
07

Opportunities for recovering phosphorus from residue streams

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Left: A large sewage treatment site in Ukraine, showing filtration ponds. Phosphorus can be recovered from wastewaters and used to make fertilisers. Photographed by Ivan Bandura on www.unsplash.com - www.ivan.graphics

Currently large amounts of phosphorus are lost in waste streams. A global commitment to recycling nutrients in wastes and residues is needed. Phosphorus recovery provides the opportunity to recover a contaminant free, high purity source of phosphorus that can be used to create customised products, and substitute effectively for phosphorus derived from phosphate rock. Phosphorus recovery and recycling will catalyse new circular economy opportunities in line with national and international policies and directives.

Suggested citation for this chapter: L. Hermann, J.W. McGrath, C. Kabbe, K.A. Macintosh, K. van Dijk, W.J. Brownlie. (2022). Chapter 7. Opportunities for recovering phosphorus from residue streams, in: W.J. Brownlie, M.A. Sutton, K.V. Heal, D.S. Reay, B.M. Spears (eds.), Our Phosphorus Future. UK Centre for Ecology & Hydrology, Edinburgh. doi: 10.13140/RG.2.2.16366.08006

Challenge 7.1: Many waste streams and residues represent a significant untapped phosphorus resource

The phosphorus in many organic waste streams and residues, including food wastes, biosolids and abattoir residues, is commonly lost to the environment. Many phosphorus-rich wastes are managed as pollution rather than valuable phosphorus resources. The ashes of incinerated residues are often landfilled or used in building materials without recovering the phosphorus they contain. There are significant opportunities to increase phosphorus recovery in all regions.

Challenge 7.2: Recovered phosphorus materials must have a competitive commercial value

Phosphorus recovery processes that do not generate industry compatible raw materials or finished products with a clearly defined market potential may fail to contribute to phosphorus recycling. Where recovered phosphorus fertiliser match mineral phosphorus fertiliser in terms of performance, systems to support large scale production, transport and handling are currently insufficient.

Challenge 7.3: There is a lack of policy and market support for phosphorus recovery

There is a global lack of tangible policy support for phosphorus recovery, which has hindered the building of commercial markets for renewable phosphorus products, including financial instruments such as subsidies, tax incentives, or support for farmers to adopt sustainable measures. Certifying recovered phosphorus products as fertilisers can provide a significant challenge for phosphorus recovery enterprises.

Solution 7.1: Establish a global commitment to recycling nutrients in wastes and residues

Nations should commit to ambitious targets to recover and recycle nutrients from livestock manure, wastewaters, abattoir residues and industrial waste streams, whilst discontinuing landfilling phosphorus-rich ashes and their displacement into building materials. A significant increase in phosphorus use efficiency, in conjunction with good management practices to reduce and mitigate phosphorus losses is also critical.

Solution 7.2: Optimise the commercial viability of recovered phosphorus products

Phosphorus recovery technologies must produce commercially viable materials with defined market potential or that are industry compatible as a raw material for fertilisers or other products. Opportunities to produce co-value products and services (i.e. produce energy, other nutrients), and the environmental sustainability of recovery processes, should be optimised. Some recovered phosphorus products/fertilisers have a potential market opportunity to provide efficient, pollutant-free fertilisers. A key challenge for phosphorus recyclers is producing relevant volumes and homogeneous quality to meet demand. The market price of recovered phosphorus products/fertiliser alone should not define the economic feasibility of phosphorus recovery. According to the "polluters pay" principle, stakeholders could share the cost of recovery, at least in more economically developed countries.

Solution 7.3: Develop policies that support phosphorus recovery and recycling

Critical policy needs to include a regulatory framework to boost the use of recovered phosphorus materials as an alternative to phosphate rock as the primary source of phosphorus in mineral fertilisers. In some regions, the necessary infrastructure to collect wastes and residues is still required. The next step could be global binding agreements and a paradigm change: taxing the consumption of natural resources and related externalities and reducing the tax burden of renewable resources and labour.

7.1 Introduction

A significant increase in the recovery and recycling of phosphorus (P) lost in organic wastes is vital if we are to improve global P sustainability. As discussed in Chapter 6, there is great potential to recycle P (and other nutrients) by applying P-rich organic wastes and manures to agricultural soils. However, in some cases P must be recovered, detoxified, and modified, from wastes, to recycle it safely and effectively and to reach higher levels of nutrient use efficiency. In this chapter, P recovery is defined, the circumstances in which P recovery is required to support P recycling are discussed and an overview of common P recovery technologies is provided.

7.1.1 Defining phosphorus recovery and its role in phosphorus recycling

The terms P recycling and P recovery have blurred definitions in the literature (Macintosh et al, 2018). In this report, P recovery refers to processes used to isolate high-quality P from organic matter (including after an intermediate step of incineration leading to inorganic ash) into recovered products that can be recycled without further processing (e.g. struvite), or recovered P materials (e.g. calcium phosphates, phosphoric acids, white P) that can be used to make recovered P fertilisers. Fertilisers made using P recovered from wastes are also referred to as secondary fertilisers in the literature. Phosphorus recovery involves a chemical P-extraction and/or chemical bond altering process induced by reducing/increasing pH or high temperatures under oxygen-depleted conditions. Recovery usually includes a pollutant removal process resulting in a purified material or product, typically qualified for assigning an end-of-waste status, that is, the waste ceases to be waste and obtains a status of a product or a secondary raw material, at least from a legal point of view. In some literature, the definition of P recovery presented here is also referred to as advanced P recovery (Lu et al., 2016; Tonini et al., 2019). Incineration alone, while destroying most organic pollutants and removing highly volatile inorganic pollutants (mercury), is not a P recovery process (but rather a stage commonly used in the P recovery processes). Furthermore, as discussed in Chapter 6, most P-rich organic materials often undergo treatment processes before application to soils, such as dewatering, composting, vermicomposting, or anaerobic digestion, however, these are also not considered P recovery processes as it does not target a specific change in the chemical form of P, for example, extracting it from organic complexes. In this report, we define P recycling as the use of P from waste and residue streams, whether in the form of a recovered P fertiliser or organic material (e.g. manure, biosolids), to produce agricultural products. This definition is described in more detail in Chapter 6. Phosphorus recovery is, therefore, not synonymous with P recycling, but is often a stage used to process P so it can be recycled. For some P-rich organic wastes and/or circumstances, P recovery is essential to recycle the P contained in the waste stream.

7.1.2 Circumstances when phosphorus recovery is required

Phosphorus recovery provides the opportunity to recover a 'safe' (i.e. low-in or free-from contaminants), high purity source of P that can be used to create customised products, and substitute effectively for P derived from phosphate rock (PR) (Withers, 2019). In some situations, large distances can separate P-rich organic waste production in livestock-dominated areas and the croplands where they can be recycled. This is common in sites where manure or nutrient-rich urban wastes are produced in high volumes (i.e. intensive livestock production, densely populated cities) and local areas that do not contain sufficient croplands to recycle the nutrients they contain (Johansson and Kaplan, 2004; Bai et al., 2016). Transporting large volumes of bulky organic material to croplands is often not economically feasible. In these situations, P recovery processes (including solid/liquid separation) can produce recovered P materials and/or fertilisers that are cheaper and easier to store and transport.

In other situations, contaminant levels in the P-rich organic wastes and residues, even after treatment, are too high for their desired use. Processes such as composting and vermicomposting can reduce contaminants in wastes (Domínguez et al., 2004; Yadav et al., 2010; Martínez-Blanco et al., 2013) (see Chapter 6). However, pathogens, hormones, antibiotics, heavy metals, and micro-plastics can persist and can accumulate in soils/biota after repeated manure/biosolid application (Kinney et al., 2008; Hill et al., 2019). Depending on the desired use of the waste, this can pose a risk to human, animal and environmental health (Laturnus et al., 2007; Cieslik et al., 2015; Malomo et al., 2018). In some industrial applications, even trace levels of contaminants are not tolerated. Most P recovery processes produce materials that contain low to no contaminants.

A high purity sustainable P material is required by industry to make a customised product. Most customised products made using recovered P are fertilisers, however, recovered P materials can be used to manufacture a range of other products (i.e. flame retardants, feedstocks). Some recovered P fertilisers are more sustainable than mineral P fertiliser (Kraus et al., 2019; Tonini et al., 2019), but with similar P content and bioavailability allowing P inputs to soils to be carefully managed to optimise plant uptake and yield, whilst avoiding P losses to the environment.

7.2 Common processes to recover phosphorus

Selecting the most effective P recovery process depends on the type of waste treated, the resources available and the products that are required. There are more than 30 different technologies available to recover P from waste streams and new ones continue to emerge (Kabbe and Rinck-Pfeiffer, 2019). Commercially established processes of P recovery exist mainly for sewage sludge and digestate, with P recovery predominantly practised in the European Union (EU), Japan and North America (Kabbe and Rinck-Pfeiffer, 2019) (Figure 7.1).

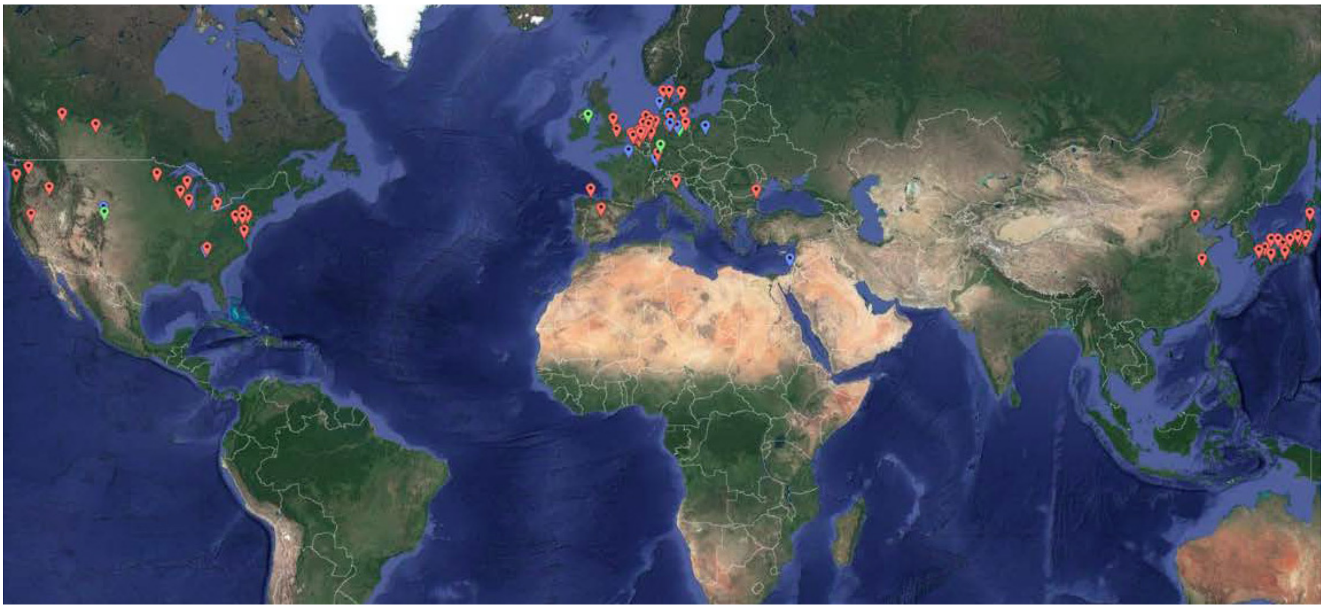

Figure 7.1 Global distribution of P recovery from sewage installations (red = operating installations, blue = installations under construction, green = planned installations), modified from Kabbe and Rinck-Pfeiffer, (2019). In 2019, P recovery installations were mainly concentrated in only the EU, Japan and the US.

However, industrial P recovery processes have also been applied, to abattoir residues (e.g. blood, meat and bone meal), poultry litter, livestock manure, food processing wastes and industrial waste streams.

Several reviews of P recovery technologies are provided in the literature, which this document does not aim to replicate (e.g. Morse et al., 1998; Le Corre et al., 2009; Rittmann et al., 2011; Cieslik et al., 2015; Tarayre et al., 2016; Schoumans et al., 2017; Mahoo, 2018; Kabbe and Rinck-Pfeiffer, 2019; Kraus et al., 2019; Ohtake and Tsuneda, 2019; Li et al., 2019a). However, they highlight there is no 'ideal' single method to recover P from wastes, and technologies are not mutually exclusive (Walker, 2017). The number of available processes does not reflect the need to continually improve on the preceding process, but the diverse range of conditions where P recovery is required. Indeed, methods to recover P must cope with high concentrations of P and organic material in low volumes in animal, human and food wastes, through to relatively low P concentrations in large volumes of water from diffuse pollution, i.e. from runoff and erosion from agriculture (Desmidt et al., 2015).

However, whilst many processes exist, some general stages are commonly followed. The following simplified overview does not cover all technologies or processes available but rather aims to provide a conceptual overview of some of the common stages found in many P recovery processes and technologies (which may occur in different orders, combinations, and with the omission or addition of stages).

In most P recovery processes, there is an early stage to concentrate the P into a reduced solid or liquid volume by solid/liquid separation. This can be commonly achieved using iron or aluminium salts (e.g. chlorides or sulphates) to precipitate P in an insoluble metal phosphate. The metal phosphate can then be settled out by sedimentation (Morse et al., 1998). Alternatively, enhanced biological phosphorus removal (EBPR) can be used to remove P from wastewater by recirculating sewage sludge through anaerobic and aerobic conditions to optimise conditions for cell uptake by polyphosphate accumulating (micro) organisms (Oehmen et al., 2007). Volume reduction of sludge/manure/digestate often includes dewatering by solid/liquid separation. Other processes utilise anaerobic digestion, which reduces the volume of the waste and frequently enhances the dewaterability, whilst converting volatile organic compounds to biogas providing a source of renewable energy (Feng and Lin, 2017). Phosphorus can be recovered from digestates. Incineration, commonly used in the processing of abattoir residues, sewage sludge and, occasionally to poultry litter, is highly effective at concentrating P, and can result in a 90% reduction in volume and a 60% reduction in weight and destroys pathogens and degrades antibiotics (Walker, 2017). In addition, incineration can convert the chemical energy in sludge to heat and electricity with an overall positive energy balance (Adam et al., 2009). Ashes may still contain heavy metals e.g. copper and aluminium, present in the original waste/residue (Donatello et al., 2010). Iron phosphate and aluminium phosphate are not bioavailable under typical pH and redox conditions found in soils and are therefore of low value for direct use as a P fertiliser (Sartorius et al., 2012) as are ashes of incinerated wastes (Cabeza et al., 2011), as such further stages are required.

If the residue has not been incinerated, P concentration/volume reduction is often then followed by a range of physico-chemical reactions to precipitate (crystallise) or adsorb the P from the liquid fraction of the residue. Precipitation of P from wastewaters using magnesium or calcium salts is a well-established technology at a commercial scale and produces struvite ($MgNH_4PO_4{\cdot}6H_2O$), or hydroxylapatite ($Ca5(PO_4)3(OH)$), respectively (Molinos-Senante et al., 2011; Kataki et al., 2016). This process also supports wastewater treatment plant (WWTP) maintenance as struvite is a known scale deposit that can block pipes/heat exchangers, therefore recovery of struvite can lessen these impacts. Struvite can make an efficient slow-release P fertiliser and can be used as a raw material blended into mineral P fertilisers (Hall et al., 2020; Kataki et al., 2016; Li et al., 2019b). Phosphorus compounds in liquid wastes can also be recovered through adsorption onto the surface of a range of materials, including iron-based sorbents such as iron oxide particles (Kang et al., 2003). Adsorbents also include hybrid anion exchange (HAIX) or ligand exchange resins, which can combine polymer anion exchange resins with metals such as zinc (Zhu and Jyo, 2005) copper (Zhao and SenGupta, 2000) and iron (Blaney et al., 2007), to selectively remove phosphates (O'Neal and Boyer, 2015). Whilst other methods are based on the change between P adsorption/desorption of certain substances under changes in pH; e.g. zirconium desorbs P in alkali solution and is reactivated in acid solution with little deterioration in P adsorption capacity (Ebie et al., 2008). Ion exchange can also recover P from liquid wastes, and is based on undesirable ions being exchanged for solid-phase ions based on their affinity (Crittenden et al., 2005). Examples include iron-based layered double hydroxides, which utilise ion-exchange between phosphate and carbonate ions (Rittmann et al., 2011), as well as hydrated ferric oxide and copper ion loading (Pan et al., 2009; Sengupta and Pandit, 2011; Nur et al., 2014). Furthermore, capacitive deionization (developed for desalination) which creates a charged electric field can be used to accumulate ions on oppositely charged carbon electrodes (i.e. phosphates from wastewaters) (Huang et al., 2014).

Commonly following these stages, the P must then be separated/solubilised from the recovery media (i.e. adsorbents, resins, metal salts etc.), or ashes if the waste has been incinerated, to isolate the P in a usable form. For most industrial applications, including the manufacture of recovered P fertilisers, a usable form would include phosphate compounds, phosphoric acid, or white phosphorus (Huygens and Saveyn, 2018). Acid leaching can be used to recover contaminant-free, high purity phosphoric acids, from ashes and the products of physico-chemical reactions (Donatello and Cheeseman, 2013; Tarayre et al., 2016; Kabbe and Rinck-Pfeiffer, 2019). Acid leaching involves lowering the pH of the wastes to <2, commonly using sulphuric or hydrochloric acid for dissolution of P and metals (Krüger and Adam, 2015; Cohen and Enfält 2017, Cohen et al. 2019). After acid leaching, dissolved heavy metals, iron and aluminium can be separated from the dissolved P by selective precipitation, solvent extraction or ion exchange but this requires further energy or chemical input (Petzet et al., 2012). Many concentration and purification processes are technically feasible, including liquid-liquid extraction used to produce a high purity monoammonium phosphate (MAP), diammonium phosphate (DAP) and phosphoric acids (Kabbe and Rinck-Pfeiffer, 2019). Alternatively, thermochemical processes can be used to remove heavy metals (Kabbe and Rinck-Pfeiffer, 2019). Examples include sewage sludge mixed with magnesium chloride, heated to 900°C in a rotary kiln, which causes volatile heavy metals or their respective compounds to evaporate, where they can be separated by off-gas cleaning systems (Adam et al., 2009). Mixing ash with sodium compounds (e.g. sodium carbonate) and heating it to 850-900°C produces a calcined phosphate with high bioavailability but is less effective in heavy metal removal (Kabbe and Rinck-Pfeiffer, 2019).

Some common stages involved in P recovery processes, end products and advantages and disadvantages of the process are summarised in Table 7.1.

In the following sections, we draw on evidence from those regions where P recovery has been developed (e.g. North America and Europe; Figure 7.1) to highlight key challenges and solutions to mainstreaming P recovery technologies and the challenges to recycling the P they recover.

Table 7.1 Description of key phosphorus (P) recovery processes for P-rich organic materials including post-treatment products, the benefits and disadvantages of the processes, and key references providing further information.

Common starting materials	P removal method	P concentration methods (maybe used in combination)	Location of P following removal/ concentration	P recovery methods (using physico-chemical processes)	Methods to separate/ solubilise P from recovery media	Products (depending on methods)	Advantages/disadvantages
Sewage sludge, livestock manure, food wastes	None needed	Anaerobic digestion, dewatering, and solid/ liquid separation	Phosphates in solution	Chemical precipitation Adsorption	Thermal/chemical hydrolysis (optional, to enhance P recovery rate)	Struvite Calcium phosphates (HAP, DCP)	A simple process, with high purity products. Reduces struvite scaling in wastewater treatment plants. Recovery rates are low, <20% without <40% with hydrolysis. The process also requires the addition of magnesium for struvite recovery. Energy and chemical demands for thermochemical hydrolysis.
	Chemical precipitation (commonly using a metal-salt (e.g. $FeCl_3$))	Anaerobic digestion, and dewatering		Chemical precipitation Adsorption	Acid leaching (required)	Struvite Calcium phosphates (HAP, DCP)	A simple process, with high purity products, and >60% P recovery rate. The use of vivianite is limited without further processing, and magnetic separation is unproven at full/large scale
		Anaerobic digestion	Metal-P compound (e.g. $FePO_4$)	Precipitation Ion-exchange	Acid leaching (required)	Phosphoric acid Calcium phosphates (HAP, DCP)	A simple process, with high purity products, and >60% P recovery rate. The use of vivianite is limited without further processing, and magnetic separation is unproven at full/large scale

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Sewage sludge, animal by-products and residues	All P-removal methods	Anaerobic digestion Dewatering Incineration (required)	P in ash (solid, dry)	Magnetic separation	None needed	Vivianite	High purity "commodity" products produced, from which customised products can be produced, i.e. MAP, DAP and TSP. Produces high volumes of by-product/ waste to be handled and recycled
				Thermal P solubilisation by additives (e,g, new P compounds)	Thermal process (>850°C for calcined phosphate >1400°C for P4)	Calcined phosphate P4	Low waste in the production of calcined phosphates. P4 can be used in a range of chemical industries, including fertiliser manufacture. Medium (calcination) to high (P4) energy consumption for thermal processes, and low purity and product flexibility for calcined phosphates.

7.3 Challenges

Challenge 7.1: Many waste streams and residues represent a significant untapped phosphorus resource

The phosphorus in many organic waste streams and residues, including food wastes, biosolids and abattoir residues, is commonly lost to the environment. Many phosphorus-rich residues are managed as pollution rather than valuable phosphorus resources. The ashes of incinerated residues are often landfilled or used in building materials without recovering the phosphorus they contain. There are significant opportunities to increase phosphorus recovery in all regions.

In a global assessment of P flows in 2013, it was estimated that ~85% of the P in human excreta and other human wastes (equivalent to ~6 Mt P) were not recycled (Chen and Graedel, 2016). Whilst data is not available for the phosphorus lost in abattoir residues globally, in the EU alone ~4 Mt of animal bone biomass is produced each year (bones are extremely high in phosphorus) (Someus and Pugliese, 2018). Much of the animal bone biomass produced in the EU is incinerated and the ashes discarded to landfill (Dawson and Hilton, 2011). In an analysis of the P flows in the EU, van Dijk et al., (2016a) calculated losses from the feed and food chains amount to 1.2 Mt P year^{-1}, which is equivalent to ~50% of the annual P input to the EU food system in feed, food and fertilisers (van Dijk et al., 2016). The EU is among the regions with the highest rates of P recycling, despite this, a system from which 50% of the input is lost to waste flows can neither be considered sustainable nor efficient. Furthermore, losses from non-food production in the EU, i.e. iron ore beneficiation, pulp and paper and fibre production, add a further 0.2 Mt P year^{-1} to waste flows (van Dijk et al., 2016).

Application of manure to soils, following low technology processing to reduce contaminants (i.e. not P recovery processes) is widely practised and is discussed in detail in Chapter 6. However, in regions of intensive livestock production, manure production can be so high that regional cropland areas are not large enough to recycle the nutrients they contain. A similar situation exists for cities (especially densely populated cities), where human wastes can represent a significant source of P that may not be easily recycled due to a lack of peri-urban croplands. With a strong global trend of urbanisation, P will be increasingly concentrated in urban regions (Powers et al., 2019). Furthermore, intensive livestock production tends to cluster in locations with cost advantages, such as close to cities (Johansson and Kaplan, 2004; Bai et al., 2016) compounding this issue. Transporting large volumes of bulky P-rich organic wastes to crops, where they can be sustainably recycled, can be prohibitively expensive. In some cases, to avoid such expense, manure and wastes are mismanaged, with P losses to landfill and/or the environment (Chapter 6). In the Netherlands, livestock densities are amongst the highest globally (Backus, 2017). Animal feeds imported to maintain

Dutch intensive livestock systems, have led to manure production at levels that cause regional nutrient accumulation, with persistent harmful and degrading impacts to water quality and ecosystem health (Lürling and Mucci, 2020). Despite being unpopular with farmers, in the Netherlands policies to reduce pig manure production by incremental reduction and imposed limitations on animal production have been implemented (Schröder and Neeteson, 2008; Erisman et al., 2011). However whilst the number of pig farms in the Netherlands has decreased, from 34,000 in 1984 to 5,000 in 2015, pig production has remained relatively stable and exports have continued to grow (Backus, 2017). In such cases, alternative strategies, such as P recovery, are needed to handle the accumulation of P-rich organic wastes.

Globally, many P-rich organic wastes are managed as pollutants, rather than as a valuable nutrient resource. Whilst in many high-income countries, legislation has been developed to enforce P removal from wastewaters the driver is to prevent pollution, with little focus on recovering P in a form that can be easily recycled (Christodoulou and Stamatelatou, 2016; Jupp et al., 2020). For example, ferric dosing of wastewaters is effective at P removal but can complicate P recovery (Morse et al., 1998; Fang et al., 2005). Sewage sludge and abattoir wastes are often incinerated and the ashes disposed of to landfill or used in building materials (i.e. cement) without recovering the P they contain (Christodoulou and Stamatelatou, 2016). In an overview of legislation regarding sewage sludge management in more economically developed countries, P recovery from sewage sludge was 'viewed as a need', but was 'not being carried out', and/or was 'yet to be developed' in Australia, much of the EU27, New Zealand, the UK, and the USA (Christodoulou and Stamatelatou, 2016). In low-income countries, only 8% of wastewater undergoes treatment of any kind (WWAP, 2017; Chapter 5). Phosphorus losses are not just confined to organic residue streams and dairy processing waste, opportunities to recover P in industrial wastes, such as steel-making wastes, are also often ignored (Matsubae et al., 2015). Iron ore tailings and steel-making slags may contain as much as 1.0 MT P year^{-1} worldwide, equivalent to ~5% of P in world PR consumption (extrapolated from (Matsubae et al., 2015)).

Challenge 7.2: Recovered phosphorus materials must have a competitive commercial value

Phosphorus recovery processes that do not generate industry compatible raw materials or finished products with a clearly defined market potential may fail to contribute to phosphorus recycling. Where recovered phosphorus fertiliser match mineral phosphorus fertiliser in terms of performance, systems to support large scale production, transport and handling are currently insufficient.

If a P recovery process is to contribute significantly to P recycling, it should be able to generate an industry-compatible raw material (e.g. as an alternative to PR), or a finished product (i.e. a recovered P fertiliser) with a clearly defined market potential (Schipper, 2019). However, recovered P products that can replace mineral P fertilisers in terms of P concentrations and bioavailability are, currently, scarce and more costly. The most common P recovery product, struvite, is activated by plant exudates and has high bioavailability and, in comparison to mineral P fertilisers, produces similar crop yields (Hall et al., 2020). Additionally, the manufacturing systems, and transport and handling networks associated with mineral P fertiliser are well-established, global and large-scale, which gives them a commercial and economic advantage over the more costly, small-scale, and emerging P recovery technologies. Furthermore, some P recovery processes, despite achieving high P recovery rates, produce materials with low commercial viability because the physical form of the material is not compatible with existing machinery for fertiliser production. For example, struvite, when in a granular form has the physical appearance of standard, granulated fertiliser, and tends to be generally sellable, whereas struvite recovered as a sludge or fine crystals is not, as it is incompatible with fertiliser-spreading equipment and needs further processing (Schipper, 2019).

Many economic feasibility assessments of P recovery technologies are conflicting, ranging from economically unfeasible, to profitable, and focus on struvite recovery from wastewaters (Jaffer et al., 2002; Dockhorn, 2009; Cornel and Schaum, 2009; Molinos-Senante et al., 2011; Kataki et al., 2016; Kabbe and Rinck-Pfeiffer, 2019). However, it is widely acknowledged that the economic viability of P recovery is dynamic and depends on many factors (Giesen, 1999; Dockhorn, 2009; de Boer et al., 2019). That withstanding, the lack of current economic incentives to stimulate P recovery remains a significant challenge globally. The specific cost of recovering P to manufacture a recovered P fertiliser can be several times higher than the market price of mineral P fertiliser (based on equivalent weights of P) (Cornel and Schaum, 2009; Molinos-Senante et al., 2011; Mayer et al., 2016). However, context is important; local or even regional conditions and value chains can have a huge impact on the cost of P recovery processes, which may include variability in the cost for ash disposal, transportation, and uptake or competition with mineral P fertiliser industries. Upstream loading of P to wastes can impact the economic viability of P recovery. For example, the introduction of phosphate-free detergents in Dutch households reduced P levels in municipal wastewaters making P recovery from effluent less economically attractive, leading to the closure of struvite recovery plants (Giesen, 1999). The market price of PR, which spiked in 2008 (see Chapter 2 and 3), can also impact the economic potential of P recovery (Nakagawa and Ohta, 2019). Indeed it has been proposed that for P recovery and recycling from wastewater to be economically self-sufficient, PR prices need to be at least US\$100 t^{-1} (Von Horn and Sartorius, 2009). As of October 2020, prices were just above US\$80 t^{-1} (for Moroccan PR) but have been steadily declining from US\$200 t^{-1} since 2012 (IndexMundi, 2020).

However, potentially the most important determinant of economic viability for a P recovery technology is the presence of a market for its recovered P materials, products and/or recovered P fertilisers (Kabbe and Rinck-Pfeiffer, 2019; Nakagawa and Ohta, 2019; Schipper, 2019).

Challenge 7.3: There is a lack of policy and market support for phosphorus recovery

There is a global lack of tangible policy support for phosphorus recovery, which has hindered the building of commercial markets for renewable phosphorus products, including financial instruments such as subsidies, tax incentives, or support for farmers to adopt sustainable measures. Certifying recovered phosphorus products as fertilisers can provide a significant challenge for phosphorus recovery enterprises.

Policy and regulations to support P recovery and the use of recovered P products/ fertiliser are scarce or absent in large parts of the world (Cordell and White, 2015; Christodoulou and Stamatelatou, 2016; Matsubae and Webeck, 2019) (Chapter 6). With limited economic incentives for P recovery, policy and legislation are the critical drivers (Hukari et al., 2016). Whilst the type of policy support required will vary between regions, the aim should be the same; to make it increasingly easy to sell and purchase recovered P fertilisers, and increasingly difficult to apply all fertilisers (including recycled ones) in excess of crop nutritional requirements for optimal yields.

Currently, from an economic and farm systems perspective, many farmers may find it difficult to switch to the use of recovered P fertilisers even if they deliver on multiple ecosystem services (e.g. cropping systems, cover crops, buffer strips), because in general, they are more expensive to buy, and/or may require capital investments (e.g. machinery to apply P recovered fertilisers; Macintosh et al., 2019). In most regions, farmers are often not compensated for investing in more sustainable practices, including a transition from mineral P fertiliser to recovered P fertiliser use. For example, the EU Common Agricultural Policy (CAP), currently under review, does not include adequate incentives, i.e. direct payments, subsidies and tax incentives, to farmers to invest in P recovery and P recycling measures (Hermann et al., 2019). Furthermore, whilst farmers are key players in the production of raw materials, they tend to have the least power in the food-value chain, and a limited ability to demand higher food prices (to cover potential costs of more sustainable practices) (European Commission, 2015; Hukari et al., 2016; Sexton and Xia, 2018; Hermann et al., 2019; Freidberg, 2020).

In industrialised food systems, power has become increasingly concentrated in a small number of large companies (Gordon et al., 2017; Godfray et al., 2018). The concentration of power lies with a comparatively small number of retail groups, who control food retail prices, and keep most of the business value (Vorley, 2001; Clapp and Fuchs, 2009; Sexton and Xia, 2018; Freidberg, 2020). For example, in the EU28 countries, some 22 million farmers produce food for more than 500 million consumers, whilst food distribution and retail are controlled by a few large companies. In the Dutch food chain, 65,000 farmers and horticulturists, provide food to 6,500 food manufacturers, which provide food to 1,500 suppliers, which are ultimately bought by only five purchasing companies that supply 25 supermarket companies (PBL Netherlands

Environmental Assessment Agency, 2012). Furthermore, agricultural producers also face higher variability of prices for their inputs and for the products they sell, which makes their income more variable than that of other actors in the chain (European Commission, 2015).

The ongoing lack of policy and economic support has hindered the markets for recovered P materials and recovered P fertilisers. A significant challenge is achieving certification of recovered P products as fertilisers. For example, this is evident for the EU market, where certification criteria differ between nations (Hukari et al., 2016; de Boer et al., 2018). To recover P, operators must navigate market regulations, and health and environmental law. The placing of new products on the market is frequently difficult, time-consuming and sometimes even impossible due to national policies (Hukari et al., 2016; de Boer et al., 2018). In the EU this often requires attaining permits after lengthy authorisation processes for both recovery installations (e.g. environment impact assessments) and the recovered P products (End-of-Waste (EoW), REACH; Hukari et al., 2016).

All chemical substances that are traded in Europe must be approved through the European Chemical Regulation (REACH) legislative framework. Approval for struvite was obtained in 2015, alleviating an important legislative hurdle. However, an important obstacle for the reuse of recovered P products in the EU was the lack of an end-of-waste status, which is now being resolved by the EU Fertilising Products Regulation (de Boer et al., 2018). For recyclers aiming to access the EU market, implementation and interaction of the REACH and EoW criteria are central (Hukari et al., 2016). Furthermore, the legislation and regulation for recovered P and recovered P products differs between countries, which can make it challenging for companies who wish to trade beyond national markets. However, if recovered fertilisers meet the requirements of the new Fertilising Products Regulation (EU) 2019/1009 (to be fully applied in July 2022), they can be labelled as EC fertilisers (safe and effective fertilisers on the EU market including EU-wide end-of-waste). This can drastically improve the marketing position of recycled fertilisers.

7.4 Solutions

Solution 7.1: Establish a global commitment to recycling nutrients in wastes and residues

Nations should commit to ambitious targets to recover and recycle nutrients from livestock manure, wastewaters, abattoir wastes and industrial waste streams, whilst discontinuing landfilling phosphorus-rich ashes and their displacement into building materials. A significant increase in phosphorus use efficiency, in conjunction with good management practices to reduce and mitigate phosphorus losses is also critical.

Over the last couple of decades, the importance of using P-rich organic wastes as a sustainable P resource has been widely acknowledged in the literature, emphasising a need to shift the focus from P removal to P recovery in a 'usable' form, to facilitate recycling (Withers et al., 2015; Tonini et al., 2019; Smol, 2019; Jupp et al., 2020). However, to make significant improvements in sustainable P management, all countries must commit to reducing P losses in wastes and residues. This should be underpinned by clear targets to increase P recovery and P recycling, within specified time ranges.

Policy and regulation that enforce ambitious targets to recycle nutrients from wastewaters are required, globally. Cohen et al., (2019b) estimate by 2030, Europe could recover 105,000 t P year^{-1} from incinerated sewage sludge ashes, equivalent to ~10% of the P imported in mineral P fertilisers (Figure 7.2). Whilst Mihelcic et al., (2011) estimates, globally, the total P content excreted by humans (just considering available P from faeces and urine) could meet 22% of the P demand. In high-income countries, a range of P recovery processes can be retrofitted into wastewater treatment plants to recover P from wastewaters and sewage sludge (as orthophosphate or polyphosphate), or ash after sludge mono-incineration. Furthermore, current wastewater treatments can be optimised to support P recovery. For example, whilst ferric dosing is an efficient method of P removal used in wastewater treatment, the presence of iron is often perceived as negative when evaluating P recovery options, as iron may reduce the plant bioavailability of recovered P products (Morse et al., 1998; Oleszkiewicz et al., 2015; Bunce et al., 2018). However, Wilfert et al., (2015) argue a reduction in ferric dosing may not aid P recovery, as significant amounts of iron-bound P can be found in WWTP, from iron piping, equipment, and groundwater. There are ongoing discussions as to the possible value of iron phosphates as slow-release fertilisers (Chandra et al., 2009; Nieminen et al., 2011; Andelkovic et al., 2019; Wang et al., 2020), at least in iron-deficient soils. Indeed, plants and fungi use a wide variety of strategies to access iron from iron-P effectively (Bolan et al., 1987; Hinsinger, 2001; Smolders et al., 2006). Further research into P-iron interactions may help to develop methods to manipulate iron–P chemistry in wastewater treatment processes that support P recovery (Qiu et al., 2015; Wilfert et al., 2015). In many low-income countries, large parts of the population do not have access to sanitation (WWAP, 2017). Whilst P is not the priority

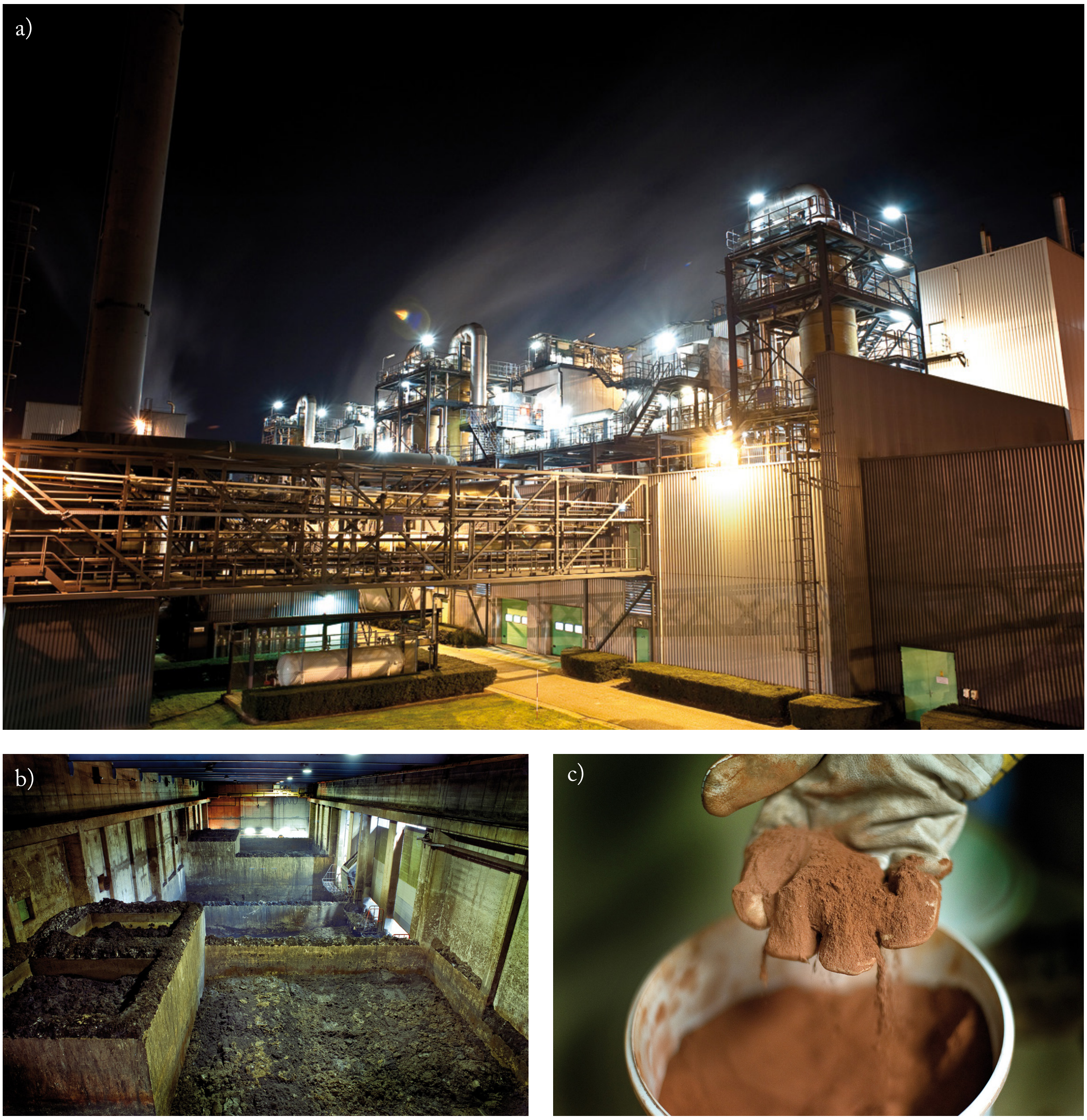

Figure 7.2 a) N.V. Slibverwerking Noord-Brabant (SNB) in Moerdijk; Europes biggest mono-incineration plant. Here, biosolids from wastewater purification in the water treatment facilities of both regional water boards and commercial parties are incinerated. **b)** Storage of ~16,000 tones of phosphorus-rich biosolids awaiting incineration and further processing. **c)** Phosphorus-rich ashes from the incineration of biosolids which can be used to make recycled fertilisers. Photographs taken by Nils Laenger - http://nilslaengner.de/

driver to improve sanitation in these regions (i.e. health risks are more important), maximising opportunities to recover P from human wastes to support sustainable agriculture is a win-win. Successful examples include the JVL Fortifer Compost Plant in Accra, Ghana, where a partnership between the local municipality, a private waste management company and the International Water Management Institute, has resulted in the production of pelletised fertiliser derived from human faecal material (IWMI, 2017).

Where manures and biosolids cannot be recycled to croplands because of large production volumes and/or transport costs, P recovery processes should be used to produce usable recovered P materials (that can be used to make recovered P fertilisers) that can be easily transported and stored. Economic value can be maximised by selecting methods to process organic materials that produce additional co-value benefits. For example, anaerobic digestion can produce renewable energy through biogas production (Mayer et al., 2016), with nutrient recovery from the digestates using struvite precipitation (Vaneeckhaute et al., 2017).

Mandatory targets to recover and recycle P from abattoir residues are required. In abattoirs, a significant loss of P is in animal bones discarded to landfill (Dawson and Hilton, 2011). Whilst the P in bonemeal has low bioavailability, it can be used as a slow-release P source (Duboc et al., 2017). For example, Thallo®, a P-rich fertiliser produced on-site at abattoirs, using a high pressure, high-temperature processing system and utilising waste products from other industries, including waste sulfuric acid and biomass power station ash (Darch et al., 2019). However, P recovery processes using heat and/or acids can recover P from bonemeal in bioavailable forms, which can be used as a replacement for PR in established fertiliser manufacturing. Furthermore, several recovered P fertilisers produced from meat and bone meal ash are already available on the market.

Opportunities to recover P lost in specific industrial waste streams such as fire extinguishers, metal surface treatment, end of life technical plastics, pharmaceuticals, electronics (Qiu et al., 2011; Ryu et al., 2012; ESPP, 2018) and steel production should also be developed (Matsubae et al., 2016). Most of these industrial streams contain very low quantities of P (compared to world PR consumption) but are concentrated and may offer feasible recovery opportunities. This may have co-benefits to industries producing the wastes, which are generally subject to stringent waste treatment and discharge requirements. On the other hand, steel-making slag is generally low in P content, 1.0 - 2.2% P (PR is around 8-15% P), but is produced in large amounts. Furthermore, dephosphorisation (i.e. processes to remove P in steel-making) can improve steel quality, however, further research is needed to identify and develop feasible/economic methods to recover P and remove contaminants at large scale (Matsubae et al., 2011, 2016).

Landfilling of P-rich ashes (i.e. from incinerated biosolids and abattoir wastes) and their use in building materials is a waste of valuable resources and should be discontinued. This also applies to the co-incineration of P-rich organic wastes with industrial waste, and co-incineration of sewage sludge or abattoir wastes and residues in cement kilns. In both cases, P is irretrievably lost to diluted and contaminated ash or cement. The landfilling of sewage sludge is illegal in the EU and should be discontinued elsewhere. In Switzerland, P-recovery from sewage sludge will be obligatory by 2026 due to new legislation introduced in 2016. In Germany, under the German Sewage Sludge Ordinance, sewage sludge incineration ash must be stored separately for future nutrient recovery, and after 2029/32 can only be landfilled after P is recovered (Bundesanzeiger Verlag, 2017). Other countries, at least in Europe and in other high-income regions, should follow these examples.

Solution 7.2: Optimise the commercial viability of recovered phosphorus products

Phosphorus recovery technologies must produce commercially viable materials with defined market potential or that are industry compatible as a raw material for fertilisers or other products. Opportunities to produce co-value products and services (i.e. produce energy, other nutrients), and the environmental sustainability of recovery processes, should be optimised. Some recovered phosphorus products/fertilisers have a potential market opportunity to provide efficient, pollutant-free fertilisers. A key challenge for phosphorus recyclers is producing relevant volumes and homogeneous quality to meet demand. The market price of recovered phosphorus products/ fertiliser alone should not define the economic feasibility of phosphorus recovery. According to the "polluters pay" principle, stakeholders could share the cost of recovery, at least in more economically developed countries.

Determining which technologies are most commercially viable, and hence should receive investment depends on region-specific factors (Cordell et al., 2011). An integrated systems framework should be used to guide decision-making for the sustainable recovery and recycling of P, as outlined by Cordell et al. (2011). This approach identifies the P that is available for recovery (i.e. quantifying P flows available for recovery from each sector), examines logistics such as regional spatial P demands (i.e. consideration for transporting products to point of use), and then identifies the tools available for P recovery, (i.e. available technologies appropriate for the region resources). Importantly, life cycle costs for P recovery, including economic, energy, environmental costs, synergies and conflicts with other industries (i.e. sanitation) are identified to ensure externalities are considered (as detailed in the analysis of Tonini et al., 2019). Through this process, the key stakeholders and institutional arrangements required to support P recovery are also identified. Failure to take a systems approach could result in investing in costly technologies that do not address the whole system, do not provide the greatest outcome for sustainability, and at worst, conflict with other related services (such as chemicals demand) (Cordell et al., 2011).

To ensure the commercial viability of recovered P products, it is important to develop P recovery processes with the direct involvement of potential users (Schipper, 2019). Common features that make recovered P materials commercially viable as an industry-compatible raw material include homogeneous quality, low to no levels of contaminants, and production levels that are high enough to ensure a reliable supply. In the best-case scenario, P from waste streams are recovered in a chemical (e.g. phosphoric acid, secondary calcium phosphates, MAP, DAP, TSP) and physical form (e.g. granules, high P content) that is already used by regional or national fertiliser manufacturers and other industries. This will allow fast and easy uptake by existing manufacturing processes. Equally, recovered P fertilisers that can be used in existing machinery and directly replace mineral P fertilisers in terms of P content and bioavailability will be more commercially viable (Schipper, 2019).

Whilst commercial viability of fertiliser is often associated with P bioavailability, standard P fertiliser tests for P bioavailability, indicated by their solubility in water or citric acid, should be reconsidered in the context of increasingly diverse recovered P fertilisers (Duboc et al., 2017). The bioavailability of many recovered P products and fertilisers is more accurately indicated by their dissolution in soil, and this can vary between soil types (Cabeza et al., 2011). Whereas fast nutrient solubility in water has been a key quality parameter of fertilisers for several decades, 'slow release', non-water-soluble P in fertilisers is increasingly being acknowledged as being important for effective nutrient supply (Shu et al., 2006; McLaughlin et al., 2011; Kataki et al., 2016; Li et al., 2019a). In the new EU Fertilising Products Regulation (EU) 2019/1009, a fertiliser is given the status of an EU fertilising product if it functions to provide nutrients to plants or mushrooms (European Parliment, 2019). However, mineral P fertilisers must fulfil certain P solubility criteria, including 40% of the declared P content must be water-soluble or 75% soluble in neutral ammonium citrate. The regulation now includes organic fertilisers and organo-mineral fertilisers, as well as other non-fertiliser products (including soil improvers, agronomic additives, plant bio-stimulants) within its scope of 'fertilising products' (Halleux, 2019). However, the high water solubility of P, a frequently used parameter for assessing the market value for mineral P fertilisers, is not justified as a good indication of bioavailability, shown by several recent comparative experiments (Cabeza et al., 2011; Duboc et al., 2017). Consequently, the plant nutrition value of some non-water-soluble recovered fertilising products may be comparable to PR-derived fertilisers and consequently should have a similar market price.

In the EU, a potential market opportunity for some recovered P fertilisers and materials is by providing pollutant-free alternatives to PR derived and non-decontaminated recycled fertilisers. The heavy metal content of municipal wastewater derived struvite is found to be significantly lower than that of PR derived phosphates (Hall et al., 2020; Forrest et al., 2008; Latifian et al., 2012) and below most regulatory limits, for example in Germany and Turkey (Antonini et al., 2012; Latifian et al., 2012; Uysal and Demir, 2013) (Figure 7.3).

The perception that the market value of recovered P products defines the economic feasibility of P recovery technologies is incorrect (Mayer et al., 2016). The market value of recovered P materials/products is among a list of the wider co-benefits of P recovery, which carry economic co-benefits (Cordell et al., 2011; Mayer et al., 2016; Tonini et al., 2019; Withers, 2019; Chrispim et al., 2019). Indeed, when comparing the externalities associated with mining PR and the manufacture of mineral P fertilisers, and those for recovered P fertilisers, the focus of P

Figure 7.3 Phosphorus recovered from wastewaters in the form of struvite produced from a Huber SE precipitation reactor. Photograph courtesy of The Sustainable Sanitation Alliance (SuSanA).

recovery processes can shift from the exclusive supply of a 'product' to a 'service' which combines decreased emissions to the environment (i.e. soil, air and water), reduction in waste generation, with the combination of high-quality P fertilisers. Societal costs incurred for recovered P products derived from sewage sludge, manure and meat and bone meal, are up to 81%, 50% and 10% lower than for PR derived superphosphate, respectively (Tonini et al., 2019). When factoring in externalities, Tonini et al., (2019) found the environmental and health life cycle impacts are often lower for P recovered fertilisers than for mineral P fertilisers, especially in areas of high livestock and population density. Furthermore, this does not factor in the risks of P depletion, or sanitation of manures, which would further modify the balance towards P recovery.

Many co-benefits remain unquantified, and therefore assessing the economic feasibility of P recovery often does not accurately represent the true net societal gains. When the total value of P recovery is accounted for, including products, services and externalities, additional incentives emerge in support of P recovery and reuse (Mayer et al., 2016; Tonini et al., 2019; Hörtenhuber et al., 2019). For example, P recovery in WWTPs is used mainly for operational benefits (i.e. reduction of struvite build-up) and is not driven by the market value of the recovered P (Kabbe and Rinck-Pfeiffer, 2019).

Phosphorus recovery technologies can be developed that carry increased value-added benefits. These may include aligning dual or multiple nutrient recovery processes alongside P recovery, such as nitrogen and micronutrients like magnesium, copper, and zinc (Timotijevic et al., 2011; de Haes et al., 2012; Kupfernagel et al., 2017). Phosphorus recovery naturally opens opportunities to recycle other nutrients, partly due to similar drivers and partly due to directing the attention of researchers and stakeholders to the related possibilities (Mayer et al., 2016; Vaneeckhaute et al., 2019; Barampouti et al., 2020). For example, currently, nitrogen in sewage sludge and wastewaters is frequently treated by nitrification/denitrification releasing nitrogen into the atmosphere, however, this can be replaced by technologies that recover both nitrogen and P, as demonstrated for biogas plants (Shi et al., 2018; Khoshnevisan et al., 2021). Anaerobic digestion can also produce renewable energy, through biogas production (Guilayn et al., 2020). The potential to produce bio-energy as a co-product, as well as optimising the use of renewable energy in the energy demand of the recovery process (i.e. for thermal treatments), can help to lower the energy footprint of P recovery technologies (Balmér, 2004; De Graaff et al., 2011). The benefits of fractionation, recovery and recycling of nutrient flows from anaerobic digestion plants are demonstrated and reported in the Horizon 2020 project SYSTEMIC (www.systemicproject.com).

Recycled P will improve farmer fertiliser security and protection against fluctuations in PR price and supply shocks. A lack of purchasing power prevents many poor farmers from accessing mineral fertiliser markets (Cordell and White, 2014). Small-scale and decentralised sanitation systems (ranging from individual onsite systems through to community-scale) have been developed due to their lower cost, or appropriateness for serving remote or low-density populations (Cordell et al., 2011). In this way, locally recovered P can contribute to farmer fertiliser security and hence food security (see Chapter 3 and 8), whilst recovered and recycled phosphates reduce the exposure of farmers and food systems to market fluctuations in PR prices. Regional factors drive the costs and prices of recycled P and are largely predictable and usually as stable as the economy in the region. Whilst recycled P on average costs more than mineral P in fertilisers, decentralisation of P recovery may lead to lower transport costs and prices may not be subject to the volatility of commodity prices (see Chapter 2).

Solution 7.3: Develop policies that support phosphorus recovery and recycling

Critical policy needs to include a regulatory framework to boost the use of recovered phosphorus materials as an alternative to phosphate rock as the primary source of phosphorus in mineral fertilisers. In some regions, the necessary infrastructure to collect wastes and residues is still required. The next step could be global binding agreements and a paradigm change: taxing the consumption of natural resources and related externalities and reducing the tax burden of renewable resources and labour.

Policy and financial support should be developed to increase the feasibility and opportunity for P recovery and recycling, this is especially important as current economic incentives are not sufficient (Hukari et al., 2016). A focus on supporting emerging industries will be key. For example, P recovery and recycling can contribute to the development of new more sustainable business opportunities. Frequently, small to medium enterprises (SMEs) provide the services associated with P recovery and recycling, potentially creating job opportunities that could reduce rural-urban migration (Steffen et al., 2015). In 2019, more than 100 P recovery plants were operational in Europe, Canada, Japan, and the US (Kabbe and Rinck-Pfeiffer, 2019). In an assessment of P flows in the EU, the P flows in effluents from livestock farming were estimated to be three times larger than the P contained in municipal waste flows (van Dijk et al., 2016) offering opportunities for P-recovery and recycling process operators in rural areas. Most suppliers and rural operators are SMEs, representing a possibility for new high-quality jobs related to agricultural activities. In addition, P recovery and recycling will catalyse new circular economy opportunities in line with national and international policies and directives. Considering global warming and finite resources, globally acknowledged by the Paris Climate Change Agreement (COP21) and the SDGs agreed in 2015, the Circular Economy is a must, with business as usual, not an option. The European Commission selected P for implementation within its "Circular economy: A zero waste programme for Europe" due to being a critical and non-replaceable element in agriculture (European Commission, 2014a). The feasibility of P-recovery within the prevailing socio-economic system could create a convincing narrative for introducing circular principles in other economic activities.

In most nations, the establishment and implementation of stringent regulations to enforce time-bound targets for P recovery (and recycling) are required. Global advocacy, and awareness-raising of the environmental benefits of P recovery and recycling, will help to improve public and political support (Matsubae and Webeck, 2019) (see Chapter 6). In the EU, the need to recover P from waste streams is already underpinned in policy through the inclusion of PR, and elementary phosphorus (P4) in the EU critical raw materials list (European Commission, 2014b). Indeed, globally, most policies and regulation regarding P recovery and recycling are currently found in the EU (Christodoulou and Stamatelatou, 2016). Currently, only Switzerland (in 2016) (The Swiss Federal Council, 2015) and Germany (in 2017) (Bundesanzeiger Verlag, 2017) have adopted regulations that make P recovery mandatory. In Switzerland, from 2016, under its Ordinance on the Avoidance and Disposal of Waste, a ten-year transition began that will make the recovery of P from sewage sludge and slaughterhouse residues obligatory (The Federal Council - Switzerland, 2016). Switzerland banned direct use of sewage sludge on land in 2006, so the regulation will lead to technical recovery and recycling in the form of inorganic products. Swiss sludge and slaughterhouse waste together represent an annual flow of 9100 t of phosphorus whereas technical recycling from the wastewater stream in Europe today totals of up to 5,000 t of P in the form of struvite (Kabbe and Rinck-Pfeiffer, 2019). A similar policy was implemented in Germany in 2018 and outlines obligatory P recovery from sewage sludge for 60% of wastewater treatment works (i.e. those that serve >50,000 people) (BMU, 2017).

Developing international targets to reduce nutrient losses that align with existing regional targets, will help to fuel momentum towards a global increase in P recovery and P recycling. The 2020 European Green Deal and with its flagship Farm-to-Fork Strategy provides an ambitious framework requiring a 50% reduction in nutrient losses by 2030, only achievable by massive improvements of full-chain nutrient use efficiency (NUE) (for definitions of full chain NUE see Chapter 5). This represents an opportunity to increase the use of recovered P fertilisers, as a sustainable alternative to mineral P fertiliser, with known and homogeneous P content allowing farmers to carefully match P inputs to crop needs (this is often difficult to achieve with manures).

Regional targets should be developed and integrated, with existing agricultural policy to ensure sufficient support is in place, for targets to be achieved. For example, the European Commission's Farm-to-Fork Strategy must be supported by the Common Agricultural Policy (CAP) and implemented by supporting policy instruments (e.g. subsidies for nutrient stewardship and biodiversity protection) in member states. In the EU within the Common Agricultural Policy (CAP), whilst currently under development the proposed 'eco-schemes' (to be implemented in 2022), may provide financial assistance to EU farmers to adopt sustainable practices (see Chapter 6). Ensuring 'eco-schemes' include the use of recovered P fertiliser as a sustainable measure is therefore important. Many less economically developed countries lack relevant environmental regulations to support P recovery, whilst in some countries/regions, significant investment in the necessary infrastructure to collect and treat P-rich waste streams is still required (Matsubae and Webeck, 2019). Subsidies and tax incentives to farmers for use of recovered P fertilisers are needed. Direct economic benefits, increased productivity or profitability seem to be an essential condition for farmers to adopt sustainable practices in the short term (Garbach et al., 2012; Piñeiro et al., 2020).

In regions of intensive livestock agriculture, policies to reduce P losses from manures can indirectly support an increase in P recovery and P recycling. For example, the Dutch government have used an extensive range of policy instruments, in comparison to other countries, to address mismanagement of manures (e.g. the excess application of manure to soils leading to P losses) (Schröder and Neeteson, 2008; Erisman et al., 2011; Backus, 2017). In an overview of Dutch manure management policy instruments from 1984 to 2016, Backus (2017) found restrictions on manure spreading, the requirement to inject manure into the soil, support for flagship farms, and limits on the number of animals were among the most successful and cost-effective measures to reduce nutrient pollution from manures. Between 1980 to 2010, the application of manure P in the Netherlands has been reduced by 50% (i.e. from 160 to 84 kg phosphate as P_2O_5 ha^{-1}) (Backus, 2017). In addition, in 2006, to prevent animal manure from being replaced by mineral P fertiliser, P application limits were extended to both manure and mineral P fertilisers, resulting in a decreased use of mineral P fertilisers and reduced nutrient dispersion into the environment (Malomo et al., 2018). A further outcome of restrictions placed on manure spreading is that many farmers must pay (e.g. crop farmers) for manure disposal (Backus, 2017). In the Netherlands, annual costs for manure disposal in 2007 were estimated at €274 million (CBS, 2016). In 2017, for the average pig farm with no land, costs for manure disposal accounted for ~10% of pig meat production costs (Backus, 2017). The knock-on effect of this has been an increase in the circularity of P flows in agricultural systems, with an increase in farmers' incentives to seek valuable uses of manure, such as processing manure into recovered P fertilisers (Backus, 2017; Malomo et al., 2018). Similar impacts are observed in the US, where since 2006, intensive livestock production has been increasingly regulated. The National Pollutant Discharge Elimination System (NPDES) permitting program regulates the discharge of P to waters, from point sources including concentrated animal feeding operations. Similar to the situation in the Netherlands, polices to reduce P pollution, have led to greater interest in alternative management schemes for further treating or processing manures to make value-added products that can be exported off the farm (e.g., composts or concentrated P products such as struvite; Westerman and Bicudo, 2005).

For many high-income countries, the fertiliser market itself poses a problem, requiring a regulatory framework to provide a level playing field between mineral and recovered P fertilisers (Matsubae and Webeck, 2019). The EU Fertilising Products Regulation aims to level the market for mineral and recovered P fertilisers and help mitigate mineral P fertiliser demand. In June 2019, the European Commission adopted the new Fertilising Products Regulation (EU) 2019/1009, which will apply fully from July 2022 (European Parliment, 2019). This new Fertilising Products Regulation, as a flagship initiative of the first European Circular Economy Package (2015), modernises the conformity assessment and market surveillance in line with the 'new legislative framework' for product legislation. This will mean market access for a wider range of fertilising products, including those manufactured from recovered P materials that were previously excluded (Halleux, 2019), making it easier to sell recovered P fertilisers across the EU, and giving more choice to farmers (European Parliament, 2018). According to the European Commission, the Fertilising Products Regulation will deliver a range of benefits, including the creation of about 120,000 jobs in P recovery, bio-waste recycling, organic fertiliser production and will reduce dependency on PR imports (Halleux, 2019).

Importantly, the Fertilising Products Regulation introduces an initial limit of 60 mg cadmium kg^{-1} P in fertilisers (see Chapter 2). Fertiliser cadmium limits may help boost markets for recovered P fertilisers, as they contain lower/negligible levels of cadmium (1.06-2.30 mg kg^{-1} P_2O_5) in comparison to many mineral P fertilisers (de Boer et al., 2019) and some recovered products have very low levels of impurities and heavy metals. However, bridging the gap between P recovery and actual recycling remains the biggest challenge (Kabbe and Rinck-Pfeiffer, 2019). Part of the issue is ensuring P recovery can produce sufficient volumes of recycled P material; P recovery enterprises are currently much smaller in scale than the mineral P processing industry. Instead of broadening the range of P recovery technologies, investments should be directed towards the development of full-scale demonstrations of the most promising options (Schipper, 2019). Market penetration and replication will only happen with full-scale demonstrations, with the first large-scale operation often requiring some form of government support (Schipper, 2019). Research incentives, among others provided by the EU Horizon 2020 Program, for example, have contributed to funding the development of several pilot technologies that are now ready to be implemented at industrial scales (European Commission, 2019). However, an integrated systems framework should be used to guide decision-making on the most promising options for the local resources and circumstances (Cordell et al., 2011).

The United Nations has adopted global, albeit non-legally binding, normative agreements (e.g. the SDGs and the Paris Agreement) which offer the potential to drive increasing nutrient recovery and recycling (Kanter and Brownlie, 2019). In 2020, the European Union has adopted the European Green Deal and the Farm-to-Fork Strategy for a fair, healthy and environment-friendly food system. These initiatives provide a more favourable framework for P recovery if technologies and products comply with the objectives of high nutrient use efficiency and reducing nutrient losses. In the EU, the post-2020 Common Agricultural Policies include conditionalities, i.e. sustainable practices entitling farmers to premiums. Phosphorus recovery can and should be part of such practices while recovered and PR-derived fertilisers should equally comply with the highest standards to optimise nutrient use efficiency and avoid losses, thus improving water quality outcomes.

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