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Phosphorus from Wastewater: Novel Technologies for Advanced Treatment and Re-use

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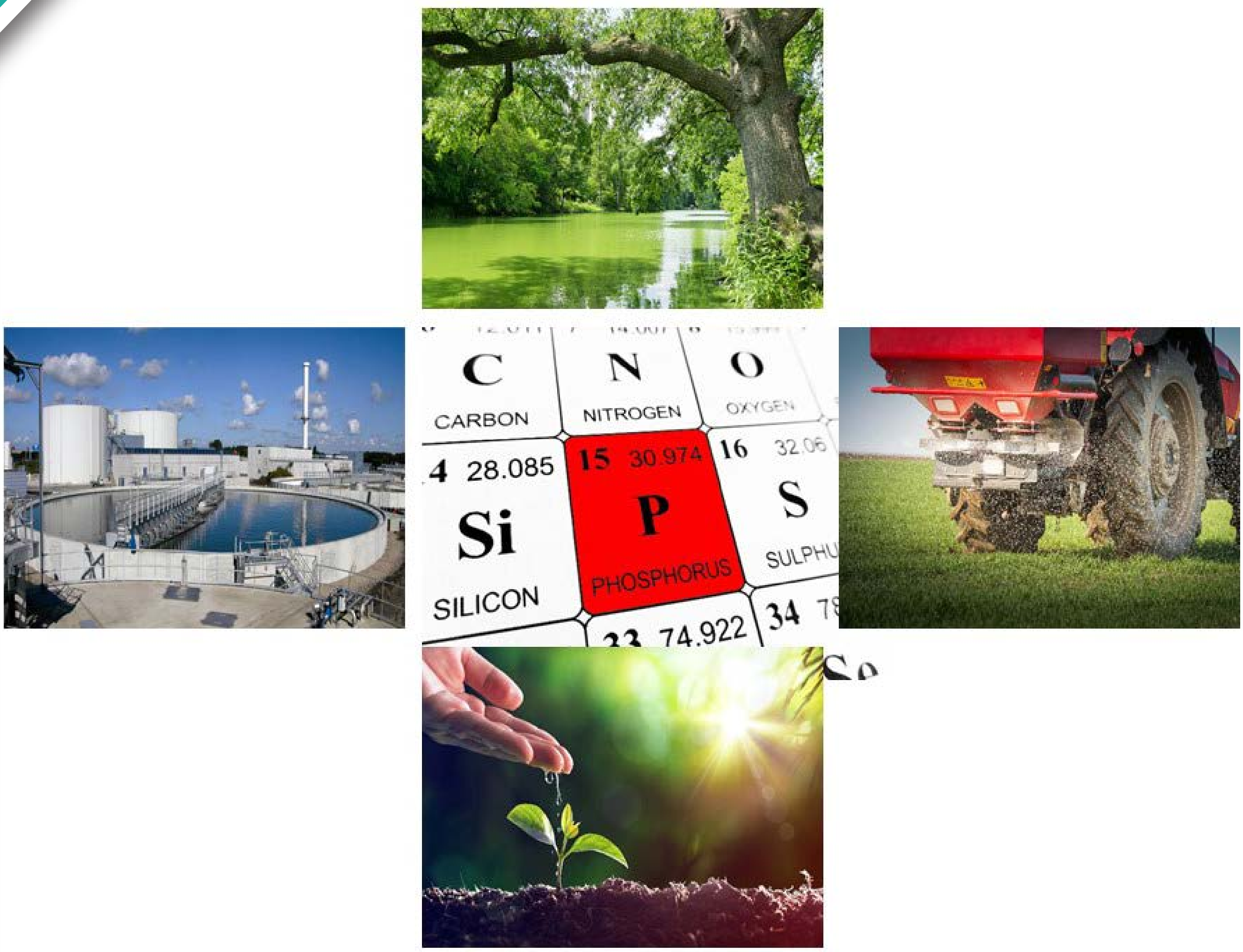

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Government of Ireland

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EPA RESEARCH PROGRAMME 2014–2020

Phosphorus from Wastewater: Novel Technologies for Advanced Treatment and Re-use

(2014-W-LS-7)

EPA Research Report

End of project report available for download on http://erc.epa.ie/safer/reports

Prepared for the Environmental Protection Agency

by

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

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Executive Summary

Phosphorus (P) is a finite, non-renewable commodity that is critical to our ability to produce food. In many terrestrial and aquatic environments, P is the growth-limiting nutrient, whereas, in others, human activity has led to an excess of P and consequent problems of eutrophication and environmental damage. Paradoxically, global P reserves are limited and, although timelines for “peak P” are contentious (current estimates suggest that rock phosphate reserves may last for 45–300 years), it is clear that the rock that remains is of lower grade and more difficult to access, thereby increasing processing costs. P demand is further exacerbated by the expected 40–50% increase in human P synthetic fertiliser usage over the next 50 years, required to feed the increasing global population. Moreover, P supplies come from just a few key countries. Indeed, Europe’s P production is minimal, with Morocco, the USA, China and Russia responsible for more than 75% of the worldwide raw material production. Concomitantly, Ireland and the wider European community, which has for many years seen itself as a food-secure region, now recognises its high vulnerability to P scarcity. Security of P supply to European countries is therefore a key issue, with P now classified as one of the 20 most “critical raw materials” within the European Union. The agri-food industry in Ireland is therefore highly exposed to the dual issues of P security and cost.

Wastewater streams from domestic, industrial and agri-food sources offer a compelling opportunity to recover and reuse P. For example, legislation such as the Urban Wastewater Treatment Directive requires P to be removed from sewage, so implementation of this Directive, from a water company’s perspective, results in the production of a P-rich waste and elevated disposal costs. For those industries that utilise P as a raw material, however, these sludges could potentially be a valuable and abundant resource. Indeed P-rich sludge could supply a significant proportion of industry’s annual P requirement. This project (1) reviewed the current state of the art with respect to P removal and recycling from waste in terms of the technologies involved and their economic and technological feasibility for adoption within the Irish waste treatment sector; (2) assessed the potential of three novel P removal and recovery systems through assessment of their robustness and effectiveness as P recycling processes; and (3) facilitated an All Island Phosphorus Sustainability Workshop to capture stakeholder perspectives on regulatory P management and the P circular economy across the regulatory, wastewater, academic and agri-food sectors in relation to P reuse, recovery and recycling, as well as future directions for P sustainability in Ireland. A key outcome is the need for a stakeholder-led, all-island nutrient platform to be established to engage across sectors in the development and implementation of sustainable nutrient (and co-recoverable resource) management and value chain development.

1 Introduction

1.1 Purpose of the Synthesis Report

This synthesis report provides a summary of work completed as part of Environmental Protection Agency (EPA) project 2014-W-LS-7 (Phosphorus from Wastewater: Novel Technologies for Advanced Treatment and Re-use). A full technical report is also available.

Phosphorus (P) is a non-renewable commodity, with around 20 million tonnes of phosphate rock mined each year; approximately 80% of this is used in food production as fertiliser (Venkiteshwaran *et al*. 2018). Europe's P production is minimal, with P supplies coming predominantly from Morocco, the USA, China and Russia; globally these finite P reserves are being rapidly depleted. As a P importer, Ireland and the wider European community, which has for many years seen itself as a food-secure region, now recognises its high vulnerability to P scarcity; P is one of 20 materials listed by the European Union (EU) as a "critical raw material" (Schröder *et al*., 2010; EC, 2014). As agriculture is an important industry across the island of Ireland, P economics and security of supply are key factors for sustainability and food security.

Paradoxically, eutrophication, caused by freshwater P enrichment, constitutes an important threat to good water quality throughout Ireland and internationally (Withers *et al*., 2014; Macintosh *et al*., 2019a). P discharges to freshwater systems are controlled by European legislation, such as the Urban Wastewater Treatment Directive (91/271/EEC) and Water Framework Directive (2000/60/EC). Adequate P removal during wastewater treatment (provision for effective P removal) within the domestic, industrial and agri-food sectors, in addition to the control of P run-off from agriculture, are prerequisites for the maintenance of natural capital, ecosystem services and water quality.

This project sought to address the two contrasting issues of P sustainability – P supply in the light of dwindling natural reserves, and P pollution, i.e. prevention of freshwater eutrophication caused by the discharge of excess P as waste to receiving waters – by:

1. reviewing the current state of the art with respect to commercial processes for P removal and recovery from wastewater through literature analysis and industrial liaison, and by exploring the suitability and cost-effectiveness of these technologies for adoption within the Irish wastewater treatment sector (both urban and industrial);
2. dissecting the scientific basis of three novel P removal and recovery systems developed within Queen's University Belfast (QUB) and the National University of Ireland Galway (NUIG) through the assessment of their robustness, scalability and effectiveness as P recycling technologies;
3. facilitation of an All Island Phosphorus Sustainability Workshop to capture perspectives on P regulatory management and the P circular economy from relevant stakeholders across the regulatory, wastewater, academic and agri-food sectors in relation to P reuse, recovery and recycling, as well as future directions for P sustainability and research in Ireland.

1.2 Structure of the Synthesis Report

Work package 1 commenced with a review of the current state of the art with respect to P removal and recovery technologies, providing an evaluation of both full-scale and near-to-market P recycling processes. The applicability of these systems to the Irish wastewater treatment sector was also assessed.

Work packages 2 and 3 focused on the development and optimisation of a range of novel processes for efficient and sustainable P recycling from wastewater by the project teams in both NUIG and QUB. These included (1) a pumice biofilm-based process developed for inducing P removal within anaerobic digester reactors, (2) an aerobic process whereby enhanced microbial P accumulation is induced by prior carbon starvation of microbial biomass and (3) a novel biopolymer-based technology for P capture and recovery from wastewater effluent.

Work package 4 collected and evaluated sector-wide views on key P management issues on the island of Ireland via a stakeholder-focused workshop event.

1.3 Project Dissemination

The project team used a wide variety of approaches to disseminate the outcomes of this project. These included (1) five publications in peer-reviewed journals; (2) attendance and presentation at workshops and conferences linked to major existing international programmes in the field of P removal, recovery and reuse [e.g. at European Sustainable Phosphorus Platform (ESPP) events and at US Phosphorus Research Coordination Network (P-RCN) meetings]; (3) the establishment of a project website and Twitter account (@Phosphorus_ie, with over 800 followers); and (4) the organisation and facilitation of both a project workshop and a conference, attended by over 100 delegates. Full details of the publications produced and the conferences and workshops attended during the project are provided in the EPA technical report (http://erc.epa.ie/safer/reports).

2 Phosphorus Removal and Recovery: Practices, Feasibility and Future Trends

2.1 Scope and Methodology

Work package 1 of this research programme sought to deliver a review document that would:

1. compare currently available P removal and recovery technologies;
2. inform policy and business decision-makers within the regulatory and wastewater treatment sectors, and other allied industries, e.g. the agri-food sector, about such technologies;
3. highlight research needs within the context of P recycling and recovery.

The review was conducted in collaboration with Dr Christian Kabbe from the European P-Rex project (an H2020-funded programme designed to assess advanced technology options for P recycling within the EU: https://cordis.europa.eu/result/rcn/187939_en.html) and Dr Chris Thornton, Director of the ESPP (https://phosphorusplatform.eu). The ESPP is an EU-wide stakeholder platform composed of members from across the P industry, including the mining and processing, water and waste treatment, food, agri-food, agriculture and P reuse and recycling sectors, as well as university and governmental organisations.

In summary, the review considers P removal technologies within three broad categories: (1) chemical-based processes (controlled struvite crystallisation; use of sorbents); (2) physical processes (incineration, pyrolysis, gasification); and (3) biotechnologically based approaches [e.g. enhanced biological phosphate removal (EBPR), recovering nutrients using aquatic species and the use of phosphate-solubilising bacteria with bioleaching of heavy metals]. An analysis of the commercial viability of these processes, and their feasibility (both technical and socio-economic), for implementation within the Irish waste sector is presented here in short and in full in the EPA technical report. The full technical report also considers P recycling in the context of the source, e.g. from wastewater, biosolids, urine, poultry litter, food waste streams (such as those arising from the dairy industry), thermally converted biomass and sewage sludge ash, manure and bone meal ash. The review concludes with a consideration of (1) how a circular P economy could be developed within Ireland through local reuse, recovery and recycling, and the economic feasibility of this; (2) what methodologies or processes could be used by stakeholders (local authority and industry) to facilitate a circular P economy to develop business opportunities to build a P value chain; and (3) what can be learned from successful business models or case experiences worldwide with respect to P recycling or the recycling of other resources.

2.2 Phosphorus: A Critical Raw Material

Phosphorus is a finite, life-essential, non-renewable element required for all living organisms for which there is no substitute (Cordell *et al.*, 2009; Macintosh *et al.*, 2018, 2019b). It is an essential part of the global food web, being a key component of fertilisers and animal feed stocks. P is also utilised in numerous industrial technologies across the agricultural, pharmaceutical and chemical sectors (Withers *et al.*, 2014). Global P reserves are limited and, although timelines for “peak P” are under debate (current estimates suggest that phosphate rock reserves may last for 45–300 years), it is clear that the rock that remains is of lower grade, contains higher concentrations of heavy metals (such as cadmium) and is more difficult to access, thereby increasing processing costs (Gilbert, 2009; Blank, 2012; Cordell and White, 2013).

This is further exacerbated by the expected 40–50% increase in human P synthetic fertiliser usage over the next 50 years, required to feed the ever-increasing global population. Moreover, P supplies come from just a few key countries. Indeed, Europe’s P production is minimal, with Morocco, the USA, China and Russia responsible for more than 75% of the worldwide raw material production. In tandem, Ireland and the wider European community, which has for many years seen itself as a food-secure region, now recognises its high vulnerability to P scarcity (EC, 2014).

The security of P supply to European countries is therefore a key issue, especially given the geopolitical situation in many P-rich countries (Ashley *et al.*, 2011). Decreasing phosphate rock quality, dwindling resources and security of supply are all reflected in the escalating price of P. In September 2002, 1 tonne of ammonium phosphate fertiliser cost €90; this figure had risen to €440 per tonne by August 2012, with a peak in August 2008 of €780 per tonne. The current price in 2019 is approximately €300 per tonne. This has prompted a number of countries, including the USA and China, to control exports of P to allow for the stockpiling of fertiliser raw materials; China currently imposes a 135% export tax on P (Ulrich *et al.*, 2009). P is also one of 20 materials listed by the EU as a "critical raw material" (EC, 2014). The agri-food industry in Ireland, which is due to increase primary output by €1.5 billion, value-added output by €3 billion and exports to €12 billion (+42%) by 2020 (DAFM, 2011), is thus highly exposed to these dual issues of P security and cost.

A corollary of increased human exploitation of natural P reserves is an increase in environmental problems associated with disposal of P-rich wastes. Eutrophication of freshwater environments, via excessive nutrient input, poses the most widespread single threat to good water quality globally (Jarvie *et al.*, 2015, 2017). The sources of P in wastewaters include fertilisers, human excreta and materials used in industrial processes. Nutrient enrichment leads to increased water purification costs, declines in amenity and conservation value of impoundments, the loss of livestock and a rise in human health issues through algal blooms (Smith and Schindler, 2009). Restoration of these freshwater systems to EU-imposed standards (under the Water Framework Directive) is costly: the current management costs of eutrophication in the UK and Ireland stand at >€250 million per annum (Pretty *et al.*, 2002).

Phosphorus enters surface waters either from diffuse run-off from land or via point source discharge, e.g. from a wastewater treatment works (WWTWs). To control the latter, stringent legislation puts strict limits on point source P discharges. Within Europe, this is reflected through both the Urban Wastewater Treatment Directive, which designates areas as "sensitive" to eutrophication and requires an effluent standard of no more than 1 $mg\,L^{-1}$ P and/or a minimum percentage P reduction of 80% for large (>100,000 population equivalents) treatment works, and the Water Framework Directive. Under the latter, water bodies within EU Member States must reach a number of targets for "good ecological status" by 2021.

Future issues of P sustainability, and the need for a circular P economy, will drive changes in regulatory frameworks away from the current paradigm of "removal" to that of "recovery".

2.3 Methods for the Removal and Recovery of Phosphorus from Wastewater

This section of the synthesis report reviews the technologies currently available for the removal and recovery of P from wastewater:

- P removal
  - aluminium (Al), iron (Fe) and lime (calcium oxide or calcium hydroxide) salt dosing (section 2.3.1.1);
  - tertiary filtration with granular-medium filters (section 2.3.1.2);
  - adsorption (section 2.3.1.3);
  - EBPR (section 2.3.1.4).
- P recovery
  - struvite precipitation (magnesium salt dosing) (section 2.3.2.1);
  - ion exchange (section 2.3.2.2);
  - physico-chemical recovery from sewage sludge or sewage sludge ash (section 2.3.2.3).

2.3.1 P removal

2.3.1.1 Aluminium, iron and lime (calcium oxide or calcium hydroxide) salt dosing

Chemical dosing with Al, Fe or calcium (Ca) salts is the most widespread and effective method of P removal from wastewater (Environment Agency, 2012) and is often used by water companies to achieve discharge compliance in a cost-effective manner. The method is capable of producing an effluent quality of around 1 $mg\,L^{-1}$ P, with the ability to reduce soluble P concentrations by up to 90%, and is relatively easy and inexpensive to install into existing facilities. It is described as a low-tech method.

The major disadvantage of chemical precipitation processes is that the amount of sludge produced can be up to three times higher than that produced by conventional sewage treatment. The resulting sludge also contains P that is strongly bound to the Al/Fe/Ca precipitant and is therefore not biologically available to plants for growth unless it is processed further (Mehta *et al*., 2014). If Fe is used, the material also cannot be further processed by the P industry (Schipper *et al*., 2001). Furthermore, chemical treatment using Fe also lowers biogas production during anaerobic digestion (AD) (Tarayre *et al*., 2016).

Chemical salt precipitation is a low-cost option compared with biological removal or tertiary filtration that is easily retrofitted to existing WWTWs. However, chemical treatment produces large volumes of metal-enriched sludge for disposal and requires large amounts of chemicals. Nevertheless, precipitation is the preferred option for P removal and is widely practised globally.

2.3.1.2 Tertiary filtration with granular-medium filters

Tertiary filtration is recognised as a final polishing step. P concentrations of less than 1 mg L^{-1} appear to be feasible but entail high costs in terms of economic and environmental factors (Environment Agency, 2012). The effectiveness of filters is governed by the concentration and size of particles entering the filter. This method is often applied as part of the treatment process (with chemical P precipitation) to achieve total P limits of 1 mg L^{-1} or lower. Key granular-medium filters are:

- single or two-stage configurations of filters;
- travelling bridge filters with shallow granular media;
- pressure filters with conventional sand media that are contained in closed containers and are used under pressure.

Filters are often used in facilities that need to reach concentrations of 1 mg L^{-1} of total P or below. Limits below 0.05 mg L^{-1} of total P can be achieved by tertiary clarification, microfiltration and reverse osmosis when supplemented by chemical addition (Environment Agency, 2012). Filtration has a low impact on sludge and is better suited to the liquid phase; effluent must have a low suspended solids concentration content to avoid filter clogging. A number of filter-based technologies either have been commercialised or are at demonstration scale (Cornel and Schaum, 2009; Environment Agency, 2012). Many of these systems incorporate chemical precipitation in the filter system. Waste streams with high nutrient loads tend to be associated with high levels of suspended solids, which raises the issue of mechanical binding for technologies such as ion exchange. Resin-based as opposed to mineral-based ion exchange technologies may not be able to deal with high nutrient loads, regardless of the amount of suspended solids. Such technologies are therefore more likely to be appropriate for sectors in which removal of low concentrations of nutrients is the only need. These technologies are reviewed in the full EPA technical report.

2.3.1.3 Adsorption

The removal of P using adsorption technologies offers an efficient treatment method that produces no additional sludge and has no additional requirements for chemicals. Adsorbents should have the following properties to be economically viable: (1) be low cost to ensure supply and (2) have high selectivity. Adsorbents tend to be either natural or synthetic materials. Although some natural adsorbents offer the recovery of a high-quality P product that can be used in agriculture, e.g. orange peel, sawdust, straw, biochar, shells and fly ash, synthetic adsorbents tend not to give rise to recovered products. Adsorption technology is growing in interest because of its simplicity, its cost-effectiveness (use of natural materials, e.g. shells), the ability to retrofit and the limited environmental impact in terms of P recovery. The selectivity of adsorption technologies is highly attractive in terms of recovering P in a ready-to-use form, with the product able to be sold as a raw material or fertiliser. Nevertheless, much of the research into adsorbing materials has mainly been performed in university laboratories, with field testing and applications remaining limited. The use of natural adsorbents for P recovery is a recognised area for future development. Examples of these adsorbents include lanthanum bentonite (minerals), zeolite, silicates and ochre. Full details of these technologies are reviewed in the EPA Technical Report.

2.3.1.4 Enhanced biological phosphate removal

A growing alternative to chemical precipitation for P removal is EBPR (reviewed by McGrath and Quinn, 2003, 2004). The EBPR process is based on the exposure of activated sludge to alternating anaerobic and aerobic conditions. This is achieved by configuring the treatment system such that an anaerobic zone is added upstream of the traditional aerobic phase. In the initial anaerobic phase a specialised group (or groups) of microorganisms is able to gain a selective advantage through their ability to take up short-chain fatty acid molecules and to convert these to the carbon storage polymer polyphosphate (poly-P). The energy required for the uptake comes at the expense of the P biopolymer poly-P. Poly-P consists of a linear chain of phosphate groups linked together by high-energy phosphoanhydride bonds and ranges in length from 3 to greater than 1000 orthophosphate groups (Kulaev, 1979). Hydrolysis of the intracellular poly-P reserves stored by EBPR microorganisms provides the energy required for their accumulation of polyhydroxybutyrate (PHB) under anaerobic conditions; as a result, P release to the extracellular medium is characteristic of this phase of the EBPR process. In the subsequent, aerobic stage of EBPR those microorganisms that contain stored PHB/polyhydroxyvalerate (PHV) are able to replenish their internal poly-P reserves; in doing so they remove not only the P released during the anaerobic phase of the process but also almost all of the available P from the surrounding oxygen-rich environment, thereby producing a P-rich sludge suitable for agricultural land application or for the recovery of P as a mineral product, such as struvite, from the dewatering liquor. Both low temperatures and the presence of nitrate within the anaerobic zone are known to cause issues with EBPR process efficiency. Furthermore, there is a requirement for relatively high concentrations of short-chain fatty acids within the wastewater for the formation of PHB/PHV during the anaerobic phase. EBPR plants often therefore have pre-fermentation stages upstream of the anaerobic chamber. In many cases, chemical polishing of the final effluent from EPBR plants is required to meet discharge standards (McGrath and Quinn, 2003).

2.3.1.5 Summary

Chemical dosing with Al, Fe or Ca salts is the most widespread and effective method of P removal from wastewater and is often used to enable water companies to achieve their permit conditions in a cost-effective manner. The major disadvantage of chemical precipitation processes is that the amount of sludge produced can be anything up to two or three times higher than that produced by conventional sewage treatment. The resulting sludge also contains P that is strongly bound to Al/Fe and therefore it is not biologically available to plants for growth unless it is processed further. In comparison, the use of filters, resins and ion exchange to remove P is more expensive. A growing alternative to chemical precipitation for P removal is biological P removal.

2.3.2 P recovery

Unlike P removal technologies, which are well established, P recovery systems are still being developed and have not been widely implemented. Moreover, the size of wastewater treatment facilities commonly limits P recovery in terms of cost-effectiveness, as many of the currently available technologies are not economically viable at the level of small to medium-sized wastewater treatment plants (< 200,000 people). Further research is therefore needed to develop cost-effective technologies for P recovery from small treatment works and industrial effluents, for example from agri-food waste streams. Current legislation requires P removal only to protect water quality; however, moving forward this is anticipated to change as some countries in Europe, such as Germany and Austria, have implemented ambitious national P recovery legislation and targets. The main commercially available method to recover P from wastewater is by struvite formation, but other technologies and processes are emerging onto the market.

2.3.2.1 Struvite precipitation

Wastewater treatment plants – especially those employing secondary and tertiary treatments – have historically encountered P precipitates, with one of the most common being struvite (known as magnesium ammonia phosphate). Struvite formation can foul and coat the sludge return pipelines, along with the associated pumps and valves. This increases pumping and maintenance costs, as well as reducing the overall capacity of the plant system in terms of the lost hydraulic capacity and lowered biological treatment capacity. Controlled struvite precipitation, however, offers an attractive process option for P recovery from wastewater streams.

A number of technologies exist for recovering P from wastewater in the form of struvite, for example using fluidised bed reactors, which incorporate the dosing of magnesium oxide, or by inclusion of a sludge digestion and struvite crystallisation step within the EBPR process design. Controlled formation of struvite growth can have many benefits, including reducing maintenance costs, as well as providing extra revenue from the sale of the struvite crystals as fertilisers. Tarayre *et al*. (2016) noted that, although struvite is not a common commercial product at present, it has a potential market value of approximately €684 per ton. The benefits of struvite production include lower sludge disposal costs, reduced chemical demands for flocculation, lower maintenance costs for pipe clogging and abrasion of centrifuges and an overall higher energy efficiency (Schoumans *et al*., 2015). Commercial struvite recovery systems are supplied by 15 technology providers (11 full scale; 4 demonstration). Each of these processes is reviewed in full in the EPA technical report.

2.3.2.2 Ion exchange

Ion exchange is a resin-based process whereby ions bound to the ion exchange media are exchanged for a target ion. The target can then be removed and/or recovered. The exchange and release process is controlled by environmental variables, such as pH and/or the presence/absence of ions that are more strongly attracted to the media. For effective P recovery ion exchange resins should be:

- low cost;
- highly selective;
- recyclable;
- able to recover P in a suitable form.

Resin-based ion exchange systems are currently most widely used in the supply of drinking water to remove nitrogen (N). Other applications include the supply of purified water to industry; they are also used domestically in household water nitrate filters and by home aquarists. They are generally not suitable for water or waste streams with a high suspended solid content because of “fouling”, whereby the surface of the media becomes physically obstructed. Resins are most commonly made of synthetic organic materials rather than natural polymeric materials. Resin-based ion exchange media can be deployed as fluidised or packed beds. Ion exchange systems for P recovery are reviewed in detail in the EPA technical report.

2.3.2.3 Physico-chemical recovery from sewage sludge or sewage sludge ash

In Europe, incineration of sewage sludge became commonplace when the EU Landfill Directive (99/31/EC) banned landfill disposal of biosolids (Havukainen *et al*., 2016). Incineration requires sludge to be dewatered and thermally dried prior to its incineration to ash, using mono-incinerators (ash from the co-incineration of sewage sludge is generally not suitable for P recovery; Havukainen *et al*., 2016). Mono-incinerated sewage sludge ash has a high concentration of P (approximately 7–10%) and thus may have value as a recovered P source. Direct application of this to agricultural land has, however, been restricted because of the concomitant high levels of heavy metals present, such as cadmium (Havukainen *et al*., 2016). P recovery from ash, i.e. separation from the contaminating heavy metals, is thus required prior to its use.

Phosphorus recovery from ash has been accomplished at a commercial scale via leaching; using acidic, alkaline or a combination of acid–base solutions; and via a number of thermo-chemical processes. Thermo-chemical treatment is often used when the heavy metal content of the sludge is too high, with the heavy metals evaporated off as chlorides (Oenema *et al*., 2012), but it is expensive and energy intensive. Nevertheless, the fertiliser industry recognises the potential of P-rich ash as a phosphate rock alternative for the production of high-grade P fertilisers (Oenema *et al*., 2012). Thermo-chemical processes such as thermal hydrolysis, wet oxidation, incineration, gasification and pyrolysis can greatly reduce the bulk volume of wastes by destroying a large proportion of the organic material and, in the case of incineration, gasification and pyrolysis, by evaporating off much of the moisture. The char, ash or oil that is produced from these thermo-chemical treatments – depending on the process – retains most of the P, but N is lost as gas vapours during the burning process. Incinerated ash can be used as a secondary material to phosphate rock in the P industry.

Treated ashes are up to 100% bioavailable as a result of a series of chemical reactions and the formation of new P-bearing mineral phases during the thermo-chemical treatment and removal of heavy metals. Currently available technologies for P recovery from ash are reviewed in full in the EPA technical report.

2.3.2.4 Summary

Struvite is magnesium ammonia phosphate and can be recovered at WWTWs operating EBPR to produce a slow-release, plant-activated fertiliser. Struvite crystallisation is attracting much interest in the wastewater sector. The benefits of struvite production include lower sludge disposal costs, reduced chemical demands for flocculation, lower maintenance costs for pipe clogging and abrasion of centrifuges and an overall higher energy efficiency. The economic benefits of struvite production are achieved by reduced disposal costs because of improved dewatering of sludge, lower polymer demand and lower maintenance costs (scaling in pipes and abrasion in centrifuges). The integration of struvite is currently economically feasible only at larger WWTWs.

2.4 Cost Comparison of Technologies

Although it is difficult to compare technologies that have different outputs or that are designed for different purposes or industries, there are certain attributes that can be compared to help understand the limitations of each technology. It is possible to get a sense from the literature of which technologies are likely to cost more to install and/or run; this information is summarised in Table 2.1.

2.4.1 Summary

Up to 75% of wastewater sludge is combustible; typically, ash is disposed to landfill unless technologies have been implemented to recover P and other metals from the ash (Irish Water, 2016). Mono-incineration and P recovery from ash have very high capital and operational costs. Methods for P recovery from ash include leaching; using acidic, alkaline or a combination of acid–base solutions; and thermo-chemical processes.

2.5 Technology Evaluation and Feasibility for Adoption in Ireland

Current legislative controls on the emission of P via discharge limits relate to its role as an environmental pollutant contributing to surface water and groundwater eutrophication, rather than considering it as a recoverable, finite resource. The sustainability aspect of legislation, in relation to P reuse and recovery, must therefore be further developed to promote a "circular economy" and the future sustainability of P for food security. As a direct result of the current legislative focus, P removal appears to be the priority for most sectors, and the range of currently marketed technologies reflects this. Technology feasibility recommendations for P recovery and reuse from wastewater for adoption in Ireland are as follows:

Table 2.1. Technology comparison summary

Technology	Nutrient	CAPEX cost	OPEX cost	Retrofit	Technology maturity	Saleable product?
Fe/Al salt dosing	P	Green	Purple	Green	Green	Low-/no-value sludge
Struvite (magnesium dosing)	P	Red	Green	Green	Red	Medium-/high-value fertiliser
Ion exchange	P	Purple	No data	No data	Green	Potentially medium-value fertiliser
EBPR	P	Purple	Green	Red	Green	Low-/no-value sludge
Thermo-chemical	P	Red	Red	Red	Red	Medium-value fertiliser

Purple, high/difficult – prototype or demo; red, medium – short term, commercially proven; green, low/easy – long term, commercially proven.

CAPEX, capital expenditure; OPEX, operational expenditure.

- Move away from the practice of chemical treatment to remove P as the cost of chemicals for P removal and sludge production volumes increase.
- At smaller works (< 200,000 people) experiencing unwanted or nuisance struvite precipitation, infrastructural updates should be implemented to recover P as struvite. EBPR and the production of struvite (where economically viable) as a commercially saleable product and soil conditioner should be implemented.
- Develop innovative new technologies for smaller plants or for application in the agri-food sector where struvite precipitation is not economically viable.
- AD of sludge to recover energy (biogas, electricity, heat) reduces sludge volumes and produces a P-rich liquid sidestream for struvite production. AD plants should be viewed as future “biorefineries”, not only for the production of fuel, heat, power and nutrients but also for the recovery of value-added chemicals from biomass, which can be used to produce bioplastics, biopolymers and biochemicals. This will offer a sustainable and renewable alternative to traditional crude oil-based refineries for plastic and chemical production, as well as increase the cost-effectiveness of the AD process.
- Mono-incinerate the final sludge from the AD process and plan for future treatment of ash for P recovery, or seek alternative uses for the ash, such as in the cement industry. Mono-incineration requires significant investment costs. In relation to mono-incineration, explore the potential for a large incinerator for the island of Ireland (North and South) through shared investment and potential economies of scale.
- Conduct research into the use of recovered P fertiliser products (e.g. struvite) as slow-release fertilisers within the Irish agricultural sector. To date, limited studies have investigated their use as fertiliser in Ireland. Further to this, research should also be conducted into the development of alternative formulations of slow-release fertiliser encapsulated with recovered P and N.
- Develop an Irish Nutrient Sustainability Platform (www.nutrientsustainability.ie) as a vehicle to promote and facilitate the coalescence of multiple stakeholders involved in the future adoption of circular and bioeconomies in Ireland.

3 Combined Anaerobic Digestion and Phosphate Removal in a Novel Bioreactor Process

3.1 Introduction

High-rate AD wastewater treatment technologies provide low-cost and effective removal of pollutants, with many advantages over other catalytic processes, combined with the recovery of energy in the form of biogas (methane). Despite many instances of its successful application, a drawback associated with AD wastewater treatment has been the inability to achieve even moderate levels of inorganic nutrient, in particular P, removal that would reduce the need for extensive aerobic biological or chemical post treatment (McGrath and Quinn, 2003; Caravelli *et al.*, 2012; Hauduc *et al.*, 2015). Moreover, although anaerobic treatment technologies have been successfully implemented for low-strength industrial wastewaters and domestic sewage, this has mainly been confined to tropical/warm temperature regions (Smith *et al.*, 2012). The recent development of low-temperature (LT) AD has overcome this latter drawback and allows for the economically efficient application of AD to low-strength wastewaters in temperate regions (McKeown *et al.*, 2012; Keating *et al.*, 2016). The focus of this work package was to combine a novel biological P removal process with LTAD to significantly advance the potential for direct AD of dilute wastewaters.

To date, the well-established EBPR systems (see section 2.3.1.4) have been applied for biological P removal from wastewaters. EBPR is based on the exposure of activated sludge to alternating anaerobic and aerobic phases. P removal across the system is achieved via the intracellular accumulation of poly-P by a specialised group (or groups) of microorganisms. However, in reality these systems can demonstrate variability in performance, as poly-P uptake is dependent on a number of operational and microbiological conditions that remain to be fully elucidated (McGrath and Quinn, 2003; Zeng *et al.*, 2013; Yu *et al.*, 2014).

The potential for efficient removal and recovery of P during AD of dilute wastewaters was significantly advanced by Hughes *et al.* (2011) using a novel hybrid bioreactor system incorporating a fixed-film section based on a pumice stone matrix. The biological nature of P removal during such AD wastewater treatment, through the formation of poly-P, has recently been reported by this EPA project team in a groundbreaking paper (Keating *et al.*, 2016).

Our hypotheses were that high levels of biologically mediated P removal during AD could be achievable during low-temperature, high-rate treatment of dilute industrial wastewaters and sewage. Our aim was to test this in laboratory- and pilot-scale bioreactor systems during work package 2. Details of the experimental set-up, materials, methods and results are contained in the full EPA technical report.

3.2 Treatment Efficiencies for Municipal and Industrial Wastewaters

3.2.1 Laboratory-scale treatment of SYNTHES wastewater

The technical aim of the laboratory-scale work was to establish operating parameters for the subsequent pilot-scale treatment of municipal wastewaters.
The wastewater was a synthetic municipal stream, designed to mimic raw domestic sewage (Aiyuk and Verstraete, 2004). P removal from the wastewater, significantly in excess of microbial growth requirements (1.5–2% of sludge dry weight), was achieved during this trial. P removal on start-up (35 days) was initially low, but it increased significantly during phase 1, with values of >70% consistently achieved. It appeared that P uptake required a period of acclimation, or perhaps more likely a period of development associated with the colonisation of biofilms onto the pumice stones. As loading rates were increased to the system, P removal efficiency decreased considerably and became more unstable. Nevertheless, considerable removal (*c*.50%) of the influent P was, on average, maintained by the process during these periods. The P removal in the systems was mainly biological in nature, mediated by biofilms within the reactor and the fixed-film unit

rather than chemical precipitation (Hughes *et al*., 2011; Keating *et al*., 2016).

3.2.2 Pilot-scale treatment of dairy processing wastewater

The dairy processing sector in Ireland is a major, and growing, producer of P-rich wastewaters. As a result of production cycles and varied product lines, dairy processing wastewaters are usually produced in an intermittent manner. This affects both the flow and characteristics of the incoming wastewater. Seasonal variations in flow are also a feature of dairy processing; typically, high flows are common in summer and low flows are common in winter, although increased demand coupled with better land and herd management has seen the "peak/summer" period extended. The organic fraction of dairy wastewater is composed of easily degradable carbohydrates, primarily lactose, and the less biodegradable proteins and lipids, and as such can be defined as a complex type of substrate. Dairy wastewater can have a significant fat/lipid content. This fraction causes varying degrees of difficulty for biological treatment systems depending on the type and concentration of lipids.

In this work package, a 1.3 m^3 NUIG AD pilot plant was installed at a dairy processing industrial site. Two process trials were completed between October 2016 and October 2017. In trial 1, the pilot plant treated a combined wastewater stream, with a line sourced from a large balancing tank. The second trial was carried out to assess the impact of re-seeding the reactor with a fresh, low temperature-tolerant inoculum mix, similar to those deployed for the laboratory-scale experiments.

In summary, the data obtained from the two dairy processing industry trials demonstrated that P removal rates of 40–50% were achievable and that this level of performance could be sustained despite fluctuating ambient temperatures and loading rates and occasional spikes in organic loading.

3.2.3 Pilot-scale treatment of municipal wastewater

The United Nations (UN) *World Water Development Report* states that, by 2030, the global energy and water demand will grow by 40% and 50%, respectively (WWAP, 2017). Most of this growth is expected to occur within urban centres, which raises questions about our current approaches to wastewater management. The conventional activated sludge aerobic wastewater treatment currently used to treat municipal wastewater in developed countries does not meet basic sustainability criteria (McKeown *et al*., 2012). The emergence, therefore, of high-rate AD as a low-cost alternative to the conventional activated sludge process would be a significant advancement in municipal wastewater treatment (McKeown *et al*., 2012; Smith *et al*., 2012).

High-rate AD of low-strength municipal wastewater has already been successfully adopted in tropical regions at temperatures above 20°C, and its capabilities are well documented (Foresti *et al*., 2006). One of the major milestones that led to the development of municipal AD was the implementation of the expanded granular sludge-based (EGSB) style configuration (Kato *et al*., 1999). Low temperatures and low organic matter concentrations can, however, result in a loss of granular integrity in EGSB systems as a result of high up-flow velocities (Hughes *et al*., 2011). The EGSB–anaerobic filter hybrid bioreactor, which was the focus of this research, is a variation on the EGSB design that incorporates an anaerobic filter section to retain active biomass lost through granular shearing and to provide a robust technology for diluted wastewater treatment under low ambient temperature conditions (Collins *et al*., 2005; McHugh *et al*., 2006). There are three main factors that influence the implementation of direct LTAD for municipal wastewater: the biodegradability of suspended solids, the operational temperature of the bioreactor and the sludge retention time (SRT). During AD of municipal wastewater at lower temperatures, the rate-limiting step is considered to be the hydrolysis of retained particulates, which requires relatively long retention times (Lettinga *et al*., 2001). These suspended solids in the influent tend to accumulate in the sludge bed as a result of the longer SRT, resulting in reduced methanogenic activity. Direct AD at these lower temperatures therefore remains challenging because of changes in the physio-chemical properties of the wastewater and slower biochemical processes.

The AD pilot plant was installed and commissioned at the Tuam Wastewater Treatment Plant in County Galway and a trial was carried out for 91 days to establish the feasibility of LTAD with P removal for the treatment of municipal wastewater. The pilot plant treated a wastewater stream, with a line sourced from the influent to the aeration basin. In summary, the data obtained from the municipal pilot trial demonstrated that P removal rates of 40–60% were achievable and that this level of performance could be sustained despite fluctuating ambient temperatures and loading rates and wide variations in hydraulic and organic loading.

3.3 Key Findings

We have demonstrated a potentially important new method for the sequestration of P using luxury poly-P uptake under anaerobic conditions. We have shown that the process is scalable and that it can be deployed at pilot scale in real-word industrial and municipal settings. These findings support the idea that modified AD systems could provide the basis for significant recovery and reuse of P from wastewaters, a significant advance in the field.

At this point, however, there are two areas that require optimisation before technology transfer, or application of the novel process at full scale, can be considered. First, there is a need to improve the extent of P removal during long-term wastewater treatment to levels mirroring our previous results at laboratory scale (70–80%) and, second, the applicable loading rates where high levels of P removal were recorded at pilot scale in this study are too low to favour economically attractive scale-up. To address these questions, the precise environmental and biological triggers that promote the process of anaerobic P removal, the exact role of the microbial biomass and the pumice filter unit, and the precise mechanisms and conditions for anaerobic poly-P formation must be fully elucidated. These questions are a focus for ongoing research efforts to improve the extent and stability of anaerobic P removal and to increase the applicable loading rates towards implementation of a full-scale technological solution.

If high-rate AD technology and P removal technology are to be considered for the dairy processing industry, the provision of sufficient balancing capacity is a key criterion. The incorporation of effective mixing in the balance would help to ensure more consistent wastewater characteristics. Consistency of wastewater strength is a key consideration in AD systems, as it leads to a more stable performance with respect to P removal and also more consistent biogas production. Fats, oil and grease pose a significant challenge for high-rate AD systems and, indeed, for aerobic activated sludge plants, as biodegradation rates for fats, oil and grease are low and their physical effects on the microorganisms involved can lead to process issues and even process failure.

Successful scale-up and implementation of LTAD and AD P removal for the treatment of municipal wastewaters will require implementation of de-gassing strategies to recover the dissolved methane in order to maximise the energy values of the process and also to avoid post-treatment losses of methane to the atmosphere.

4 Carbon Starvation-inducing Compounds as a Means of Enhancing Phosphorus Removal and Poly-P Accumulation in Microbes

4.1 Introduction

The accumulation of inorganic phosphate (Pi) as intracellular poly-P granules in bacteria has been extensively studied and several applications for this have been developed. For example, the induction of this process by changing oxic–anoxic conditions is the basis of EBPR (see section 2.3.1.4). However, EBPR requires significant capital expenditure to implement and has proven to be very highly dependent on factors such as the volatile fatty acid (VFA) concentration of the influent being treated. In regions such as Ireland, where wastewater tends to have comparatively low VFA concentrations, this has reduced the effectiveness, and therefore impeded the adoption, of EBPR.

Enhanced biological phosphate removal induces poly-P accumulation using oxidative stress, but other triggers of poly-P accumulation have been described. Preliminary data have suggested that periods of carbon starvation followed by incubation in carbon-replete medium (a process termed starvation-induced biological P removal or SIBPR) could increase phosphate removal from growth medium by up to 50% in aerobic cultures of bacteria. Work package 3 sought to explore the use of SIBPR and carbon starvation-inducing (CSI) compounds to induce stress in microbes for the purpose of increasing Pi removal from growth medium, to optimise the conditions for triggering these effects and to investigate the potential applicability of these processes to larger scale systems. Details of the experimental set-up, materials, methods and results are contained in the full EPA technical report.

4.2 Key Findings

We investigated the effects of SIBPR and CSI compounds on the ability of microorganisms to accumulate Pi from culture medium as poly-P and determined whether or not these approaches could potentially be applicable to larger scale systems. Unfortunately, we were unable to reliably induce Pi removal using the SIBPR system. Incubation of cultures with CSI compounds did show statistically significant increases in Pi uptake; however, the effects were strongly influenced by both the available carbon sources and the organism(s) present in the experiments.

Although the conditions of the carbon starvation (SIBPR) experiments were designed to replicate those under which a preliminary effect had been observed, there may be additional factors that had an influence on the outcome of the experiments. The subsequent CSI experiments showed that the carbon source can affect the responses of the microorganisms, and so extending these experiments to glucose-fed cultures may show an effect on SIBPR. Ultimately, however, SIBPR could not successfully be used to induce Pi uptake, and the apparent variation of CSI effects between different organisms, concentrations and carbon substrates would thus inhibit the adoption of this process in, for example, an industrial setting. A more robust method of phosphate removal, such as the use of novel P-binding biopolymers, as described in Chapter 5, is likely to prove more reliable and effective for the development of a P recycling process from wastewater.

5 Application of a Biopolymer for Phosphorus Capture from Wastewater

5.1 Introduction

Researchers at QUB have previously developed a natural biopolymer-based material for the removal and recovery of P from wastewater. Work within this project involved the trialling of this P sorbent at a small WWTW as a final polishing step. Figure 5.1 illustrates how the application of this biopolymer could be used to recycle P from wastewater.

5.2 Testing of the Biopolymer

Figure 5.2 shows the current design of the biopolymer, which is based on partial cross-linking of the material to generate robust spherical beads in a rapid, reproducible and high-yielding manner.

Laboratory experiments have successfully demonstrated P capture from synthetic wastewater, with the biopolymer achieving binding values of up to 100 mg P g^{-1} sorbent; over 90% of the P bound to the biopolymer was recovered after elution.

To further test the feasibility of our P-binding biopolymer for P recycling from wastewater, Northern Ireland Water provided access to a small WWTW serving 2773 people, which does not use ferric dose to remove P. Wastewater samples were collected at the inlet to and outlet from the works. Samples were analysed by the team using ion chromatography for P, as well as other chemicals of interest. Duplicate samples were also analysed by Northern Ireland Water laboratories for total P and soluble reactive P. The biopolymer was housed in a plastic cartridge, designed by the Northern Ireland Technology Centre (QUB), to facilitate the gravity flow of effluent through the biopolymer via a rig set-up (Figure 5.3).

5.3 Key Findings

When a synthetic wastewater solution was passed through the rig set-up, with two filters (containing biopolymer), the P concentration was reduced from 3.28 mg L^{-1} to less than 0.5 mg L^{-1}, a removal rate of 87%. The polymer also removed 15% of the sulphate, 10% of the chloride and 12% of the nitrate from the synthetic wastewater sample. Using wastewater, the P concentration was reduced from 3.22 mg L^{-1} to 1.36 mg L^{-1} (58% removal), with the polymer also

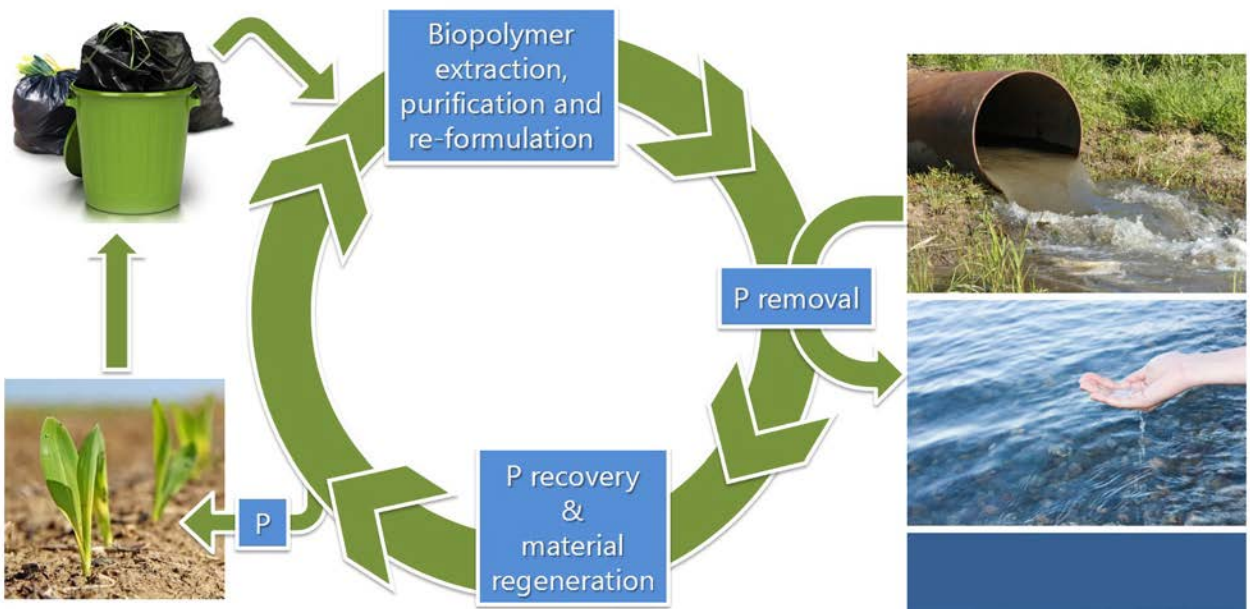
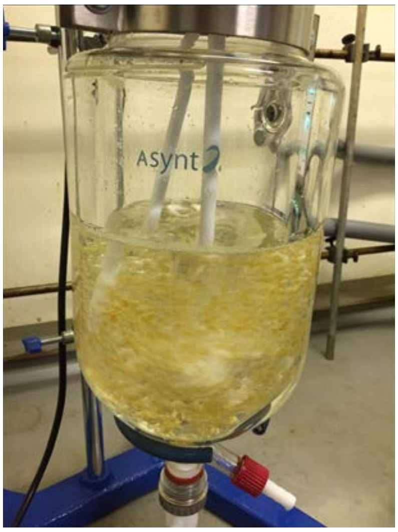


Figure 5.1. Removal and recovery of P from wastewater using biopolymers.

(a)



(b)

Figure 5.2. (a) Production of biopolymer beads in the laboratory; (b) biopolymer beads to be housed in a cartridge and attached to the outflow effluent from the WWTW.

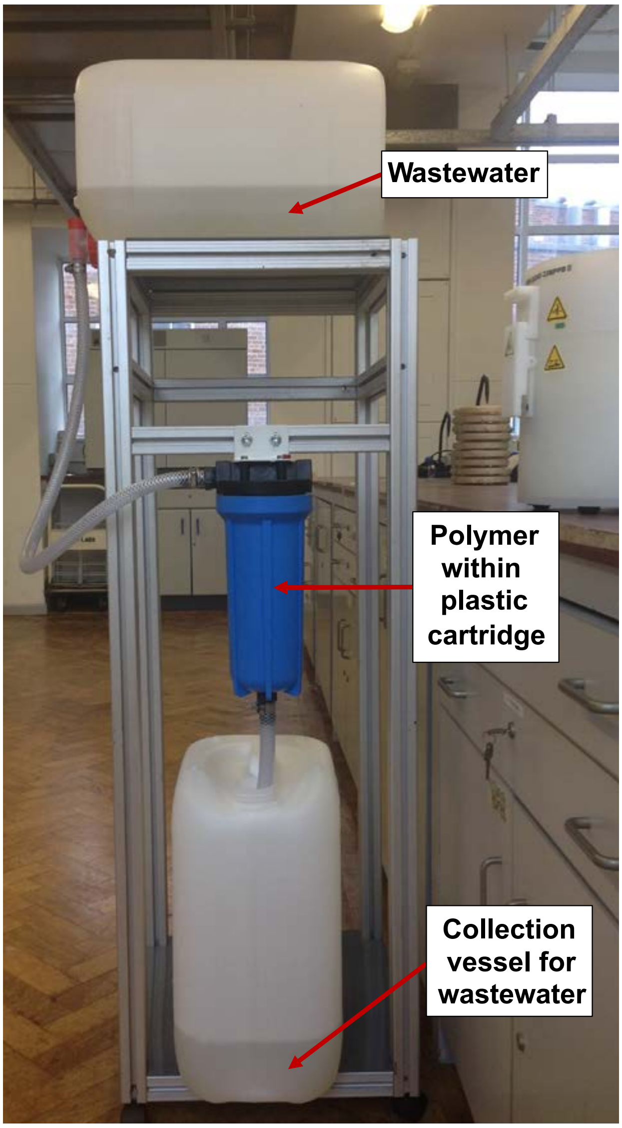


Figure 5.3. Biopolymer rig set-up.

removing 46% of the sulphate, 63% of the nitrate and 32% of the chloride.

Although it is beneficial that the biopolymer does not only remove phosphate in terms of polishing the final wastewater, this has posed a problem in terms of increasing the capacity of the biopolymer to deal with increased volumes of water. This needs to be further explored to enable continuous field deployment.

Further research at QUB is ongoing to develop other versions of the biopolymer that exclusively bind P and also to increase the P-binding capacity of the current biopolymer. Field trials of the biopolymer, both in terms of utilisation within an aerobic activated sludge system and as a bolt-on module to AD units, are currently being planned.

6 Evaluation of Sector-wide Views on Phosphorus Management Issues on the Island of Ireland

6.1 All Island Phosphorus Sustainability Workshop

An All Island Phosphorus Sustainability Workshop was facilitated to capture perspectives on regulatory P management and the circular economy from relevant stakeholders across the regulatory, wastewater, academic and agri-food sectors in relation to P reuse, recovery and recycling, as well as future directions for P sustainability and research in Ireland (Macintosh *et al.*, 2019b). The aim of the 1-day workshop was to bring together diverse stakeholders to discuss solutions to P sustainability and P management issues on the island of Ireland. Sessions at the workshop were convened on regulatory perspectives on P management; perspectives on P recovery, recycling and reuse; and future directions for P sustainability. Through keynote talks, panel member discussions and delegate breakout groups, the workshop aims were to (1) discuss scenarios for effective P management, (2) increase awareness of existing P recycling technologies and envisage their implementation within the agri-food and waste treatment sectors and (3) develop a market understanding of technological and management gaps requiring further research with respect to P management. The objectives of the workshop were to:

- identify the key issues relating to P management on the island of Ireland;
- develop a conceptual model for transformational change for P sustainability on the island of Ireland;
- consider the establishment of an island of Ireland nutrient platform.

A list of keynote speakers and panel members who presented at the workshop is provided in the EPA technical report. A total of 76 delegates attended the workshop; a breakdown by sector is also detailed in the full EPA technical report.

The workshop was facilitated by Dr Brent Jacobs and Dr Dana Cordell (Institute for Sustainable Futures, University of Technology Sydney, Australia). The transformational change model, a social science approach developed by Jacobs *et al*. (2017), was used to capture and record information arising from the workshop by asking delegates:

- What is current, business-as-usual practice – what is the current status in terms of P?
- What would a transformed system be – what would a future system look like?
- What are the transition pathways from current to optimal practice – how could we achieve a transformed system? What are the barriers, constraints, enablers and drivers of change?

Workshop delegates were seated at round tables throughout the course of the day and discussed and recorded their perspectives using written notes, Post-it notes and poster sheets, as well as electronically or interactively online. Each table of delegates had a trained facilitator and note-taker. Table facilitators were PhD students from QUB and NUIG who had attended a table facilitation training session held by Dr Dana Cordell and Dr Brent Jacobs in advance of the workshop. All delegate responses were treated confidentially. Figure 6.1 depicts delegates participating at the workshop.

Information obtained from the workshop was synthesised to produce a model for P transformational change for the island of Ireland. The transformative model, based on theories of transition management and economies of increasing returns, was used to identify what an ideal future would look like to stakeholders in terms of P sustainability (the "transformed system"), to establish how these stakeholders viewed the existing status of P sustainability ("business as usual") and to determine how they felt the current P situation could most effectively be transitioned into the idealised future that they had identified ("transition pathways").

Figure 6.1. Speakers, panel members, chairs and delegates participating in the All Island Phosphorus Sustainability Workshop.

Additionally, the stakeholders described which issues they felt were impeding the adoption of this idealised future (“barriers”) and which factors could facilitate transition into the idealised paradigm (“enablers”). Finally, stakeholders were asked to identify factors that could stimulate society to begin the transition to a sustainable P future (“drivers of change”).

Delegate responses captured at the workshop were analysed in collaboration with Dr Dana Cordell and Dr Brent Jacobs. During this synthesis, responses were categorised as:

- drivers of change;
- business as usual;
- future transformed system;
- transition pathways;
- barriers;
- enablers.

Responses were then further grouped according to the following categories:

- governance;
- technology;
- markets, economics and business;
- biophysical;
- social/behavioural engagement;
- not elsewhere classified;
- whole-system issues;
- knowledge, communication and research.

The conceptual model of transformative change for P sustainability on the island of Ireland that emanated from the synthesis of stakeholder data collected during the workshop is published in Macintosh *et al.* (2019b). Full details of the model, its development and the outcomes can be found in the EPA technical report.

6.2 Nutrient Platforms and the Establishment of an Irish Nutrient Sustainability Platform to Deliver on United Nations Sustainable Development Goals

In response to growing governmental concerns over P security, expanding environmental legislation and EU sustainability agendas, a number of stakeholder-led P platforms have been established worldwide to focus particularly on P security and sustainability (Figure 6.2). The ESPP (https://phosphorusplatform.eu/) is an EU-level, non-profit organisation that acts as an advocate for nutrient sustainability by bringing together diverse stakeholders, including government, research institutions, universities, industry, the wastewater and waste treatment sectors, treatment and recycling technology providers, research and innovation hubs, non-governmental organisations and the farming community. A number of regional P platforms have also been founded, e.g. in the Netherlands (2010) and Germany (2015), to respond to regionally identified nutrient sustainability challenges. In the USA, the Sustainable Phosphorus Alliance platform (https://phosphorusalliance.org/) was launched in May 2017 as a follow-on from the National Science Foundation-sponsored P-RCN. Each platform is staffed by a programme manager responsible for promoting the regional activities of their organisation and members.

The All Island Phosphorus Sustainability Workshop laid the foundations for establishing an Irish Nutrient Sustainability Platform (www.nutrientsustainability.ie), which will actively engage both the private and the public sectors in the coherent delivery of Sustainable Development Goal targets. An EPA UN Sustainable Development Goal grant was applied for, and secured, in 2017 to develop and establish an Irish platform. The aim of the proposal was to begin developing such a stakeholder-driven network to address nutrient (and co-recoverable resource) sustainability across the island of Ireland in the context of UN Sustainable Development Goals (and cognate expanding national and EU legislation). Mentorship in platform

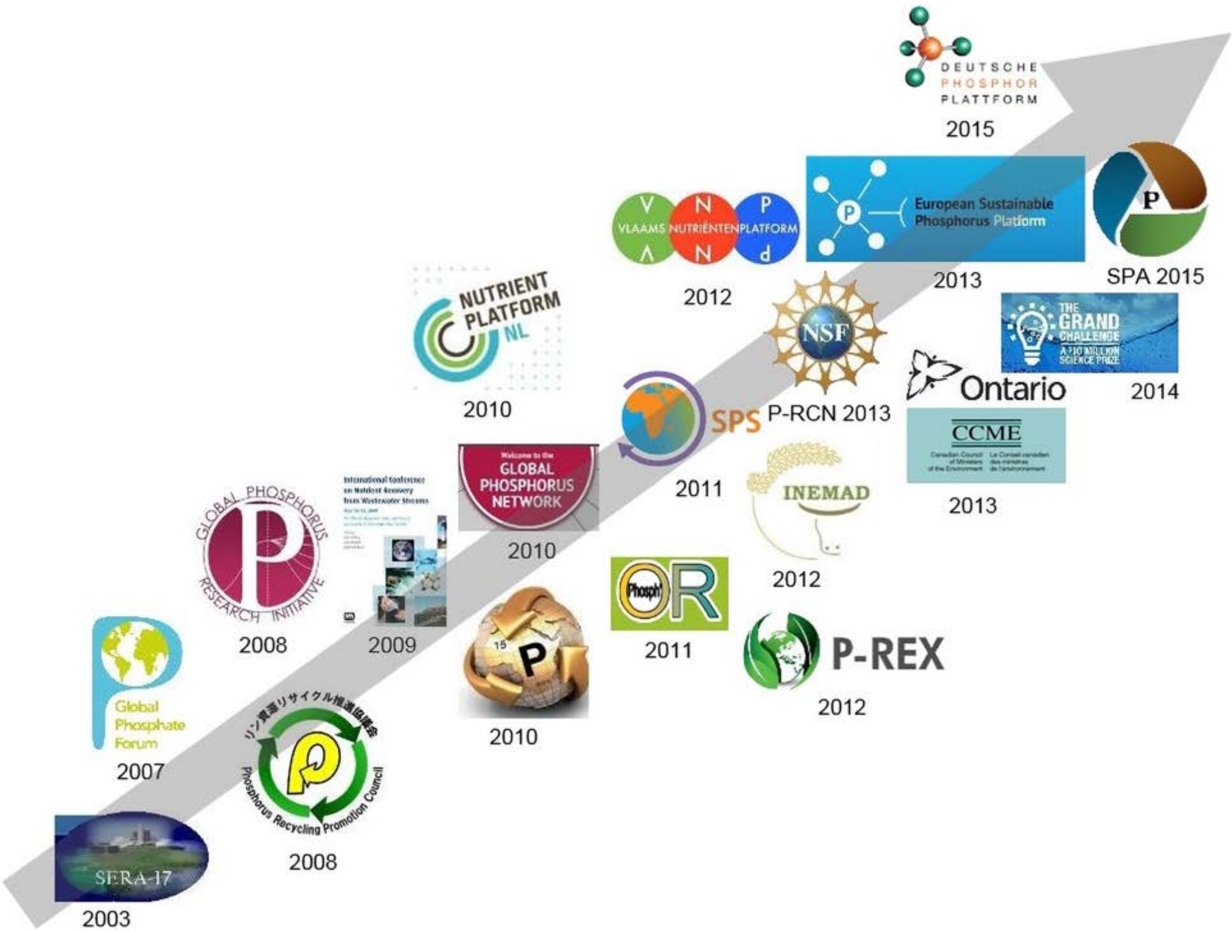


Figure 6.2. International nutrient platform movement.

establishment has been agreed with the German Phosphorus Platform, the ESPP and the Sustainable Phosphorus Alliance. The project is collaborative between QUB and NUI Galway and a direct output from this project.

6.3 Microbial Resources for the Agriculture and Food Security Conference

A P sustainability-focused conference followed the workshop. As microorganisms play a pivotal role not only in P recycling, but also across the agri-food sector, the conference focused on their diverse roles in agriculture, from increasing farming efficiency to safe environmental management and the production of value-added products from agri-food and biobased waste streams. Keynote talks encompassed biogeochemistry, microbiology, crop science, modelling and process engineering. The meeting promoted a multi-disciplinary understanding of new approaches and biotechnological possibilities to improve our ability to harness microbial processes, thereby providing more efficient and sustainable agri-food systems with better environmental stewardship.

The conference included the following sessions:

1. nutrients in the environment with a focus on agricultural systems;
2. microbial ecosystems and nutrient cycling;
3. harnessing microbial processes within the agri-food sector.

A list of keynote speakers and papers presented at the workshop is provided in the full EPA technical report. A total of 25 posters were also displayed during the workshop and conference.

Sponsors included the EPA, Science Foundation Ireland, Devenish Nutrition, Ostara and Athena SWAN at the School of Biological Sciences at QUB. Further sponsorship and co-promotion was provided by the Microbiology Society. Exhibitors included Ostara, Premier Scientific, Sartorius, WVR, Constant Systems, Mason Technology, and Davidson and Hardy (Figure 6.3). Overall, the conference and workshop helped to develop ideas and identify challenges to Irish P sustainability, while also generating much discussion around the latest research in the field.

Figure 6.3. Exhibitor and poster hall at the workshop and conference.

7 Key Recommendations

This research project sought to address the complex issue of P sustainability on the island of Ireland, in the context of identifying pressures, informing policy, developing solutions and identifying future research needs, by:

1. reviewing the current state of the art with respect to commercial processes for P removal and recovery from waste streams through literature analysis and industrial liaison, and by exploring the suitability and cost-effectiveness of these technologies for adoption within the Irish wastewater treatment sector (both urban and industrial);
2. dissecting the scientific basis of two novel P removal and recovery systems developed within QUB–NUIG through the assessment of their robustness, scalability and effectiveness as P recycling technologies;
3. facilitation of an All Island Phosphorus Sustainability Workshop to capture perspectives on regulatory P management and the P circular economy from relevant stakeholders from across the regulatory, wastewater, academic and agri-food sectors in relation to P reuse, recovery and recycling, as well as future directions for P sustainability and research in Ireland.

Key recommendations from this important study are summarised below.

Legislation and policy:

- There are currently fewer legislative drivers for P recovery than for removal, but this landscape is changing with, for example, national P recovery legislation in Germany and Austria and proposed EU regulations to mandate the recovery of up to 30% of P from waste by 2050.
- The current market situation for primary sources of P (phosphate rock) means that recovery processes are economically viable only on a large scale. This could, however, be offset by factors around security of supply, future EU legislation around permissible cadmium levels in fertiliser products and the production of “blended” fertilisers, which contain a proportion of recycled P product.
- Ireland should consider setting a target (in terms of both percentage reduction and date) for reducing P imports. P importation should be reduced through the development and implementation of nutrient recycling technologies across both the wastewater and the agri-food industries.
- An all-island Irish Nutrient Sustainability Platform (www.nutrientsustainability.ie) should be established with a similar remit to cognate platforms in operation across the EU and globally, to engage the public and private sectors in the development and implementation of nutrient (and co-recoverable resource) management and value chain development.

Technology:

- Water and wastewater streams from different sectors have very different properties, such as volume, concentration of nutrients and levels of suspended solids, which influence the types of technologies that can be applied for P recycling. This will also influence the economics of nutrient recovery.
- P recovery is not well developed in many sectors, although some outputs from nutrient management are currently being marketed, e.g. struvite. Nevertheless, commercial opportunities do exist for the recovery and recycling of P from both the wastewater and the agri-food sectors.
- Utility providers and industries should consider a move away from the practice of chemical treatment of wastewaters for P removal because of the escalating cost of precipitants, the increased sludge volumes produced when using chemical precipitation and the difficulty in recycling P from chemically precipitated sewage sludge. Alternative technologies for P removal should thus be considered (e.g. EBPR) or developed (e.g. through the use of polymer-based adsorbents – this study) and should not result in any breach of P emission limit values in relation to discharges to water.

- At WWTWs (> 200,000 people) experiencing unwanted or nuisance struvite precipitation, infrastructural upgrades should be implemented to recover P as struvite.
- Globally, there is a significant research effort under way to develop P recycling technologies. Many of these systems are based on struvite production at the laboratory or pilot scale. There remains, however, a significant commercial opportunity to develop low-cost P recycling technologies for small to medium urban WWTWs and for use within the agri-food sector, where current struvite production is either not economical or not technically feasible.
- If mono-incineration of sewage sludge becomes a technology adopted within Ireland, plans for the future treatment of ash for P recovery should be developed, or alternative uses for ash should be considered, for example within the cement industry. Incinerated ash could also be stored in segregated landfill for future mining when P extraction technologies from ash are more advanced, commercially available and cost-effective. Future developments in Germany, Switzerland and Austria regarding P recovery from ash should be monitored, as 100% of sewage sludge is incinerated in these countries and P recovery is now a priority target. In relation to mono-incineration, the potential for a large incinerator for the island of Ireland (North and South) through shared investment and potential economies of scale should be considered.
- AD of sludge to recover energy (biogas, electricity, heat) reduces sludge volumes and produces a P-rich liquid sidestream from which P can be recovered. Efforts should, however, be made to produce a nutrient-balanced liquid digestate and/or biosolid fraction (through, for example, the use of decanting centrifuges). Further investment in both the research and the application of AD-based biorefinery processes is also required to deliver "value-added products" in addition to methane, for example the removal and recovery of N, P, carbon dioxide, VFAs and bioplastics. This is particularly relevant in the context of circular economy and bioeconomy policy at both national and EU levels and given the keystone role of AD-based systems in addressing national climate targets.

Future research:

- Research is required on both the agronomic value of recycled P products across the Irish agricultural sector and methodologies to stabilise nutrient levels in agri-food wastes (e.g. composts) to produce new innovative fertiliser products that perform, in terms of yield, comparably to traditional chemical fertilisers. The development of alternative formulations of slow-release fertiliser encapsulated with recovered P and N should also be considered. Further research is also needed to elucidate the factors that trigger the release of P from struvite within soils.
- In utilising recovered products as fertilisers (or other commercial products), the presence of microbiological (e.g. vegetative cells, toxins, spores, parasites), chemical (e.g. organic residues such as antibiotics, veterinary products) and physical (e.g. microplastics) contaminants requires evaluation. The follow-on effect of such fertiliser application on the soil and, in turn, on the gut microbiome of receiving animals and humans also requires consideration.
- Approximately 36% of European freshwater systems fail Water Framework Directive targets despite imposition of the Urban Wastewater Treatment Directive and the control of discharge to sensitive areas. Much of this can be attributed to "legacy" nutrients within freshwater sediments. Greater research is needed to understand the biogeochemistry of legacy nutrient cycling in freshwater systems and, in particular, the role played by the microbial community. This includes the development of lake observatory facilities (which are lacking). Furthermore, there is a need to develop better biogeochemical models to link microbial function with lake geochemistry to develop predictive tools for legacy nutrient uptake and release and greenhouse gas emissions. An assessment of whole-lake P remediation technologies (e.g. the use of lanthanum bentonite dosing for P capture) alongside the development of new technologies is required. In addition to freshwater systems, a better understanding of nutrient cycling in marine and coastal waters is also needed to mitigate against eutrophication and to protect the aquaculture industry.
- Increased on-farm soil testing, adoption of nutrient management tools and uptake of

recovered product fertilisers (e.g. struvite, pasteurised chicken litter) across the agricultural community should be encouraged by working in association with regional farmers' unions and associations, both assisting, and learning from, the farming community with respect to nutrient management and the improvements that could be made therein. Transference of knowledge on best nutrient management and P loss mitigation practices across the Irish farming sector is required.

- From a research perspective, a greater understanding of the effects of nutrient (organic, recovered or synthetic product fertiliser) addition to the soil system is required. This is particularly important in the context of nutrient bioavailability (assessed using technologies such as diffusive gels in thin films), microbial community and function, higher organism functioning (e.g. earthworms) and soil architecture and soil compaction. Moreover, an assessment of recovered/organic product fertiliser value in terms of crop productivity (yield), and losses via surface and groundwater run-off compared with traditional chemical fertilisers, is needed. Integrating recovered fertiliser products into existing decision support tools for agricultural use is also required, and there is a need to develop better support tools, robust low-cost sensors and mobile testing kits for monitoring nutrient levels (in soils, waters and organic residues) that calibrate with existing, but cumbersome, measures of nutrient concentrations, for example Olsen and/or Morgan P tests.
- In terms of the P recycling technologies being developed at QUB and NUIG and assessed within this study, those based on the use of a pumice biofilter to enhance biological P uptake within an AD reactor, and the development of recyclable P sorbents, showed the most promise. Scaling and combining these technologies will be the focus of future studies. Success would offer the prospect of a simple P recycling technology, with a proven (bio)chemical basis, that could effectively compete with existing technologies and, in particular, provide solutions for small- to medium-scale wastewater treatment plants and the agri-food sector.

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Abbreviations

AD	Anaerobic digestion
Al	Aluminium
Ca	Calcium
CSI	Carbon starvation inducing
EBPR	Enhanced biological phosphate removal
EGSB	Expanded granular sludge-based
EPA	Environmental Protection Agency
ESPP	European Sustainable Phosphorus Platform
EU	European Union
Fe	Iron
FOG	Fat, oil and grease
LT	Low temperature
N	Nitrogen
NUIG	National University of Ireland Galway
P	Phosphorus
PHB	Polyhydroxybutyrate
PHV	Polyhydroxyvalerate
Pi	Inorganic phosphate
P-RCN	Phosphorus Research Coordination Network
QUB	Queen's University Belfast
SIBPR	Starvation-induced biological P removal
SRT	Sludge retention time
UN	United Nations
VFA	Volatile fatty acid
WWTW	Wastewater treatment work

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

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

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

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

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

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

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

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

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

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

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

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

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

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

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

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

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Phosphorus from Wastewater: Novel Technologies for Advanced Treatment and Re-use

Authors: Katrina A. Macintosh, Jason Chin, Daren McHugh, Jasmine Connolly, Juan Castilla Archilla, José Antonio Pícon, Pia McAleenan, John P. Quinn, Panagiotis Manesiotis, Vincent O'Flaherty and John W. McGrath

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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying pressures

Phosphorus (P) is a non-renewable commodity that plays an essential role in the global food web. Europe's P production is minimal. Globally, finite reserves are being rapidly depleted, with supplies coming predominantly from Morocco, the USA, China and Russia. As a P importer, Ireland and the wider European community, which has for many years seen itself as a food-secure region, now recognises its high vulnerability to P scarcity. Paradoxically, eutrophication, caused by freshwater P enrichment, constitutes an important threat to good water quality. This research sought to address the two contrasting issues of P sustainability and the pollution of receiving waters by:

- reviewing the current state of the art with respect to commercial processes for P removal and recovery from wastewater;
- dissecting the scientific basis of three novel P removal and recovery systems through assessment of their robustness, scalability and effectiveness as P recycling technologies;
- capturing perspectives from relevant stakeholders from across the regulatory, wastewater, academic and agri-food sectors in relation to P reuse, recovery and recycling, as well as future directions for P sustainability and research on the island of Ireland.

Water and wastewater streams from different sectors have very different properties, such as volume, concentration of nutrients and levels of suspended solids, which influence the types of technologies that can be applied for P recycling. This also influences the economics of nutrient recovery. P recovery is not well developed in many sectors, although some outputs from nutrient management are currently being marketed, for example struvite. Nevertheless, commercial opportunities do exist for the recovery and recycling of P from both the wastewater and the agri-food sectors.

Informing policy

The findings from this research suggest that legislation needs to move away from "removal" only and towards "recovery", to stimulate the adoption of the P circular economy on the island of Ireland. P reuse and recovery needs to be incentivised and value chains need to be developed to promote uptake. Further research is needed to develop markets and value chains for recovered P products. The current market situation for primary sources of P means that recovery processes are economically viable only at large scale. This could, however, be offset by factors around security of supply, future EU legislation around permissible cadmium levels in fertiliser products, and the production of "blended" fertilisers, which contain a proportion of recycled P product. Ireland should consider setting a target (in terms of both percentage reduction and date) for reducing P imports. The findings suggest a robust justification for the establishment of an Irish Nutrient Sustainability Platform (www.nutrientsustainability.ie), to engage the public and private sectors in the development and implementation of nutrient (and co-recoverable resource) management and value chain development.

Developing solutions

Research is required on the agronomic value of recycled P products across the Irish agricultural sector and on methodologies to stabilise nutrient levels in agri-food wastes to produce new innovative fertiliser products that perform, in terms of yield, comparably to traditional chemical fertilisers. The development of alternative formulations of slow-release fertiliser encapsulated with recovered P and nitrogen should also be considered. In utilising recovered products as fertilisers (or other commercial products), the presence of microbiological, chemical and physical contaminants requires evaluation. Increased on-farm soil testing, adoption of nutrient management tools and uptake of recovered product fertilisers across the agricultural community should be encouraged by working in association with regional farmer's unions and associations, both assisting, and learning from, the farming community with respect to nutrient management and the improvements that could be made therein. Knowledge transfer with regard to P loss mitigation practices across the Irish farming sector is key. Finally, investment in both research into and the application of anaerobic digestion-based biorefinery processes is needed to deliver "value-added products" in addition to methane.

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