction in the P content of sludge cake destined for  
254 agricultural land: recovery of  $71.6\pm 7.4\%$  reduces the total P content from  $1.17\pm 0.05\%$  to  $1.07\pm 0.01\%$  (as  
255 percentage of dry solids). With continued P recovery, the P content of the sludge is expected to decrease  
256 further, increasing the available land to which sludge cake can be safely applied. Struvite fertiliser can be  
257 applied to land as a more efficient source of slow release P for agriculture. Slow release fertilisers have low  
258 leach rates, slowly releasing nutrients during the growing seasons, a distinct advantage over current practices  
259 in applying sludge cake-to-land (De-Bashan and Bashan, 2004).

260

### 261 *3.5 National Potential for P Recovery*

262 Like the food production system in the EU as a whole, food production in the UK is heavily reliant on imported  
263 P and vulnerable to fluctuating phosphate rock prices. In 2009, the UK imported a total of 138 kt P and  
264 exported 23.5 kt, a net import of 114.5 kt P (Cooper and Carliell-Marquet, 2012). One method to reduce  
265 reliance on imported P fertiliser is to produce fertiliser from waste resources within countries with sufficient  
266 infrastructure to do so. In the UK, 96% of the population is connected to sewerage systems, which collect over  
267 11 billion litres/year of wastewater from homes, municipal, commercial, and industrial sources (DEFRA, 2012).  
268 Globally, wastewater contains 0.5–1.2 kg P/person/year depending on regional diets (Schroeder et al., 2009).  
269 The current population of the UK is approximately 64.1 million people; UK WWTPs accept between 32.05 and  
270 76.92 kt P/year, representing a significant potential source of P to offset imports.

271

### 272 *3.6 National Effects of P Recovery from WWTP*

273 Figure 9 shows an adapted version of Cooper and Carliell-Marquet's (2012) SFA model of P flows in the UK,  
274 based on data from 2009. According to their analysis, WWTPs in the UK received a total of 55 kt P. The  
275 majority of this P flowed to water bodies through WWTP effluent discharge, while a significant amount  
276 accrued in agricultural land through sewage sludge application to land. Another proportion of P was either  
277 directly landfilled or incinerated followed by landfilling, where it accumulated, assuming no P leaching from  
278 this stock. A smaller proportion of P within sewage sludge was spread to non-agricultural land for land  
279 reclamation, industrial crops and composting. There is great potential within each of these waste streams to  
280 recover P for further use. Other than sludge application to land, there is no P recycling for fertiliser use in the  
281 UK.

282 Using the Ostara P recovery technology under review, it is possible to transfer  $9\pm 1\%$  of the total P entering  
283 WWTPs into struvite fertiliser product (see Table 2). Of the WWTPs in the UK, 24 use BNR and BNR supported  
284 by iron dosing for P removal, representing a PE of over 4.8 million (Cooper, 2014). In the UK, 1 PE emits  
285 approximately 2.5g P/day, so that about 4.4kt P/year flow into the WWTPs that use BNR and iron supported  
286 BNR (OSPAR, 2004). This P can be recovered from sludge dewatering liquors using nutrient recovery  
287 technologies such as Ostara or Phospaq, both currently operating in the UK and achieving  $9\pm 1\%$  recovery,  
288 resulting in a total of  $0.4\pm 0.1$ kt/year recoverable P. To increase this value, it will be necessary to develop  
289 methods of P recovery from chemically dosed WWTP, not just those using BNR.

290 In Section 3.2, it was concluded that 9-20% total P recovery could be achieved in WWTPs using current  
291 technologies. It is reasonable to assume that new technologies under development would be capable of

292 achieving comparable recoveries. Wilfert et al. (2015) suggest that it may be possible to induce formation of  
293 specific Fe/P compounds from which P is easily extractable. Assuming it is possible to recover 15±5% influent  
294 total P at all WWTPs using suitable technologies, 7.05±2.01 kt P/year could be recovered, providing a national  
295 source of P fertiliser in the UK, reducing P fertiliser imports by 9.1±2.6% from the 2009 figure of 77.5 kt (see  
296 Figure 10). Comparing Figures 9 and 10, P recovery from WWTP influent markedly reduces P losses to landfill,  
297 compost/other disposal, and water bodies. P flows into water bodies would reduce by 9.5±2.7%, primarily due  
298 to the reduction in final effluent total P concentrations. Agricultural land's stock of P would be reduced by  
299 3.0±0.9% (Figure 10) due to reduced P in sewage sludge. This reduces P contained in the land bank, allowing  
300 more sludge cake to be applied to land, reducing sludge disposal issues faced by wastewater companies. P  
301 recovery from WWTP sludge dewatering liquors represents a small yet meaningful source of fertiliser in the UK  
302 of 7.05±2.01 kt P/year. However, Figure 10 shows other streams (sewage sludge to agriculture, and sewage  
303 sludge to incineration/landfill) from which P could be recovered with greater impact on P efficiency and losses,  
304 as subsequently described.

305

### 306 *3.7 National Effects of P Recovery from WWTP and ISSA*

307 In addition to sludge dewatering liquors, P can be recovered from sludge from wastewater treatment. In 2009,  
308 sludge containing 5.5 kt P was sent to incineration/landfill as shown in Figure 9 (Cooper and Carliell-Marquet,  
309 2012). This P was either lost to landfill or leached into water bodies, worsening eutrophication. Maaß et al.  
310 (2014) recognise the advantages in combining P recovery from WWTP and thermal treatment of sludges by  
311 incineration, pyrolysis or gasification, together referred to as Advanced Energy Recovery (AER) and enabling  
312 higher P yields than recovery as struvite. While processes to recover P from incinerated sewage sludge ash  
313 (ISSA) are chemically and energetically intensive, recovery from this source exerts the greatest impact on the  
314 national P budget (Figure 11). Rising P prices make recovery from AER residues economically attractive.  
315 Recovery of P from ISSA is particularly attractive with potentially greater P recovery and efficiency of use  
316 compared to spreading on land (see below), economies of scale due to centralised recovery and destruction of  
317 unwanted compounds during thermal treatment (Wilfert et al., 2015).

318 It is possible to recover up to 90% of the P in ISSA (Cleaner Production Germany, 2015). Following the  
319 assumption that 15±5% of the total P entering all WWTP can be recovered using suitable technologies (see  
320 Section 3.6), P losses to landfill would be reduced by 32.1±0.6%, to 4.70±0.23 kt/year (Figure 11). Recovering  
321 90% P from ISSA corresponds to a further recovery of 4.23±0.21 kt P/year. Together with P recovered from  
322 wastewaters (Section 3.6), a national source of P fertiliser of 11.28±1.81 kt P/year would be created, reducing  
323 P fertiliser imports by 14.6±2.3% compared to 2009. Further effects of P recovery from WWTP and ISSA are  
324 available in Table B, Supplementary Data.

325 According to the SFA model (Figure 9), 9.5 kt P was lost to compost/disposal in 2009 [but this delayed loss can](#)  
326 [be recovered, turning it into a future gain \(Scholz and Wellmer, 2015\)](#). It may be possible to combine this  
327 stream with sludge destined for incineration. Diverting sludge from disposal to AER increases potential P  
328 capture, as shown in Figure 12, increasing the P entering AER to 7.64±0.37 kt/year. At 90% P recovery from  
329 incinerated sludge, 6.89±0.34 kt P would be recovered. Together with P recovered at WWTPs, this represents a  
330 national P fertiliser source of 13.89±1.67 kt/year, reducing imports of P fertiliser by 17.9±2.2% relative to 2009.

331 The second largest P flow from WWTPs is the sludge currently spread on agricultural land. Sludge spreading is  
332 regarded as an environmentally unfavourable disposal option (Lundin et al., 2004). It is an inefficient way to  
333 recycle P, with nearly 50% of the P lost from the land to water bodies; a pure high grade P fertiliser is therefore  
334 preferred over complex and variable sludge (Wilfert et al., 2015). Energy is required to transport and spread  
335 sludge to land, whereas AER of sludge produces energy (Lundin et al., 2004). Sludge spreading on land releases



336 acidifying substances and heavy metals which accumulate in soils (Lundin et al., 2004). Spreading to land is  
337 cheaper than AER but represents a cost whereas producing P-rich fertiliser from AER wastes represents a  
338 potential revenue stream. A more beneficial long term solution to achieving a closed loop P system is  
339 therefore to extract P from sludge (Bateman et al., 2011). While precipitation of struvite from sludge is  
340 possible, a convenient and potentially economically viable method is to process sludge using AER technologies  
341 onsite and transport residues to a central facility for P recovery. Assuming all sewage sludge undergoes AER  
342 processing, the total P recovered from sewage sludge ash for use as fertiliser would be  $21.71 \pm 0.95$  kt P/year  
343 (Figure 13). Combining this with the other potential sources of recovered P would provide a national P fertiliser  
344 source of  $28.04 \pm 0.89$  kt P/year, reducing P fertiliser imports by  $36.2 \pm 1.1\%$  relative to 2009. Diverting sewage  
345 sludge from application to agricultural land to AER with P recovery would reduce flows of P to water bodies by  
346  $21.7 \pm 1.9\%$  (Figure 13). The majority of P stock remaining in agricultural land comes from animal manure and  
347 direct fertiliser application, as can be seen in the original figure presented by Cooper and Carliell-Marquet  
348 (2012). Details of the effects of P recovery on the national P budget are available in Table B, Supplementary  
349 Data.

350 Figure 14 summarises the potential to produce P rich fertiliser from WWTPs and the associated waste streams.  
351 Based on data for 2009, as much as  $28.04 \pm 0.89$  kt P fertiliser can be produced in the UK, meeting  $36.2 \pm 1.1\%$  of  
352 the P fertiliser demand in the UK. However, the amount of sludge produced varies year to year. According to  
353 DEFRA (2012), in 2010 1.4 million tonnes of sewage sludge were produced in the UK. Incineration of sewage  
354 sludge reduces its mass by up to 90%; leaving 140,000 tonnes of ISSA containing 8.2–14.3% P (Thygesen and  
355 Johnsen, 2010), so that between 11.5 and 20 kt P could have been recovered from sewage sludge in 2010.  
356 Added to P potentially recoverable from WWTPs, this represents a potential production of 16.4–29.1 kt of P as  
357 fertiliser. UK population is projected to increase to 73.2 million by 2035, leading to a corresponding increase in  
358 P entering WWTPs and sewage sludge production (Office for National Statistics, 2011). As wastewater  
359 treatment processes improve, greater amounts of sewage sludge containing P will be produced. Thus  
360 wastewater presents a continuing source of P in point sources ideal for recovery. Assuming ISSA in landfills can  
361 be located, it may be possible to mine landfilled ISSA for untapped P resources, reducing future P emissions  
362 and boosting P fertiliser availability further. Reducing UK demand renders P more available to countries which  
363 do not yet have sufficient infrastructure to recover P from waste. Reducing imports of P fertiliser may reduce  
364 carbon footprint and P distribution losses associated with importing P from outside the EU. Life Cycle Analysis  
365 (LCA) analysis showed struvite precipitation from dewatering liquors resulted in net environmental benefit  
366 across a full range of environmental impacts: eutrophication, global warming, human toxicity, terrestrial  
367 ecotoxicity and depletion of fossil fuels and other abiotic resources (Bradford-Hartke et al., 2015).

368

### 369 *3.8 Potential Savings from Recovering P*

370 At current volatile prices, recovering P from wastes can potentially offer savings to UK agriculture by reducing  
371 the costs of imports and transportation. In August 2015, triplesuperphosphate (TSP) cost £256.30/tonne while  
372 diammonium phosphate (DAP) cost £293.77/tonne (Indexmundi, 2015). Struvite fertiliser contains  
373 approximately 12.62% P, along with N and Mg. Assuming  $28.04 \pm 0.89$  kt of P was recovered and transformed  
374 into struvite, it is possible to produce  $222.54 \pm 7.6$  kt struvite fertiliser per year; at £100 per tonne, this  
375 represents potential struvite sales of £22.3±7.6 million. At the current market price, replacing imported TSP or  
376 DAP with nationally produced struvite fertiliser would reduce fertiliser costs by £45-54 million per year in the  
377 UK. This would also create a new market for recovered P fertiliser in the UK. The market power currently  
378 exerted through the concentration of P resources would be lessened with the production of P locally and  
379 would provide a buffer against price volatility (Seyhan et al., 2012).

380

381 **3.9 Achieving P Recovery**

382 Recovering P from WWTP dewatering liquors is beneficial for the operation of the WWTP and is economically  
383 feasible. However, not all WWTPs are suitable for the current P technologies, which can be deployed only at  
384 WWTPs with BNR. To achieve greater P recovery, technologies suitable for chemically dosed WWTPs must be  
385 developed. This would enable P recovery in 452 WWTPs, compared to the 24 BNR WWTPs in the UK which can  
386 deploy current P recovery technologies (Cooper, 2014). Increasing understanding of Fe and P interactions is  
387 required to improve and develop P recovery technologies. It may be possible to encourage the precipitation of  
388 a specific Fe/P complex from which P is easily extracted (Wilfert et al., 2015). Water companies will only invest  
389 in P recovery technologies if they are economically feasible, provide operational savings and/or a revenue  
390 stream or are regulated to recover P. Therefore, along with technologies to recover P, case studies are needed  
391 to reveal the benefits and dis-benefits of P recovery for WWTPs.

392 The current regulation of the UK water industry requires it to operate on five-yearly cycles called Asset  
393 Management Plan (AMP) periods: every 5 years, water companies create business plans detailing objectives  
394 for the next AMP period, demonstrating compliance with the EU Water Framework Directives and the  
395 expectations of the Environment Agency. In the current AMP6 period, the EU Water Framework Directive and  
396 Environment Agency are seeking to improve quality of water bodies, requiring water utilities to reduce levels  
397 of nutrients in treated effluent discharged into rivers (Thames Water, 2013). The business plan created for  
398 each AMP period is an ideal format for water companies to commit to P recovery. However, P recovery must  
399 first appear on the UK Environment Agency and EU agendas. To achieve P recovery, information regarding P  
400 flows and prices should be used to highlight the efficiencies and opportunities associated with national P  
401 recovery strategies. Using case studies, SFA models and LCA, researchers can highlight to governments the P  
402 issues facing the UK and EU. Supported by industry detailing the technological interventions, P recovery can  
403 appear on the national and EU agenda. Much like regulations requiring final effluent discharge P  
404 concentrations, regulations may need to be introduced setting P recovery targets.

405 Another aspect to consider when encouraging P recovery from WWTPs is whether agricultural workers are  
406 willing to use the product. Currently in the UK, 40.9% of sewage sludge produced at WWTPs is applied to  
407 agricultural land. Since sludge spreading is widely accepted in the UK, it is likely that agricultural workers would  
408 be willing to use P fertiliser recovered from wastewater. The struvite 'prills' produced from the Ostara process  
409 are dense, odourless, free of potentially harmful microorganisms and registered as fertiliser (Baur, 2010).  
410 Struvite fertiliser contains lower heavy metal concentrations than phosphate rocks (Driver et al., 1999). Ahmed  
411 et al. (2015) have shown that struvite has a slow dissolution rate, making it an efficient fertiliser.

412

413 **4. Conclusions**

414 WWTPs are ideal sources for P recovery to produce P rich fertilisers, thus reducing P imports. However, the  
415 benefits, savings, and revenues for water utilities recovering P at full scale installations have not yet been  
416 thoroughly documented and to date there have been few attempts to develop comparisons via LCA. To entice  
417 water utilities to install P recovery technologies, P recovery must be economically feasible and benefit  
418 individual WWTPs. At Slough WWTP, operated by Thames Water, running the Ostara system at average 72±7%  
419 P recovery resulted in 8.8±0.7% total P and 20.5±3.2% PO<sub>4</sub>-P recovery as struvite fertiliser. As a result of P  
420 recovery, P flows through the WWTP process reduce. The contribution of centrate to the internal recycle  
421 stream is decreased from 42.1±11.8 to 30.4±9.7% total P and from 78.6±1.6 to 47.2±3.6% PO<sub>4</sub>-P, while P flows  
422 to BNR and final effluent reduce allowing the site to meet discharge consents more easily.

423 In addition to the revenue from struvite fertiliser sales, amounting to ~£20K/year, much of the benefit arises  
424 from operational and maintenance savings. Three quarters of UK BNR style WWTPs are supported by chemical

425 dosing to avoid odour and ensure discharge consents are met. P recovery from BNR WWTPs requires the  
426 reduction of chemical dosing to increase bioavailable  $\text{PO}_4\text{-P}$  for recovery as struvite. Reduced chemical dosing  
427 alone provides savings of over £65K, including cost savings associated with reduced sludge cake production.  
428 Savings from reduced use of polymer and anti-scaling chemicals, operational and maintenance costs amount  
429 to more than £113K for the whole site. In total the savings and sales revenue amount to £133K while the costs  
430 amount to approximately £90K.

431 The benefits of P recovery at WWTP scale are demonstrated, but there must be benefits at a national level for  
432 P recovery to be encouraged by governments. To achieve more significant benefits of P recovery, technologies  
433 for recovery from chemically dosed WWTPs must be developed; such technologies could be deployed at a  
434 further 452 WWTPs in the UK. A combination of new and current P recovery technologies averaging  $15\pm 5\%$  P  
435 recovery would yield  $7.05\pm 2.01\text{kt}$  P fertiliser/year in the UK. While small, this would reduce P fertiliser imports  
436 by  $9.1\pm 2.6\%$  based on 2009 flows. A further  $21.71\pm 0.95\text{kt}$  P/year can be recovered by incinerating sewage  
437 sludge currently destined for agriculture and other disposal and extracting P from the resulting ash (ISSA),  
438 while the incineration of sewage sludge produces energy, an additional revenue stream for water utilities.  
439 Recovering  $15\pm 5\%$  of the P from WWTP influent and 90% of the P in ISSA represents a source of  $28.04\pm 0.89\text{kt}$   
440 P/year, reducing P fertiliser imports by  $36.2\pm 1.1\%$ . This flow would reduce UK vulnerability to uncertain P  
441 availability and prices, and also reduce the carbon and energy footprints associated with transport of P to UK  
442 (see Figure 15). P recovery from WWTP influent and ISSA would reduce P losses to water bodies by  $21.7\pm 1.9\%$   
443 compared to 2009 P flows. The beneficial impacts should motivate the UK Environment Agency, DEFRA, and  
444 the government to legislate for P recovery in the UK.

445 The local and national effects of P recovery from UK WWTPs are summarised in the flow diagram presented in  
446 Figure 15. The two interventions - P recovery from WWTP influent and from ISSA - can provide significant  
447 benefits both locally in WWTPs and nationally in the UK. Using such flow diagrams and mass balances, it may  
448 be possible to influence key actors to bring about a change in the current P system through legislative and  
449 regulatory measures. Water utilities should be targeted as key actors to achieve P recovery at WWTPs by  
450 highlighting the benefits of P recovery.

451

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457

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