The Phos4You partnership December 2021

Final report of the Phos4You partnership: deploying phosphorus recycling from wastewater in North-West Europe

www.nweurope.eu/phos4you

EGLV Lippeverband

Interreg North-West Europe Phos4You

Final report of the Phos4You partnership: deploying phosphorus recycling from wastewater in North-West Europe

RECOVER	*INTEGRATE*	*ENGAGE WITH*
Phosphorus	**P-materials**	**Stakeholders**
from wastewater	into value chains	on the market

edited by

LIPPEVERBAND
Ploteau, Marie-Edith; Althoff, Anke; Nafo, Issa; Teichgräber, Burkhard

Impressum

This report was prepared by the partners of the Phos4You project, funded through INTERREG VB North-West Europe programme (2014-2020) under the grant NWE292.

DOI number: https://doi.org/10.17185/duepublico/75173

This digital report is available for download at: www.nweurope.eu/phos4you

Please cite this report and its contributions as follows:

Ploteau Marie-Edith, Althoff Anke, Nafo Issa, Teichgräber Burkhard, “Final report of the Phos4You partnership: deploying phosphorus recycling from wastewater in North-West Europe”, December 2021, edited by LIPPEVERBAND, DOI n°10.17185/duepublico/75173

and

Individual chapters are to be cited by naming the authors listed in each case.

Editor: LIPPEVERBAND
Kronprinzenstrasse 24
45128 Essen
Tel: +49 201 1040
www.eglv.de

First edition

December 2021

Essen (Germany)

List of contributors

Ploteau, Marie-Edith[1]
Althoff, Anke[1]
Blöhse, Dennis[1]
Nafo, Issa[1]
Bogaczyk, Dirk[1]
Léonard, Angélique[2]
Pfennig, Andreas[2]
Shariff, Zaheer[2]
Leleu, David[2]
Groslambert, Sylvie[2]
Chantrain, Gaspard[2]
Daumer, Marie-Line[3]
Bioteau, Thierry[3]
Thiriet, Pierre[3]
Coquery, Marina[3]
Le Guédard, Marina[3.1]
Harrington, Joe[4]
Barnett, Denise[4]
Power, Niahm[4]
Siddiqui, Asif[4]
O´Donnell, Ciaran[4]
Egan, Aoife[4]
Mahler, Matthias[5]
Cairoli, Dario[5]
Nättorp, Anders[5]
Jutz, Maurice[5]
Michels, Evi [6]
Robles-Aguilar, Ana Alejandra[6]
Bogdan, Aleksandra[6]
Meers, Erik[6]
Escudero, Ania[7]
Reichelt, Lena-Dorothea[7]
Pahl, Ole[7]
Helwig, Karin[7]
Teedon, Paul[7]
Roberts, Joanne[7]
Hunter, Colin[7]
Bremner, Barbara[8]
Pap, Szabolcs[8]
Taggart, Mark[8]
Mébarki, Cédric[9]
Vedrenne, Fabien[9]
Schmelz, Karl-Georg[10]
Klein, Daniel[10]
Zepke, Frank[11]
Klose, Siegfried[11]
Ruijter, Josien[12]
Sijstermans, Luc[13]
Wubben, Jeroen[14]
Kennedy, Tamsyn[15]
Baran, Anna[15]

[1] Lippeverband, [2] Université de Liège, [3] Institut national de recherche pour l’agriculture, l’alimentation et l’environnement, [3.1] ADERA-LEB Aquitaine, [4] Munster Technological University, [5] Fachhochschule Nordwestschweiz, [6] Universiteit Ghent, [7] Glasgow Caledonian University, [8] Environmental Research Institute, The North Highland College, University of the Highlands and Islands, [9] Veolia, [10] Emschergenossenschaft, [11] EuPhoRe GmbH, [12] HVC Group, [13] Slibverwerking Noord-Brabant, [14] HHSK, [15] Scottish Water

Picture credit on first page: Till Möller † /LIPPEVERBAND

Interreg North-West Europe
Phos4You

Abstract in four languages (EN, DE, FR, NL)

[EN] To encourage phosphorus (P) recycling from wastewater, the objectives of the INTERREG VB North-West Europe project Phos4You were 1) to prove technologies that recover P from wastewater, 2) to showcase possible values chains to reuse the recovered P materials, 3) to prepare pathways for the deployment of P-recycling in urban and rural territories.

Phos4You partners cooperated across region to demonstrate the effectiveness of P-recovery technologies on different streams of the wastewater treatment. This included demonstrators in large urban and industrial areas, as well as in rural settings. The quality of the materials recovered from the demonstrators was evaluated through practical and scientific assessment. For the assessment of the product quality, as well as for the life cycle assessment of processes, different methodological approaches were applied and compared. In addition, alongside the technical demonstrations, partners prepared scenarios for the deployment of P-recycling in several urban regions. In the more rural regions, stakeholders engagement activities were carried out to ascertain potential for deployment. Complementing these activities, a GIS-tool was developed to support the P-recovery related decision-making process. Significantly, the partners interacted with stakeholders, particularly those invested in incorporating the recovered P-materials into the value chains. Cross-sectoral exchanges, enabled through the nutrient platforms at European and national levels, provided essential clarification of the changing legal framework.

The tested processes proved to be technically feasible and ready for further upscaling. The recovered P-materials (and by-products) basically satisfied end users´ requirements for further integration into the identified value chains. The available quantity of each ‘product’ is very likely to influence decisions about local, regional, or international valorisation pathways. The detailed scenarios (or business cases) prepared in German, Dutch and Swiss regions lays the groundwork for future steps towards implementation by the operators of WWTP or SSIP. The solutions proposed for recovering P at small-scale WWTP were technically successful but their deployment in rural, remote and island areas remains subject to further stakeholders engagement. The GIS-based tool enables an interactive exploration of spatial datasets related to sewage sludge and P-recovery.

Based on lessons learned and experiences across the region, the Phos4You partnership have proposed recommendations on policies and on methodologies (LCA, quality assessment) aimed mainly at decision-makers, funding bodies and standardisation bodies at European and/or national levels.

[DE] Um Phosphor (P) Recycling aus Abwasser zu fördern, hatte das INTERREG VB Nordwesteuropa Projekt Phos4You folgende Ziele: 1) Technologien zur Rückgewinnung von P aus Abwasser zu erproben, 2) mögliche Wertschöpfungsketten zur Wiederverwendung der P Rezyklate aufzuzeigen, 3) die Umsetzung von Phosphorrecycling in städtischen und ländlichen Gebieten vorzubereiten.

Die Phos4You-Partner arbeiteten regional zusammen, um die Wirksamkeit von Technologien zur Phosphorrückgewinnung in verschiedenen Abwasserströmen zu demonstrieren. Dazu gehörten Demonstrationsanlagen in urbanen, industriellen Gebieten sowie in ländlichen Gegenden. Die Qualität der aus den Demonstrationsanlagen zurückgewonnenen Materialien wurde durch praktische und wissenschaftliche Untersuchungen bewertet. Sowohl für die Bewertung der Produktqualität als auch für die Ökobilanz der Prozesse wurden verschiedene methodische Ansätze angewandt und verglichen. Zusätzlich zu den technischen Demonstrationen haben die Partner Szenarien für Phosphorrecycling in verschiedenen urbanen Regionen ausgearbeitet. In den ländlicheren Regionen wurden partizipative Aktivitäten mit Interessengruppen durchgeführt, um das Umsetzungspotenzial zu ermitteln. Ergänzend dazu wurde ein GIS-basiertes Instrument entwickelt, um den Entscheidungsprozess zur Phosphorrückgewinnung zu unterstützen. Die Partner kooperierten insbesondere mit den Interessengruppen, die in die Einbindung der Phosphor Rezyklate in Wertschöpfungsketten investieren. Der sektorübergreifende Austausch, ermöglicht vor allem durch die Nährstoffplattformen auf europäischer und nationaler Ebene, war wichtig zur Klärung des sich ändernden Rechtsrahmens.

Die getesteten Verfahren erwiesen sich als technisch machbar und sind für ein weiteres Hochskalieren geeignet. Die Phosphor Rezyklate (und Nebenprodukte) erfüllten im Wesentlichen die Anforderungen der Endnutzer für die weitere Einbindung in die identifizierten Wertschöpfungsketten. Die verfügbare Menge jedes "Produkts" hat Einfluss auf die Entscheidungen über lokale, regionale oder internationale Verwertungswege. Die erstellten Szenarien für deutsche, niederländische und Schweizer Regionen bilden die Grundlage für künftige Schritte durch die Betreiber von Kläranlagen oder Klärschlammverbrennungsanlagen. Die vorgeschlagenen Lösungen für die Rückgewinnung von P in kleinen Kläranlagen waren technisch erfolgreich, aber ihre Einführung in ländlichen, abgelegenen und Inselgebieten ist noch von der Einbeziehung weiterer Interessengruppen abhängig. Das GIS-basierte Instrument ermöglicht eine interaktive Erkundung räumlicher Datensätzen zu Klärschlamm und Phosphorrückgewinnung.

Auf der Grundlage der in der Region gewonnenen Erkenntnisse und Erfahrungen formulierte die Phos4You-Partnerschaft Empfehlungen zu Maßnahmen (Politik) und Methoden (Ökobilanz, Qualitätsbewertung), die sich vor allem an Entscheidungsträger, Finanzierungsstellen und Normungsgremien auf europäischer und/oder nationaler Ebene richten.

[FR] Pour encourager le recyclage du phosphore (P) à partir des eaux usées, les objectifs du projet INTERREG VB Europe du Nord-Ouest Phos4You étaient 1) de prouver l'efficacité des technologies de récupération du P à partir des eaux usées, 2) de présenter les filières possibles pour l´utilisation des matières phosphatées récupérées, 3) de préparer le déploiement du recyclage du P dans des territoires urbains et ruraux.

Les partenaires de Phos4You ont coopéré entre régions pour démontrer l'efficacité des technologies de récupération du phosphore depuis différents stades du traitement des eaux usées. Cela inclut des démonstrateurs adaptés à de grandes zones urbaines et industrielles, ainsi qu'au milieu rural. La qualité des matières récupérées à partir des démonstrateurs a été évaluée de façon pratique et scientifique. Pour l'évaluation de la qualité des produits, ainsi que pour l'analyse du cycle de vie de procédés, différentes approches méthodologiques ont été appliquées et comparées. En outre, parallèlement aux démonstrations techniques, les partenaires ont préparé des scénarios pour le déploiement du recyclage du P dans plusieurs régions urbaines. Dans les régions plus rurales, des activités de mobilisation des parties prenantes ont été menées afin d´appréhender le potentiel de déploiement. En complément de ces activités, un outil SIG a été développé pour soutenir le processus de prise de décision lié à la récupération du phosphore. Afin de progresser au mieux, les partenaires ont été en permanente interaction avec les acteurs des filières de valorisation des matières phosphatées récupérées. Les échanges intersectoriels, facilités par les plates-formes “nutriments” aux niveaux européen et national, ont permis de clarifier le cadre juridique et ses évolutions.

Les procédés testés se sont avérés techniquement réalisables et prêts à être appliqués à une échelle plus large. Les matières phosphatées (et les sous-produits) récupérées ont généralement satisfait aux exigences des utilisateurs, pour pouvoir être intégrées dans les filières identifiées. Les quantités disponibles de chaque "produit" sont très susceptibles d'influencer la decision portant sur une valorisation en filière locale, régionale ou internationale. Les scénarios détaillés (ou *business cases*) préparés dans les régions allemandes, néerlandaises et suisses jettent les bases des futures étapes de mise en œuvre par les opérateurs de stations de traitement des eaux usées ou d´usines d´incinération des boues. Les solutions proposées pour récupérer le phosphore dans les petites stations d'épuration ont été techniquement efficaces, mais leur déploiement dans les zones rurales, éloignées ou insulaires reste soumis à la mobilisation des acteurs. L'outil basé sur le SIG permet une exploration intéractive d´un grand nombre de données spatiales liées aux boues d'épuration et à la récupération du phosphore.

Sur la base des enseignemets tirés et des expériences dans la région, le partenariat Phos4You a proposé des recommandations sur les politiques et les méthodologies (ACV, évaluation de la qualité), principalement à l´intention des décideurs, des organismes de financement et des organismes de normalisation aux niveaux européen et/ou nationaux.

[NL] Om de inzet van fosfor (P) recycling uit afvalwater te stimuleren, waren de doelstellingen van het INTERREG VB Noordwest-Europa-project Phos4You 1) om het bewijs te leveren van technologieën om P uit afvalwater terug te winnen, 2) om mogelijke waardeketens te demonstreren om de teruggewonnen P-materialen te hergebruiken, 3) om de inzet van P-recycling in stedelijke en landelijke gebieden voor te bereiden.

Phos4You-partners werkten samen om P-recovery-technologieën uit verschillende stromen van de afvalwaterbehandeling in een echte omgeving te demonstreren. Dit omvatte toepassingen van installaties in grote stedelijke en industriële gebieden en op landelijke locaties. De kwaliteit van de teruggewonnen materialen van de demonstratieprojecten werden, geëvalueerd door middel van praktische en wetenschappelijke beoordelingen. Voor de beoordeling van de productkwaliteit, evenals voor de levenscyclusbeoordeling van de processen, werden verschillende methodologische benaderingen toegepast en vergeleken. Bovendien hebben partners tijdens de technische demonstratieprojecten scenario's opgesteld voor de inzet van P-recycling in verschillende stedelijke regio's. In de meer landelijke regio's werden engagementactiviteiten van belanghebbenden uitgevoerd. Aanvullend is een GIS-tool ontwikkeld ter ondersteuning van de P-recovery gerelateerde besluitvormingsprocessen. Over het algemeen hadden de partners een cruciale interactie met de belanghebbenden van de waardeketens van de teruggewonnen P-materialen om daarmee vooruitgang te boeken. De sectoroverschrijdende uitwisselingen die mogelijk werden gemaakt via de nutriëntenplatforms op Europees en nationaal niveau waren essentieel om het veranderende wettelijke kader te verduidelijken.

De gedemonstreerde technologieën bleken allemaal technisch haalbaar en klaar voor verdere opschaling. Ook voldeden de gegenereerde teruggewonnen P-materialen en bijproducten in principe aan de eisen van de gebruikers voor verdere integratie in de geïdentificeerde waardeketens. De beschikbare hoeveelheid is waarschijnlijk bepalend voor de keuze voor een lokaal, regionaal of internationaal valorisatietraject. Met betrekking tot de inzet van P-recycling zijn verschillende scenario's of businesscases intensief voorbereid in de Duitse, Nederlandse en Zwitserse regio's, zodat de volgende stappen voor implementatie kunnen worden gezet door de van afvalwaterzuiveringen en/of zuiveringsslibverbrandingsinstallaties. De oplossingen om P terug te winnen bij kleine afvalwaterzuiveringsinstallaties waren technisch succesvol, maar de inzet ervan in landelijke, afgelegen en eilandgebieden bleef onderhevig aan een sterke behoefte aan betrokkenheid van belanghebbenden. De op GIS gebaseerde tool die werd ontwikkeld, maakte een interactieve verkenning van ruimtelijke datasets met betrekking tot zuiveringsslib en P-terugwinning mogelijk.

Op basis van geleerde lessen en ervaringen formuleerde het Phos4You-partnerschap aanbevelingen over beleid en methodologieën (LCA, kwaliteitsbeoordeling), voornamelijk gericht op besluitvormers, financieringsorganen en normalisatie-instellingen op Europees en/of nationaal niveau.

Executive summary

Background

Whereas technologies to recover phosphorus (P) from wastewater, sewage sludge (SS) or sewage sludge ashes (SSA) do exist, the deployment of phosphorus recycling across the region remains a major challenge. The main drivers for operators of wastewater treatment plants (WWTP) or sewage sludge incineration plants (SSIP) to recover the phosphorus from their waste are: the legal obligation to do so in certain countries, the ambition to optimise technically, and/or economically, their waste management (e.g. lower pipelines maintenance thanks to struvite precipitation; intended cheaper SSA-disposal) and their social and environmental responsibility to act sustainably with non-substitutable resources. The main barriers that constrain rapid deployment of P-recycling are: the financial viability of the implementations; questionable reliability of the technologies due to lack of experiences at full-scale; uncertain market opportunities for the generated products (and by-products) mainly due to legal constraints; the long-term investment needed in 'fixed' technologies that may prevent desirable technological shifts in the future (e.g. investment in a P-recovery unit at a WWTP with aerobic treatment will prevent the development of an anaerobic wastewater treatment system, or an investment in a unit recovering P from SSA will impede development of a carbon based valorisation of the sewage water).

Issues addressed

In the INTERREG VB North-West Europe project Phos4You, the aim of partners was to prepare the way for deployment of phosphorus recovery in urban and rural territories, which obviously face different challenges.

In the urban territories, the focus was reduction of the phosphorus losses induced by mono- or co-incineration of sewage sludge. Depending on the technologies applied, one or several materials may be recovered. The integration of these rather new materials to existing value chains required close cooperation, and testing, with potential users, as well as clarification of the related legal aspects. As well as optimising the technologies used to recover phosphorus from sewage sludge (EuPhoRe®, STRUVIA™ coupled with biological acidification, PULSE) and sewage sludge ashes (REMONDIS TetraPhos®, PARFORCE, Phos4Life™) local demonstrations were provided. The recovered phosphorus materials together with by-products and residues (phosphate salts, SSA with bioavailable P, phosphoric acid, metal salts solutions, road salt and heavy metal containing residues) were assessed with regard to their integration into existing value chains. In addition to the technological findings, inventories and feasibility studies were used to develop concrete scenarios/ business cases that consider regional specificities in terms of transport and disposal infrastructure, availability of required chemicals, and potential market opportunities for manufactured products and by-products.

In rural areas, partners focused on elimination of phosphorus from small wastewater treatment plant in order to reduce, or prevent, the eutrophication of water bodies receiving WWTP-effluent. To avoid additional waste being generated from any new process, integral solutions were developed and tested. The aim being that recovered phosphorus material would have added value, e.g. fertilising properties, that met the needs of local/regional stakeholders. Both aspects were looked at in the project - on one side, technologies recovering phosphorus from wastewater after primary settlement or from the effluent of small-scale wastewater treatment plant were developed (Microalgae photobioreactor, Filtraflo™-P with crab-carapace adsorption material, STRUVIA™ for small-scale WWTP), and on the other, the stakeholders´ acceptance of innovative technologies and new products were appraised (especially for phosphate salts, microalgae and P-rich biomass).

The input of energy and chemicals needed for recovering phosphorus was also considered against global environmental concerns. To this end, a Life Cycle Assessment (LCA) was undertaken for some technologies. In addition, rigorous scientific assessment of the recovered materials and methodological comparisons were carried out as well as practical validation of product quality by fertiliser companies.

Finally, the project Phos4You gave significant importance to interacting with the fertiliser companies to foster the deployment of P-recycling. The ongoing clarification of recent changes in the legal framework was essential and mainly enabled through the cross-sectoral exchanges facilitated by the nutrient platforms at European and national levels.

Main findings

The demonstrated technologies (REMONDIS TetraPhos®, PARFORCE, EuPhoRe®, STRUVIA™ coupled with biological acidification, Microalgae photobioreactor, Filtraflo™-P with crab-carapace adsorption material, STRUVIA™ for small-scale WWTP), all proved to be technically feasible and ready for further upscaling. Even if a technology has been previously validated, the tests with specific waste inputs played an essential and inevitable step in validating the technology, and in refining the mass balance and estimates of investment and operating costs for specific full-scale plants. Mathematical simulation models were developed for some of the technologies and these could support the dimensioning of a recovery plant for a specific sewage sludge input.

The recovered P-materials (and by-products) basically satisfied the quality required by users for further integration into the identified value chains. Depending on the type of product, and its availability in terms of quantity and quality throughout the year, the valorisation will take place through stakeholders with either a regional or an international market outreach, or, in some cases, directly through stakeholders acting locally. The interest of users in the recovered materials was governed by several parameters such as: their price or their gate fee, their P-content, their suitability for integration into existing manufacturing chains, their storage behaviour, their compliance with the legal requirements (including heavy metals content, particle size…) and the amount available. The foreseen component material categories "precipitated phosphate salts and derivates" and "thermal oxidation materials and derivates" in the EU Fertilising Products Regulation 2019/1009 was considered a facilitator to entry into the market of the new recovered streams.

Several Phos4You scenarios and business cases for deployment of phosphorus recycling in urban areas, in German, Dutch and Swiss regions, lays the groundwork for future steps towards implementation by the operators of WWTP or SSIP. In the German case, the multiple-criteria and interdependent decision-making required for the choice of pathway for P-recycling renders the decision process very complex. The high investment necessitates a thorough evaluation of the different scenarios. Close interaction with the stakeholders implied into the P-recycling chain was found to be crucial in assessment of the strengths, weaknesses, opportunities and threats of the possible solutions.

Key-elements in the decision-making process for a P-recycling business plan include: the technical and economic feasibility of the solutions for the selected input streams; the logistical changes induced by their implementation (e.g. consider a shift from road transport to inland waterway or railway to cope with the increased volume to be transported - up to 4 x more mass would need to be transported than the mass of SSA itself if a wet chemical solution is applied to sewage sludge ash); the reliability of solutions for safe/ long-term management of waste; environmental impacts at local and global level; the location of the P-recovery plant (near to input, available reagents, or output materials); the judicial and financial set-up of the P-recycling, the compatibility with future infrastructural developments (way to treat wastewater or valorise sewage sludge in the future), timescale for implementation (legal obligation or not).

The methods used to recover phosphorus at small-scale treatment units were technically successful. Their upscaled deployment in rural remote and island areas remains subject to further stakeholders' engagement and the development of local pathways for valorisation of the recovered materials. The stakeholder analysis and surveys carried out concluded a high level of awareness of the importance of finding alternative sources of P (i.e. recycled), and the need for WWTP developers to implement the necessary changes. To support stakeholders' engagement and decision on P-recovery, a GIS-based tool was developed. It enables an interactive and user-friendly exploration of spatial datasets related to sewage sludge treatment and phosphorus recovery.

The project contributed to a reduction in disparities between the different regions in North-West Europe regarding the tackling of the phosphorus challenge. Collaboration over mutual questions, as well as engaged partners adopting a problem-solving approach to phosphorus recycling, enabled the project to address local issues and related developments, within European context. Although there is heterogeneity in sewage sludge disposal between the EU-countries, a consensus was observed that phosphorus from wastewater should be recycled – either by land spreading or by means of technical recovery.

Recommendations

Based on lessons learned and experiences, the Phos4You partnership have proposed recommendations for decision-makers at European and national levels, as well as for European and national funding bodies, operators/investors and EU standardisation bodies.

The recommendations for the European Union, i.e. the European Commission concerns:

- The regulation (EU) 2018/848 on organic farming:
    - Add phosphate salts to the restrictive list of authorised products and substances which may be used in organic farming as fertilisers, soil conditioners or nutrients:
        - Phosphate salts and renewable calcinated phosphate, as defined in the regulation (EU) 2019/1009 on fertilising products;
        - Algae and microalgae biomass grown on wastewater;
        - P-rich biomass obtained after P adsorption on chitosan/chitin material adsorbent from seafood waste.
- The regulation (EU) 2019/1009 on fertilising products:
    - United Kingdom gets it recognised and implemented;
    - EU COM works to apply harmonised limit values for cadmium content in phosphate fertilisers at Union level and for all members states, based on the lowest existing national values in the EU;

  - Add the *Chlamydomonas* family to the positive list of micro-organisms in CMC 7 that can be used, if they have undergone no other processing than drying or freeze-drying, as microbial plant biostimulant (PFC 6(A));
  - Reconsider the difference of the copper limits between the PFC 1(A), PFC 1(B) and PFC 6;
  - Set up the limits for copper and zinc based on their ratio to P;
  - Authorise liquid soil improver in PFC 3;
  - Consider the addition of the citric acid as solubility criteria in Annex II – Part II (Product specific labelling requirements).
- The Common Agricultural Policy:
  - Member States integrate as agricultural practice, into the eco-schemes developed within their CAP strategic plans the introduction and use of P-recyclates by farmers as part of their production chain.
- The directive 86/287/EEC on sewage sludge:
  - Add the obligation to recover phosphorus contained in sewage sludge (through land application or technical recovery) at EU level;
  - Align the land spreading of sewage sludge to the nutrient availability for the plant cover;
  - Prohibit or reduce the temporary storage of ssa for ulterior P-recovery;
  - Harmonise the legal framework for co-digestion at EU level, i.e. authorise co-treatment of sewage sludge with further substrates to optimise efficiency of recovery processes.
- The Directive 91/271/EEC on Urban Waste Water Treatment:
  - Consider the reduction of the lower limit of 2,000 PE to 500 PE or below, thus reinforcing the implementation of phosphorus removal and recovery from small WWTP.
- The Integrated Nutrient Management Action Plan:
  - Enable it to support knowledge and innovation transfer towards farmers, regarding nutrient and healthy soil management, especially in relation to recovered nutrients.
- Further incentives schemes/policies:
  - Request the blending of a quota of recovered phosphorus from wastewater streams into the composition of fertilising products.

The operators of P-rich installations i.e., sewage sludge incinerations plants or wastewater treatment plants, are recommended:

a) To share the risks with the stakeholders making use of the recovered P materials, generally the fertiliser sector;

b) To reinforce stakeholder's engagement actions, e.g. through contracting.

Regarding the assessment of the quality of recovered P-products, EU standardisation bodies are recommended to:

a) consider use of alternative methods for real-time assessment of P availability, such as Rhizon sampling and biomarkers;
b) include the use of standardised pot trial test for quality assessment of novel P fertilising products;
c) include monitoring of the emerging pollutants in a standardised way;
d) include ecotoxicity analysis as a proof of safety;
e) consider that several microbial colonies other than the one defined in the legislation were detected, and that their inspection may be advisable to ensure the safety of the novel P fertilising materials.

Regarding Life Cycle Assessment of P-recovery processes, EU standardisation bodies are recommended to:

a) Establish a methodological approach for sludge-based products to increase the comparability of studies aimed at quantifying the environmental impacts of these products. A *Product Category Rules* type document seems to be the most suitable to define a methodological framework for the environmental analysis of sludge-based products. This methodological framework will have to define among other things the functional unit, the boundaries of the studied system as well as the methodological approach used to take into account the wastewater treatment plant.
b) Develop a characterisation factor for phosphorus that takes into account the geographical disparity of world reserves as well as the geopolitical risks related to supply. This characterisation factor would allow a more correct consideration of the risks of phosphorus supply for Europe during environmental assessments related to this nutrient.

The EU and national funding bodies are recommended to:

a) Support the full-scale implementation of P-recovery units and the further development of P-recycling solutions, applicable for high and low phosphorus concentration;
b) Support construction of technical capacities to include P-recyclates into the production chains e.g. of fertilising products;

c) Develop economical models and incentive schemes to foster the blending of recovered P into the existing fertiliser production.

Further, EU and national funding bodies are recommended to enable applicants to:

a) Run pilot tests for the use of recovered P in another sector than the fertiliser one, for example in technical applications or in animal feed products;
b) Further explore qualities and effectiveness of the resultant P products to establish effect on water/ soil/ plant systems;
c) Carry out large scale study on supply and demand of different sources of phosphorus (e.g. ssa, H_3PO_4).

Finally, the EU and national funding bodies are recommended to support projects that:

a) Promote the benefit of P-recyclates by end-users, and foster a positive image of P-recycling based on scientific evidence;
b) Foster open mindedness in decision making and encourage a cultural shift by end-users to accept P recovered products from wastewater sources;
c) Support local collaboration between concerned public and private stakeholders and universities, for research and implementation of new technologies and development of effective and safe P products.

Acknowledgments

This work has been possible thanks to the support of many colleagues from the partners organisations involved in, associated to and external to the Phos4You project. The authors express their gratitude to the INTERREG VB North-West Europe Programme (2014-2020) for having trusted the partnership with the achievement of the project and co-funded the financial effort out of the European Regional Development Fund.

Acronyms and Abbreviation

ADWO	Ordinance on Avoidance and Disposal of Waste (ADWO) *in Switzerland*
AG	Canton Argovia *in Switzerland*
AR	*Aqua regia*
ASH1	Sewage sludge ashes from AshDec technology used in the quality assessment works (batch 1)
ASH2	Sewage sludge ashes from EuPhoRe® two-step process used in the quality assessment works (batch 1)
Ash3_FB	Sewage sludge ashes from PyroPhos technology used in the quality assessment works (batch 2)
ASH2.2RK_PI	Sewage sludge ashes obtained by partial running of the rotary kiln EuPhoRe® two-step pyrolysis/incineration process used in the quality assessment works (batch 2)
BAU	Business As Usual
BioP1_MA	Microalgae biomass obtained by the photobioreactor growing *Chlamydomonas acidophila* used in the quality assessment works (batch 2)
BioP2_CCP	Crab carapace phosphate obtain with the Filtraflo™-P reactor used in the quality assessment works (batch 2)
BL	Canton Basel country *in Switzerland*
BMEL	Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz
Bord Bia	Irish Food Board
BR 2	Bray 2
BS	Canton Basel city *in Switzerland*
CA	Citric acid
CACL	0.01 M Calcium chloride
CCM	Crab Carapace Material
CCP	Crab carapace phosphate
CIT	Cork Institute of Technology (*turned into MTU*)
CIWEM	Chartered Institution of Water and Environmental Management
CMC	Compound material category
CNS	Carbon, Nitrogen and Sulphur dry combustion analysis
C_{org}	Organic carbon
COVID	COVID-19 (Coronavirus SARS-CoV-2)
DK	Deponieklasse
DM	Dry Matter
DPP	Deutsche Phosphor Platform (*German Phosphorus Platform*)
DüMV	Düngemittelverordnung (*German Fertiliser Ordinance)*

DüV	Dünger-Verordnung *(Fertiliser regulation in Switzerland)*
EG	Emschergenossenschaft
ERI	Environmental Research Insitute
ESPP	European Sustainable Phosphorus Platform
EU	European Union
EU COM	European Commission
FeP	Iron phosphate dried sludge used in the quality assessment works (batch 1)
FHNW	Fachhochschule Nordwestschweiz
FPR	Fertilising Products Regulation *in the EU*
GIS	geographic information system
GCU	Glasgow Caledonian University
GM	Growing medium
HAP	Hydroxylapatit
HHSK	Hoogheemraadschap Schieland and Krimpenerwaard
HRMS	High-Resolution Mass Spectrometer
HVC	HVC Groep
IFOAM	International Federation of Organic Agricultural Movements
INMAP	Integrated Nutrient Management Action Plan
INRAE	France's National Research Institute for Agriculture, Food and Environment
IRSTEA	Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture *(merged into the INRAE)*
ISO	International Organization for Standardization
KOH	Kaliumhydroxid
LAP	Landelijk Afval Plan - *National Waste Management Plan in The Netherlands*
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LV	Lippeverband
MA	Mineral acids extraction
MBM	Meat and Bone Meal
MSWI	Municipal solid waste incineration
MTU	Munster Technological University
MW AR	Microwave digestion *aqua regia*
MW NA	Microwave digestion nitric acid
NAC	Neutral ammonium citrate
OPEX	Operational Expenditures
ORRChem	Chemical Risk Reduction Ordinance *in Switzerland*

P-salts	Phosphate salts
PAH	Polycyclic aromatic hydrocarbons
PBR	Photobioreactor
PC/DGDG	Phosphatidylcholine/ Digalactosyldiacylglycerol
PCB	Polychlorinated biphenyls
PCR	Product Category Rules
PE	Population Equivalent
PFAS	Perfluorinated Alkyl Substances
PFC	Product Function Category
PNRW	Die Umsetzung der Anforderungen der Klärschlamm-Verordnung zur Phosphorrückgewinnung in Nordrhein-Westfalen
POP	Persistent organic pollutants
Psalt3_CL	Chemically leached phosphorus salt using the PULSe process used in the quality assessment works (batch 2)
Psalt5_BL	P salts (HAP) obtained with the Struvia™ process combined with biological acidification used in the quality assessment works (batch 2)
Psalt4_SL	Calcium phosphate obtained with the Struvia™ process applied at small WWTP used in the quality assessment works (batch 2)
PSG	Project Steering Group
PUE	Plant Use Efficiency
QuEChERS	Quick, Easy, Cheap, Effective, Rugged, and Safe
r	Pearson's correlation coefficient
RAE	Relative Agronomical Efficiency
SBR	Sequencing batch reactor
SIP	Sludge incineration plant
SME	Small and Medium Enterprise
SNB	N.V. Slibverwerking Noord-Brabant
SO	Canton Solothurn *in Switzerland*
SS	Sewage Sludge
SSA	Sewage Sludge Ashes
SSIP	Sewage Sludge Incineration Plant
STRLQ	Struvite recovered from liquid phase of sewage sludge (liquor) using Ostara´s P-recovery technology used in the quality assessment works (batch 1)
STRSL	Struvite recovered from sewage sludge using Aquafin’s P-recovery technology used in the quality assessment works (batch 1)
SW	Scottish Water
TC	Total carbon
TN	Total nitrogen
TSP	Triple Superphosphate

UGent	Ghent University
ULiège	Liège University
UWWTD	Urban Waste Water Treatment Directive
VBSA	Association of Operators of Swiss Waste Recycling Plants
WWTP	Wastewater Treatment Plant
wwtw	Wastewater treatment works
WG	Working Groups

Contents

List of figures

List of tables

1 Introduction

Author: Marie-Edith Ploteau (Lippeverband)

The biochemical cycle of phosphorus (P) has been retained as one of the planet boundaries - those being defined as "scientifically based levels of human perturbation of the Earth System beyond which the Earth System functioning may be substantially altered" (Steffen et al. 2015). The transgression of the boundaries at the subglobal level affects the Earth system at the global level. Figure 1.1.1-A shows that large parts of Europe are beyond the zone of uncertainty (high risk) regarding the P-cycle.

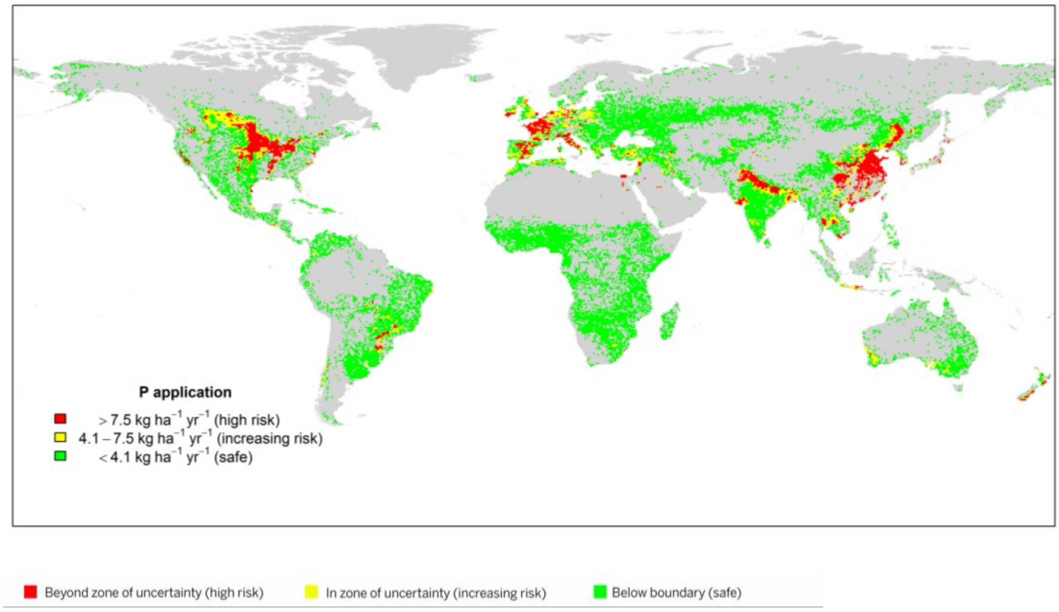


Figure 1.1.1: The subglobal distributions and current status of the control variables for biogeochemical flows of P [...] In each panel, green areas are within the boundary (safe), yellow areas are within the zone of uncertainty (increasing risk), and red areas are beyond the zone of uncertainty (high risk). Grey areas [...] are areas where P [...] fertilisers are not applied (Steffen et al. 2015, modified)

In this context, a framework at EU level considers phosphorus management as a critical issue. Eutrophication of freshwater systems (Steffen et al. 2015; European Environment Agency 2018), lack of exploitable resources of mineral P (COM(2014) 297 final; COM(2017) 490 final; COM(2020) 474 final), significant pressure of urban wastewater on EU water bodies in regard with sources of P (Pistocchi et al. 2019; UWWTD 91/271/EEC), limited understanding of the behaviours of contaminants of emerging concern in sludge and in soil when the sludge is reused in agriculture (SWD(2019) 700 final) and the loss of phosphorus resources through landfill of sewage sludge ashes (Krüger and Adam 2014) are all of the P-related concerns in the European Union.

Water authorities are one of the stakeholders that can contribute to improved management of the P cycle. The deployment of phosphorus recycling from wastewater could act as substitute to mined rock phosphate and processed P-fertilisers (Huygens et al. 2019) thus enhancing the sovereignty of Europe regarding P supply, and supporting the implementation of the circular economy in the EU.

The partners involved in the INTERREG VB North-West Europe project Phos4You joined forces to explore various technologies to recover the phosphorus contained in wastewater at the different stages of its treatment. They evaluated the quality of the recovered phosphorus materials, assessed the life cycle assessment of processes, identified P-recycling routes, and prepared the pathway for deployment of P-recycling in urban and rural areas. All tasks were performed considering transferability of results.

1.1 Background: legal, technical, political framework of phosphorus recovery in North-West Europe.

Operators of municipal wastewater treatment works and sewage sludge incineration plants face increasing requirements regarding phosphorus elimination, disposal of sewage sludge and recovery of phosphorus resources. To better understand how all this might be achieved, the Phos4You project investigated recovery and recycling of the phosphorus that is currently present within wastewater treatment systems.

The evolution of the legal frameworks between the project start, and end date, have confirmed the project´s relevance.

In the field of sewage sludge management, several countries have adopted a mandatory P-recovery. For example, operators of wastewater treatment plants located in Germany need to ensure, from 2029, the recovery of phosphorus from sewage sludge and sludge incineration ash (if the sewage sludge has a phosphorus content of 20 grams or more per kilogram of dry solids). At least 80 % of the phosphorus contained in the ashes is to be recovered. In case of recovery from sewage sludge, either 50 % of the P is to be recovered or the level of P in the sludge after recovery should decrease below 20 gram per kilogram of dry solids. In parallel, the land application of sewage sludge will be restricted from 2029 to WWTP with a capacity of less than 100,000 PE, and from 2032, to WWTP with a capacity of less than 50,000 PE (AbfKlärV). In Switzerland, the land application of sewage sludge is already forbidden (since 2006) and the mandatory phosphorus recovery will be implemented from 2026 (Abfallverordnung, VVEA). At least 50 % of the phosphorus contained in the process input (sewage liquor, sewage sludge or sewage sludges ashes) is to be recovered by 2026 (Bundesamt für Umwelt BAFU 2020a). The vision of a 75 % P-recovery rate has been postponed to 2036 (Bundesamt für Umwelt BAFU 2020b).

In other countries, the sewage sludge legislation does not foresee a mandatory P-recovery, but circular economy principles invite stakeholders to recycle nutrients. In the Netherlands, the regulatory requirements (Koninkrijk der Nederlanden 1991) have prevented all use of sewage sludge in agriculture since 1995. There is no obligation to recover phosphorus from wastewater. Nevertheless, there have been successive national commitments involving water authorities, end users and sector organisations to implement the recovery of phosphorus (Ketenakkoord Fosfaatkringloop 2011; Tweede Kamer der Staten-Generaal 2011; Green Deal Grondstoffen 2014). The phosphorus recycling ambition has been endorsed in the government programme (A Circular Economy in the Netherlands (2016)) aiming to speed up the transition to a circular economy in the Netherlands. There are several research projects which aim to recover different materials like phosphate, bioplastics, alginate, cellulose, etc. (also at European level, such as the WOW! Project (Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH 2020)). The national waste plan (LAP of Ministry of Infrastructure and Water Management 2019) supports such developments but only on the condition that these do not lead to more landfilling (of the residues) as one of the most important goals is to minimise the amount of landfilled material.

Similarly, Flanders has prohibited sewage sludge spreading in agriculture since 1999. Disposal of sewage sludge goes through incineration and co-incineration in cement industry with heat recovery (EurEau 2016). Driven by the principle of circularity, especially the reuse of sludge and materials as stated in Flemish regulation (Vlaams Reglement betreffende de Milieuvergunning 1995), Aquafin aims to incinerate all dewatered sludge from 2026, mostly by mono-incineration, with focus on the recuperation of phosphorus along with production of energy and heat (Aquafin NV 2020). In Ireland, the national wastewater sludge management plan identifies a need for alternative processes to reduce the dependence on agricultural land, being the almost exclusive end-use outlet for wastewater sludge (Irish Water 2016). To ensure the environmental sustainability of such alternatives, the recovery of the phosphorus nutrients should be considered. Similar approaches apply in France and Wallonia, especially where the land availability for sewage sludge spreading is limited.

Focusing on fertilisers, the adoption of the Fertilising Products Regulation at the EU level (EU FPR 2019/1009) is a major step towards the recycling of phosphorus materials recovered from wastewater. This regulation, which comes into force mid-2022, confers End-of-Waste status and enables a product to be sold and exported freely across the European market. To obtain the CE-Mark, compliance with all relevant rules of this regulation is needed: component and product requirements, conformity assessment procedure, REACH registration (some materials), labelling requirements. The addition of the component material categories "precipitated salts and derivates" as CMC 12 (European Commission 2021a) and "thermal oxidation materials and derivates" as CMC 13 (European Commission 2020a), both including sewage sludge as input materials, are further steps towards fostering entry into the market of phosphorus-rich materials recovered from wastewater and related streams. At national level, some revisions of the fertilisers regulations have also led to new requirements regarding fertilising products, and their use, as well as to new opportunities for recovered P materials (Bundesministerium für Ernährung und Landwirtschaft 2017; Schweizerische Bundesrat 2005).

Concerning phosphorus removal at wastewater treatment works, the European Commission launched a public consultation on the revision of the Urban Waste Water Treatment Directive (European Commission 2021d; UWWTD 91/271/EEC) to address areas of concern identified in the evaluation realised by the Joint Research Centre (Pistocchi et al. 2019; SWD(2019) 700 final). One area identified is: small agglomerations or non-connected dwellings having significant pressures on 11 % of the EU's water surface bodies. Solutions to remove phosphorus from these places are needed if the European Directive is to be extended to such areas in the future. Solutions to eliminate P in a form that can be easily recycled makes sense in these areas. At some national levels, the need to address eutrophication issues has been retained in new guidance for P mitigation, such as for Scottish lochs that suffer from high phosphorus levels (Scottish Environment Protection Agency (SEPA) 2017).

Further initiatives and action plans embedded in European Green Deal (COM(2020) 98 final) are relevant for the recycling of phosphorus in the EU: the Farm-to-Fork strategy, the Biodiversity strategy, a sustainable Common Agricultural Policy, several climate action initiatives, a cross-sectoral EU algae initiative, a new circular economy action plan, an integrated nutrient management action plan (COM(2020) 381 final; COM(2020) 380 final, European Commission 2021g, 2021b, 2021e; COM(2020) 98 final). Recognizing excess of nutrient as a source of pollution and climate impacts, "the Commission will act to reduce nutrient losses by at least 50 %, while ensuring that there is no deterioration in soil fertility. This will reduce the use of fertilisers by at least 20 % by 2030". A successful achievement will integrate the recycling of organic waste into renewable fertilisers.

1.2 Objectives of the Phos4You project

The objectives of the cooperation project Phos4You were the following: to demonstrate that phosphorus recovery from waste water is technically feasible; to showcase that value chains to reuse the recovered P materials exist and are ready to accept these new streams; to prepare the pathway for deployment of phosphorus recycling in urban and rural territories. Phosphorus recycling from wastewater faces several challenges. Firstly, the P-recovery processes need to be technically efficient for different and variable quality of inputs. Secondly, the P recovered materials must satisfy a high range of quality criteria (given by industry players and/ or within the legal frameworks) that can be assessed through diverging methods, especially in a transnational context. Thirdly, the implementation of a full-scale P-recovery unit must match with specific local requirements including potential regional or transregional cooperation but also long-term strategic planning.

By delivering the objectives, with each successful demonstration of P-recovery technologies, a scale up to the next technical level can be achieved. The samples of recovered P materials can be used to make quality assessment tests through the industry or through research institutions. The data gathered can be used to progress Life-Cycle Assessment of P-recycling processes, although this is an aspect which faces methodological challenges. By elaborating possible business plans, the operators implementing the P-recovery from wastewater gain knowledge of the strategic issues that need to be considered within the decision-making process. The implementation of P-recovery demonstrators at WWTP and the quality assessment of new recovered P materials also enhance the staff capability of wastewater treatment works operators, enterprises, research institutes and universities in the field of nutrient management.

1.3 Scope of document

This report documents the works achieved within the project lifetime of Phos4You and highlights key aspects for the deployment of phosphorus recycling based on experiences gained within the project. It shares 1) lessons learned through the implementation of the phosphorus recovery demonstrators under real life conditions, 2) interactions developed with the fertiliser sectors and further end-users to integrate recovered P materials within existing value chains and 3) steps realised towards the deployment of P-recycling in urban and rural context.

Specifically, the following aspects of the project are discussed:

- *Overall set up of the project*: including the intention of the main work packages and the complementarity in the partnership;
- *Lessons learned based on demonstration of new phosphorus recovery solutions*: here the focus is given to the lessons learned. The precise description of the P-recovery processes, and the results of the experiences obtained with the implementation of the demonstrators are given in the technical report of Phos4You (Ploteau et al. 2021);
- *Value chains for recovered P materials and their quality assessment*: this part presents possible value chains and business models that have been identified for the P materials coming out of the processes demonstrated within Phos4You. The specificity of the quality assessment of such materials is highlighted, as a synthesis of the large report dedicated to the quality assessment activities achieved within the project (Bogdan et al. [in press]);
- *Prepared territorial deployments of P-recycling in urban context*: the approaches developed for Switzerland, for The Netherlands and for Emscher-Lippe Region are presented;
- *Prepared territorial deployments of P-recycling in RRI locations:* Scottish and Irish initiatives are discussed, along with the benefit of GIS-based Decision Support Tool developed within Phos4You;
- *Conclusions and recommendations:* based on results, lessons learned and experiences of the project, recommendations are made to policy makers, standardisation bodies, research and funding bodies (mainly at a European level), as well as for operators of WWPT and SSIP.

2 Overall set up of the project

Author: Marie-Edith Ploteau (Lippeverband)

2.1 Work Packages overview

The project was carried out over a five-year period, officially from September 2016 to March 2022. To reach objectives, the activities have been split up in three main work packages, in addition to the management and communication (list of the communication tools generated by Phos4You is available in Appendix A).

The Figure 2.1.1 gives the overview of the work packages.

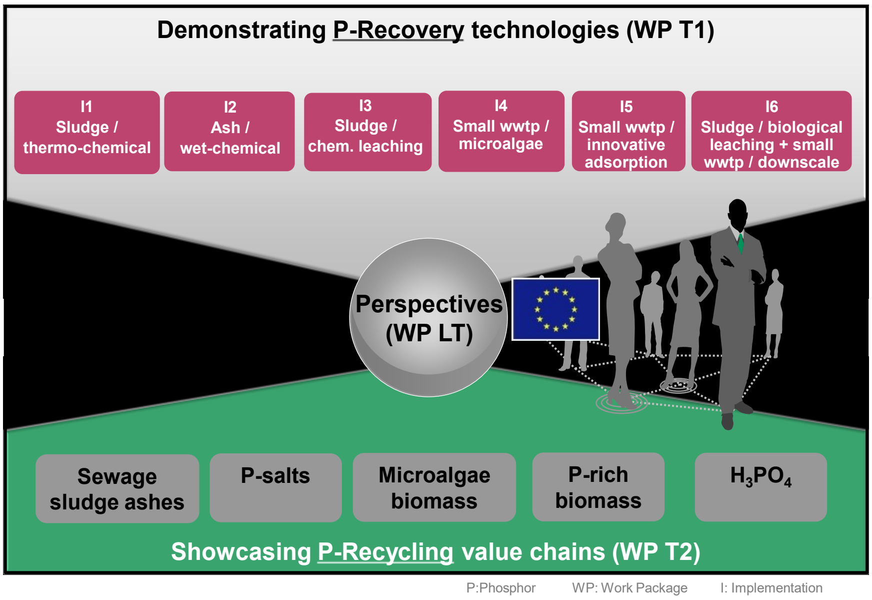


Figure 2.1.1: Overview of the work packages of Phos4You (Ploteau 2016, modified)

The work plan followed the "*Processes, Products, People*" Scheme.

In the first technical work package (WP T1) six *processes* to recover phosphorus from wastewater have been looked at. Based on existing research findings, the partners further developed (and adjusted) each process using to laboratory experimentation, design plans and authorisation protocols to end up with seven demonstrators. Once set up at different locations, partners started to make the proof of the concept for each by operating the demonstrators under real life conditions.

In a second technical work package (WP T2), the partners explored and showcased how the *products* made with the recovered phosphorus materials can be integrated into existing value chains.

In the long term-effects work package (WP LT), partners focussed on the preparation of concrete scale-up of technology and business plans that investigated practical and reasonable implementation of phosphorus recycling options for each country or region. Interactions with the range of associated stakeholders - from the technical, legal and administrative sides - have been consistent throughout the project, and together with wide ranging communication activities, have ensured that the Phos4You works served the *people* living in North-West Europe.

2.1.1 WP T1: demonstrate technological P-recovery

For the technical demonstration of P-recovery, seven processes were selected. Three processes recovered the phosphorus from sewage sludge: one thermochemical process (I1) which produced sewage sludge ashes rich in bioavailable phosphorus, and two processes precipitating phosphate salts - one after chemical dissolution of P (I3) and the other one after a biological leaching of P (I6.1). Wet-chemical processes (I2) that recovered phosphorus from sewage sludge ashes were also explored, at the location of the process providers. The three other processes, set up as pilot plants, addressed the potential for P-removal from small-scale wastewater treatment works with the aim of producing a material directly usable for fertiliser purposes. Two of them used effluent from WWTP as input (I5 and I6.2), whilst I4 used microalgae to investigate secondary and tertiary treatment of wastewater.

For the most advanced processes, Life Cycle Assessment and Life Cycle Costing were carried out. The selected methodological approaches were the multifunctional system and the avoided burden.

2.1.2 WP T2: showcase integration of recovered P materials in value chains

Recycling pathways were identified (based on information from stakeholders), for each of the five categories of materials that came from the demonstrators of Phos4You. The intention was to describe pathways that fit with the new EU Fertilising Products Regulation (EU FPR 2019/1009). The possible stakeholders involved in each P-recycling route were mapped.

To assess end-product quality, stakeholders from the fertiliser sectors were invited to test the recovered P materials according to their own requirements. End users acting at a worldwide level as well as at a regional level were involved. This allowed the diversity of possible recycling pathways to be addressed. In addition, the quality of the recovered materials has been extensively tested by the universities and research institutes involved in the project. For each of the quality criteria, several methodologies were compared. The assessed criteria included the bioavailability of phosphorus, the inorganic and organic content, and the ecotoxicity of the novel P containing materials. These methodological findings are the basis for recommendation towards a new European standard regarding quality assessment of P recycled products.

2.1.3 WP LT: prepare deployment of P-recycling in urban and rural context

In the long-term work package, business cases for urban and rural regions were prepared. Various perspectives were followed. In the Emscher-Lippe Region, the perspective of a water authority responsible for the wastewater treatment in a region was taken. In The Netherlands, the perspective of the operators of the sewage sludge incineration plants was explored. In the Swiss context, a more global reflexion in association with most of the Swiss operators of SSIP, was carried out. For the Irish and Scottish contexts, where P-recovery topic is newer than in the beforementioned countries, stakeholder engagement initiatives played a key role. GIS-based tool developed within the project was directly used to support the decision making.

To interact with the range of stakeholders involved in recycling value chains across the region, the Phos4You partnership was active in national and European nutrient related platforms. Interaction with those platforms was a useful way to transfer results and findings to national authorities in charge of the revision of the concerned legal frameworks, and to transfer knowledge between North-West European countries.

2.2 Complementarities in the partnership

The partnership selected to achieve the project objectives was well balanced. It included organisations working alongside the value chains of the phosphorus recovery and recycling. Twelve full partners from seven countries (Swiss, Germany, The Netherlands, Belgium (Flanders and Wallonia), UK/Scotland, Ireland and France) were financially involved in the project and sought to address the phosphorus challenge in North-West Europe. To advise the partnership during the implementation and ensure direct knowledge transfer, a further 25 organisations were associated to the partnership.

Organisations having phosphorus resources were represented by water authorities, operators of wastewater treatment plants and operators of sewage sludge incineration treatment plants. Organisations potentially interested in using the recovered P materials (or by-products) were involved via worldwide or regional stakeholders of the fertiliser sectors and the cement sector. P-recovery process owners were involved in the technical implementation of recovery. For advisory purposes, lobbying and knowledge transfer, the nutrient platforms became closely associated with the project. The scientific support of the project was ensured through the contribution of various universities and research institutions. The joint works between the organisations were punctuated by regular meetings as listed in Appendix B.

3 Lessons learned from the demonstrations of new phosphorus recovery solutions

Seven P-recovery processes were demonstrated during the Phos4You project. The Table 2.2.1 presents key data of the different demonstrators.

Table 2.2.1: List of the Phos4You demonstrators, including their key data (Ploteau et al. 2021, modified)

ID	Input material	Process name	Principle	P-recovery rate	Location (main phase)	Respon-sible partner	Capacity range (PE)	Operation timeframe
I1	Sewage sludge	**EuPhoRe®**	Thermo-chemical sewage sludge treatment	90 – 98 %	Germany	Emscher-genossen schaft – EuPhoRe GmbH	3850 PE	2019 Aug - 2021
I2	Sewages sludge ashes	**TetraPhos®, PARFORCE, Phos4Life™**	Leaching extraction from ssa	>80 %	Germany/ Spain	Lippe-verband	2050 PE*	2018 Mar - 2021
I3	Sewage sludge	**PULSE**	Leaching extraction from sewage sludge	60 – 70 %	Belgium	ULiège	500 PE	2020 Aug - 2021
I6.1	Sewage sludge	**STRUVIA™ optimised with bio-acidification**	Biological acidification and precipitation	50 %	France	INRAE & Veolia	1000 PE	2019 Mar - 2020 Jan
I4	Wastewater	**Microalgae *Chlamydomonas acidophila***	Microalgae growth for P-removal & recovery at small WWTP	50 – 75 %	UK/Scotland	GCU	5 PE	2018 Jul - 2019 Dec
I5	Wastewater	**Filtraflo™ P with chitosan-calcite adsorbent**	Adsorption/filtration using seafood by-product for decentral P-removal at small WWTP	60 %	UK/Scotland	ERI - Veolia	10 PE	2020 Jan - 2020 Feb
I6.2	Wwtp effluent	**STRUVIA™**	Precipitation with CaP for decentral removal at small WWTP	60 %	Ireland	MTU - Veolia	60 PE	2019 Dec - 2021 Jan

*for REMONDIS Tetraphos® and PARFORCE processes

As main outcomes, it can be stated that the seven applications were technically viable and worthy of further development and/ or implementation. This conclusion is deeply supported by the technical report of the Phos4You partnership that focusses on processes (Ploteau et al. 2021).

The following sections presents succinctly the main lessons learned from each proof of concept of the technologies demonstrated in Phos4You. All experimental details and findings are reported in the beforementioned report. The LCA approach implemented to improve the eco-design of the processes is also included there.

3.1 Demonstrator I2: Acid extraction of P from SSA (REMONDIS TetraPhos®, PARFORCE, Phos4Life™)

Authors: Dennis Blöhse, Issa Nafo (Lippeverband)

As presented in the Phos4You technical report (Blöhse and Nafo 2021), the Lippeverband has tested three different wet-chemical processes for the production of phosphoric acid from sewage sludge incineration ash:

- REMONDIS TetraPhos® process;
- Phos4Life™ process;
- PARFORCE process.

The three processes differ in the use of distinct digestion acids for the elution of the phosphates bound in the ash. In addition, the process steps used to purify the crude phosphoric acid (eluate) are different. Here, various process steps that are as selective as possible are used to separate the impurities. Essentially, in these purification steps, the following accompanying substances which also go into solution in addition to phosphorus, must be separated from the crude phosphoric acid.

- Macro in % range - calcium, iron, aluminium, potassium, magnesium and sodium
- Micro in ppm range - nickel, copper, manganese, zinc, lead and chromium.

The absolute concentrations of phosphorus as well as the accompanying substances in the eluate (crude acid) depend largely on the use of water in washing-step via separation of the ash residue as well as the dilution water of the eluent.

The elution rates with the differently used eluents (hydrochloric, sulfuric, phosphoric acid) of the abovementioned accompanying substances are in comparable order of magnitude. However, it also became apparent that there is considerable potential for optimisation, in particular by adapting the elution step to different ash compositions.

The by-products generated during the purification step can be primarily divided into calcium-based and Fe-/Al-based by-products. In addition, silicate-based residuals (ash residues) are produced, as well as occasional residuals for heavy metal removal.

Main finding with EGLV ashes: In principle, ashes with low P content and high influence of industrial dischargers can also be treated in a target-oriented manner. However, an excessive share of industrial sewage sludge is a big challenge and leads to increased efforts. The requirements of the German legislation with more than 80 % recovery rate could be met with all tested processes as well as ashes, even if adjustments of the processes are necessary in case of challenging SSA composition (high industrial share).

In general, it can be stated that the composition of the ash is of particularly good quality if there is a high P content as well as low Ca content and low Fe/Al content. This increases the yield of phosphoric acid, reduces the specific use of mineral acid and the cleaning effort as well as the mass of by-products. Possible approaches to optimise the ash composition can already be made at the wastewater treatment plant. In this context, the use of precipitants such as Fe/Al salts should be critically examined: possible overdosing can thus be avoided.

The resulting calcium-based by-products (gypsum and road salt) are low in pollutants and can be recycled in the appropriate industries.

The Fe/Al solutions can in principle be reused as precipitants at wastewater treatment plants - this is particularly advantageous if P-recovery takes place at the site of a wastewater treatment plant. In this case, the following points must be considered and, if necessary, further detailed questions must be clarified:

- In the case of centralized treatment of SSA, the amount of active substance generated by the Fe/Al solutions produced may (depending on size) exceed the requirements of a large-scale wastewater treatment plant, so that distribution to additional wastewater treatment plant sites becomes necessary.
- With regard to possible contamination with accompanying substances (e.g. heavy metals), guideline values of relevant guidelines (e.g. DWA-A 202 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2011)) should be used to determine the requirements for the purity of the precipitants.

- Due to the process, the Fe/Al solutions have lower concentrations of active substance than the precipitant products normally used in wastewater treatment plants. In case of distribution to other WWTP sites, the transportability should be checked.

Further treatment to increase the concentrations of active substance as well as to reduce possible accompanying substances may be necessary depending on the quality of the generated by-products and on the requirements of applicants. The requirements should also be coordinated in advance with the competent authorities. Furthermore, the requirements of EC Regulation No. 1907/2006 of 18.12.2006 (REACH) must be complied with [DWA-A 202] (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2011). Finally, in each individual case, preliminary lab-tests (e.g. jar test) as well as practical tests at the WWTP must be carried out to determine the extent to which the Fe/Al solution can be directly reused as a precipitant in the wastewater treatment plant.

The phosphoric acid produced can be generated in different qualities. Adjustment of the acid quality to meet demand appears feasible. The requirements must be clarified with the respective customers. Higher revenues for the production of high-quality products must cover the technical effort (possible further processing steps).

In advance, the individual process steps from elution to separation of the accompanying substances as by-product and residual material - as listed above - have to be adapted to the composition of the ash.

During elution, the elution time and the acid dosage must in particular be adjusted. In the subsequent separation of the accompanying substances, depending on the concentration of the co-eluents in the area of selective separation processes (extraction, ion exchange, electrodialysis), adjustments can be made, for example, by selecting the extraction/re-extraction agent.

Finally, wet chemical processes also offer potential for further development in order to recover additional substances in a targeted manner. The production of usable calcium-, iron-, aluminum-containing by-products is already achieved at the existing stage of development. The recovery of further substances appears conceivable as soon as they are available in dissolved form after the elution step. In this way, other valuable materials such as zinc and copper can also be integrated into the recycling process.

3.2 Demonstrator I1: Thermochemical solution to recover P from sewage sludge (EuPhoRe®)

Authors: Daniel Klein, Karl-Georg Schmelz (Emschergenossenschaft); Frank Zepke, Siegfried Klose (EuPhoRe GmbH)

Generally, the EuPhoRe® technology is suitable to transfer dewatered or pre-dried sludge into a low carbon sewage sludge ash (SSA), which, after grinding and dust binding, could directly be used as a fertiliser or as a raw material for the fertiliser industry. Nevertheless, the correlations of input material, technical settings of the plant (e.g. with regard to temperature gradients and additive dosing) and output quality still need to be elaborated into more details. The already known analysis results show that the temperature influence and the level of additives have a significant influence on the product quality. Given the wide variety of input qualities in the Emschergenossenschaft and Lippeverband area, the demonstration of the technology (demonstrator I1) focused mainly on these aspects.

In order to achieve a stable, continuous operation, the initial plant setup had to be modified and optimised. These modifications were mainly related to the (extremely) small size of the plant and its "pilot plant" character that asked for various plant-specific aggregates (and solutions) which were implemented and tested for the first time within the context of a sludge incineration plant. After having successfully modified the pilot plant, the EuPhoRe® technology could be operated as expected.

It could be shown that the EuPhoRe® technology is capable of converting sewage sludge directly in a SSA that is in accordance with the relevant limits[1] of the German Fertiliser Ordinance (DüMV) and thus, into a fertiliser or raw material for fertiliser industry. Due to the aforementioned delays in plant operation, the results could yet be confirmed for one specific type of input material, i.e. a municipal sludge with notable industrial influences, originating from a large scale WWTP.

With regard to the intensity of the heavy metal depletion, the influence of the temperature in the rotary kiln could clearly be shown. This mainly affects elements such as Ni, Cu and Zn whose volatilisation strongly depends on temperature. As mentioned

[1] The requirements on solubility criteria for recycling phosphate are expected to be modified within a revision of the DüMV as recommended by the Scientific Advisory Board for Fertilisation Issues (BMEL 2020.)

before, all elements could be reduced below the relevant limits of the DüMV. Since the temperature reached in the reactor was still below 1.000 °C (as it would be intended in a large scale EuPhoRe plant), it can be estimated that the technology is suitable for sludges with a higher heavy metal content as well.

The phosphate-containing ash produced by the EuPhoRe® process had the typical red-brown color of sewage sludge ashes, which is due to the iron oxide. The residual carbon content was most of the time below the detection limit at < 0.5 % carbon (C). Fine agglomerates are created that can be easily ground (Figure 3.2.1).

Figure 3.2.1 a and b: Physical appearance of the ashes coming out of the EuPhoRe® process (© Emschergenossenschaft/ Picture: L. Pamuk)

With regard to the influence of the additive dosing, it could clearly be shown that additives such as $MgCl_2$ are needed to volatilise some heavy metals. The exact correlation between additive dosing (e.g. 3 % or 6 % of $MgCl_2$ per DM input) and heavy metal removal still needs to be established.

The analyses showed that different additive concentrations have an influence on the heavy metal reduction rate. In future trials, the reduction rates for different additives and different additive concentrations are to be examined.

In addition to the heavy metal reduction, the suitability of the ash as fertiliser (or fertiliser raw material) could be demonstrated in several pot trials.

The analyses of the EuPhoRe-SSA produced with the demonstrator in Dinslaken showed high solubility: from 70 % to 90 % of total P content (as defined e.g. by *aqua regia*) for 2 % citric acid and > 60 % for neutral ammonium citrate solubility (LUFA Nord-West 2020-2021). Further results are underway.

3.3 Demonstrator I6.1: Bio-acidification before P precipitation from sludge (optimised Struvia™)

Authors: Marie-Line Daumer (INRAE);
Fabien Vedrenne and Cédric Mébarki (Veolia)

The demonstrator was combining bio-acidification for sludge phosphorus dissolution and precipitation with STRUVIA™ reactor either as magnesium salts (struvite) that can be used directly as mineral fertilisers or as calcium phosphate for entering formulation of organic or mineral fertiliser (Figure 3.3.1).

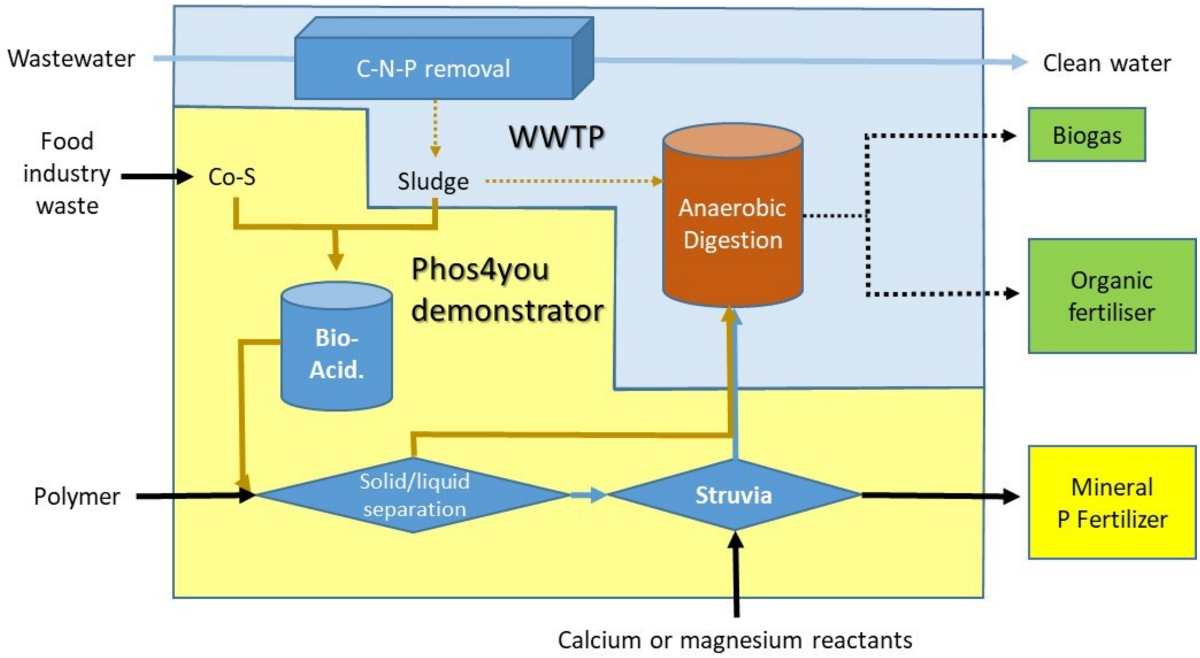


Figure 3.3.1: Implementation of the bio-acidification process in WWTP

This demonstrator has been implemented in two different WWTP. The first one was a big one (600,000 PE) located in an urban area and using both enhanced biological P-removal and aluminium salts for P-removal. The second one was a small WWTP (32,000 PE) located in a rural area with calcareous soils. Iron salts were used for P- removal in the SBR tank for carbon and nitrogen removal.

Before each demonstrator implementation, lab-scale experiments were performed to choose the best sugar rich product that could be used as co-substrate among several products and food industrials waste available, and to define the process parameters such as waste/sludge ratio, temperature, hydraulic retention time…

In the aim to increase the recovery potential from sewage sludge, some other lab-scale trials were performed to define the best strategy for iron removal and recovery. Synergies between P-removal and other sludge valorisation routes such as hydrogen or high value molecules were also considered.

The main conclusions as in Daumer et al. (2021) are listed below.

- The feasibility to reach the target of more than 50 % of P-recovery rate, either from sludge coming from WWTP combining EBPR and chemical P-removal even with aluminium salts, or from chemical P-removal using Iron salts, was proven at industrial scale.
- This process can be applied on a large range of WWTP (size and P-removal technologies).
- On an economical and environmental point of view, it is better to use a sugar rich waste available in the surrounding of the WWTP to obtain bio-acidification (low cost and no environmental impact of the co-substrate).
- The best location for the P-removal process is between the sludge dewatering and the anaerobic digestion.
- The combination of bio-acidification and Struvia allows to increase the biogas production of the plant (x2), balancing the cost of the process. This figure obtained at lab-scale has to be confirmed on a continuous anaerobic digester. It could not be performed yet because of the interruption of the trials due to COVID.
- The hydraulic retention time is short (24-48 hours) compared to anaerobic digestion and does not penalise the sludge valorisation process.
- From an economical point of view, a product acceptable for organic fertiliser formulation is more appropriate than a pure product whose production cost is too high.
- Depending on the quality of the product required, metal removal is not mandatory.
- If required, iron could be easily removed from the liquid phase by resins before P crystallisation. However, iron recovery from the resins is not economically interesting. Thanks to a literature review, other ways to recover iron have been identified and have to be tested to allow re-using iron in the WWTP.
- Electricity and polymer consumption have the highest environmental impact in the process and could probably be optimised.

- The experiments have shown that the combined bio-acidification/P-recovery process could be moved into a dark fermentation/P-recovery process if hydrogen or fatty acids would be the targeted products for sludge valorisation (Bareha et al. 2020).

3.4 Demonstrator I3: Acid leaching of P from partially/fully dried sewage sludge (PULSE)

Authors: Zaheer Shariff, David Leleu, Andreas Pfennig and Angélique Léonard (ULiège)

The demonstrator I3 of the PULSE process was operated with sludge from Germany, Belgium and Scotland. The overall P-recovery in the different trials was between 50 % and 70 %. The upper limit is determined by the fraction of inorganic P present, which can be increased e.g. by digestion. A chemical equilibrium tool was developed in MATLAB in order to simulated the solid-liquid-liquid equilibria of the different unit operations of the PUSLE process (Shariff et al. 2020). The tool was validated using lab-scale experiments and then used to optimise the operating parameters of the pilot trials so that the number of lab-scale experiments performed for process optimisation were considerably reduced. The comparison of the results between the pilot trials and the chemical equilibrium tool show a good correlation.

It was found that the drying of sludge did not influence the P-recovery efficiency compared to wet sludge. But drying of sludge offers advantages such as ease of material handling, storage of sludge without causing change in the properties of material or odor nuisance and reduction of the volumes that have to be treated downstream. A major advantage of sludge drying is that the filtration of leached solids after leaching is much easier as compared to filtration of solids after leaching of wet sludge. The major factor limiting the maximum P-recovery in the PULSE process was the dissolution or leaching of P from the sludge. The PULSE process makes use of acidic leaching to dissolve P from the sludge. Acidic leaching is mostly able to dissolve the inorganic P whereas the organic P remains incorporated in the solids. Different acids and pH were tested to study the leaching of P from the sludge and it was found that the type of acid used had no visible effect and only the pH of leaching was important. The pH required for leaching was dependent on the P and metal content of sludge. Since Fe_3PO_4 is only soluble at a very low pH, the oxidation state of Fe and its concentration is critical in determining the leaching pH. In case dried sludge, about 50 % or more of the Fe content in the leach liquor was present as Fe^{3+}. The efficiency of P-recovery could further be improved by enhancing the inorganic fraction of P by digestion of sludge or by using sludge produced by chemical precipitation. Also here dying is beneficial, because it reduces the amount of acid needed to reach a defined pH for leaching.

The PULSE process includes a solvent extraction step in order to extract the undesired metals and heavy metals into the organic phase. During solvent extraction, the concentration of metals Fe, Cd, Hg, Pb and Zn was reduced by 80 to 99 % depending on the phase ratio in a 2-stage counter-current operation and Cu concentration was reduced by 50 to 70 %. The change in P concentration of the leach liquor was negligible during extraction. The stripping of metals from the solvent was possible with alkaline ammonia solution. The efficiency of stripping was more than 85 % for all the metals in a single stage. During stripping, a metal precipitate is obtained, which can be separated from the aqueous stripping solution by filtration or settling. The solid precipitate consists of 50 % or more iron and therefore it is further possible to valorise the metals. Due to the precipitating solids, use of a horizontal mixer settler for stripping of metals is not ideal as it leads to flow problems in the settler and therefore a vertical settler may be more suitable. Due to the inclusion of solvent extraction in the P-recovery process, the PULSE process can be used to treat sludges to recover P which have high concentrations of the abovementioned metals.

For precipitation of P in leach liquor as calcium phosphate salts in the PULSE process, both $Ca(OH)_2$ and NaOH was used. It was found that pH between 5 to 6 was sufficient to precipitate essentially all P in the leach liquor.

Figure 3.4.1: A - PULSE product filter cake dried; B- granulation tests on PULSE product performed by Prayon S.A (Shariff et al. 2021)

Samples of PULSE product from the pilot trials of the different sludges were analysed by Prayon. Analysis revealed that unwashed product samples (Figure 3.4.1, A) had high concentration of Cl and Na and the P_2O_5 content ranging between 17 – 30 %. The washed samples of the same product had significantly lower Cl content and Na content also the P_2O_5 content increased to between 25 to 33 %. Therefore, washing of the final product resulted in removal of the soluble salts such as Cl^- and Na^+ and improved the P_2O_5 content. Granulation tests for the PULSE product were also performed by Prayon (Figure 3.4.1, B). The PULSE product was crushed and granulated in the typical manner that is normally used by Prayon for fertiliser production. It was concluded that the PULSE product responded well to granulation and the final form was comparable to the conventional fertiliser.

3.5 Demonstrator I4: Microalgae to recover P from small-scale WWTPs

Authors: Ania Escudero, Lena-Dorothea Reichelt, Ole Pahl (GCU)

Recovering P from small, and possibly remote, wastewater treatment plants presents several challenges as suitable systems require robustness, low maintenance and ability to cope with often high variability of P concentrations in wastewater. Scotland is considered as 97 % rural with around 1600 WWTP of a capacity lower than 500 PE, most of them concentrated in the northern part of the country. A large part of eutrophication is caused by the insufficient treatment of wastewater in septic tanks and small wastewater treatment plants (Bunce et al. 2018, pp. 1–15; Scottish Environment Protection Agency (SEPA) 2017).

The extremophilic microalgae *Chlamydomonas acidophila*, which grows at a pH of 2-3, appears to have potential for P- recovery at these sites, as it is able to recover P and N in different wastewaters at a rate of around 7 mg $L^{-1}d^{-1}$ and 9 mg $L^{-1}d^{-1}$, respectively. Furthermore, this species is mixotrophic so the presence of organic carbon in the effluent improves its nutrient recovery efficiency. One of the limiting factors in microalgae technology is light availability and *C. acidophila* has shown to require a very low light intensity to grow (40-113 µmol photons $m^{-2}s^{-1}$). Light intensity is usually the limiting factor in microalgae technology, as it contributes to higher energy consumption, cost and carbon footprint.

Additionally, the presence of micropollutants such as pharmaceuticals in urban wastewater could inhibit biological treatment processes. Here *C. acidophila* has been shown to be a resistant species as it is able to grow and consume nutrients in the presence of pharmaceuticals 1000 times higher in concentration than the ones reported for these effluents (Escudero et al. 2020a).

Different experiments were carried out in order to optimise the scaling-up of this process: On the one hand the microalgae process control parameters were studied to optimise P-recovery and cell growth efficiency; on the other hand, different reactor designs were studied for this specific microalga. These data are shown in full in the Phos4You Technical Report (Escudero et al. 2021).

Based on the results obtained from our trials, a proprietary photobioreactor (PBR) (Greenskill Environmental Technology Ltd.) was selected for implementation at Scottish Water's Wastewater Development Centre in Bo'ness, Scotland (Figure 3.5.1), as it appeared to be the most suitable for the operation of the acidophilic microalgae process. Settled municipal effluent (after primary treatment) was selected for the trials due to its higher NH_4^+ and COD concentrations (1-5 mg P-PO_4^{3-} L^{-1}, 12-33 mg NH_4^+ L^{-1}, 0.3-1.3 mg NO_3 L^{-1} and 90-215 mg COD L^{-1}). This was deemed beneficial to the requirements of the microalgae as well as harbouring the potential benefit of replacing secondary (aerobic) digestion at small treatment works.

Figure 3.5.1: 500L Photobioreactor (PBR) implemented at the Wastewater Development Centre in Bo'ness (Escudero et al. 2021)

The PBR's central unit consisted of a 500L tank fed with settled effluent at a hydraulic residence time (HRT) of 2.0 - 3.8 days. The microalgae biomass was retained in the PBR by a tangential flow filter utilising hollow fibre membranes. The tank was continuously illuminated at a low rate equivalent to 0.4 Ampere electrical current.

The microalgae achieved promising nutrients recovery after a period of acclimatization of around a month, reaching between 50-75 % of PO_4^{3-} and 75-100 % of NH_4^+ recovery under these low light intensities. Most studies on microalgae use final (aerobically digested) effluent to avoid inhibition derived from high concentrations of NH_4^+ and COD in primary effluents and competition with other organisms such as bacteria and fungi present in the wastewater (Luo et al. 2017). However, mixotrophic *C. acidophila* have shown to be able to grow and consume nutrients in primary settled effluent. In our tests, the microalgae removed around 50 % of the COD from the primary effluent, reaching values close to those reported for final effluent after conventional secondary treatment (40 – 60 mg L-1). Therefore, this technology appears to be promising as a secondary-tertiary treatment in wastewater treatment plants. Furthermore, the microalgae biomass did not foam or exhibit biofilm formation neither in the PBR nor in the filter, despite the much higher suspended solids content in the settled wastewater. Therefore, it seems that the tangential flow filter is a suitable option for retaining the cells in the reactor without getting blocked.

Over the course of the experiment, the biomass concentration in the PBR reached values of up to 4g L^{-1} beyond which 10 % of the reactor's biomass was harvested on a weekly basis. The microalgae biomass was harvested by addition of 0.5g NaOH L^{-1} to the supernatant, resulting in a pH of 10, subsequent microalgae floc formation and complete settling in around 5 minutes. The recycled P product was dried and stored for further product quality assessment.

Most advanced wastewater treatment technologies are typically not feasible in rural WWTPs, since these small sites require simple, robust and affordable systems. Based on the results obtained in the 10 months trial in Bo'ness, *Chlamydomonas acidophila* microalgae technology seems to be suitable for these sites as it has shown to be robust (resistant to NH_4^+, COD and several pollutants' concentrations and it did not foam or exhibit biofilm formation), it can be maintained long term as a mono-algal culture (without being invaded by other species, due to operation at low pH values) and it can recover P and N from wastewater with high variability of nutrients. Moreover, *C. acidophila* requires much lower light intensities and temperatures to grow and consume nutrients than other microalgae used for wastewater treatment, which leads to a lower energy consumption by the PBR.

3.6 Demonstrator I5: P adsorption for small scale use (FILTRAFLO™-P with CCM adsorbent)

Authors: Barbara Bremner, Szabolcs Pap, Mark Taggart (ERI)

Habitation and business development in remote, rural locations pose a range of challenges for municipal authorities and regulators as the cost per individual, for services and maintenance of public infrastructure, is high in relation to urban areas. Technologies which offer simple, robust solutions for recovering (and potentially re-using) nutrients from wastewater and other 'waste' sources, in such locations, may provide economic benefits as well as being highly consistent with the principles of a 'circular' economy.

Lessons learned from the implementation of Demonstrator I5, Veolia Water Technologies FILTRAFLO™-P confirm that phosphorus (P) recovery through adsorption (even under low P concentrations) is feasible and cost effective. The FILTRAFLO™-P pilot reactor using CCM adsorbent potentially offers a solution for phosphorus removal in remote areas with variable P- concentrations as the reactor has low energy consumption and is simple to apply. Furthermore, the by-product (P-saturated adsorbent) may also provide a low-cost P-rich product which may be useful as a soil improver.

Materials and methods- lessons

Several natural waste materials were examined for their P- adsorption capacity and characteristics. In experiments, crab carapace, a common waste by-product from seafood industry, showed the highest potential. However, identification of potential low P- bonding indicated that further improvement of the crab carapace (via a thermochemical activation process) was needed to produce a more effective P adsorbent (CCM) (Pap et al. 2020a; Pap et al. 2020b)

- The optimum conditions found for the CCM adsorbent production process were a 1:1 ratio of potassium hydroxide: crab carapace (g/g), with an activation temperature of 105 °C and an activation time of 150 min.
- The produced CCM possessed higher crystallisation, richer surface chemistry, a larger surface area and higher porosity when compared to raw crab carapace.
- Lab-scale studies confirmed P to be effectively adsorbed onto the CCM under slightly alkaline conditions (pH > 7) through mixed mechanisms, which included

mainly inner-sphere complexation (ligand exchange) and microprecipitation (as hydroxyapatite).

Pilot reactor testing-lessons

The FILTRAFLO™-P pilot reactor was tested using the CCM adsorbent at the Scottish Water Horizons Development Centre at Bo'ness allowing trials using influent wastewater, primary/secondary or final effluents from a fully operational WWTP (next door) that routinely employs advanced biological treatment to remove P (amongst other target variables) from wastewater.

Several trial runs were conducted. The use of secondary wastewater effluent (without residual suspended solids) limited fouling of the adsorption bed.

Main conclusions as in (Pap et al. 2021) are listed here:

- High P-removal/recovery potential was achieved in pilot scale WWTP trials even at low P concentrations, bringing the residual P level below 1 mg/L (the EU limit for sensitive water bodies).
- Surface microprecipitation and inner-sphere complexation were postulated as key P adsorption mechanisms in real wastewater effluent trials due to reduced concentrations of Fe, Ca, Cu, Mn and Ca. Also, the high inorganic carbon (carbonate) concentration in treated effluent indicated ligand-exchange through these metals (mainly Ca).
- The slightly increased turbidity noted in treated water (e.g., likely due to magnesium and potassium carbonates) may require integration/combination of the FILTRAFLO™-P unit with slow sand filtration.
- The results showed that the FILTRAFLO™-P unit with CCM could serve as a water polishing unit (with low P concentration effluents) and/or as a P-harvesting unit (where P concentrations were high).
- The P-loaded CCM was amenable to efficient desorption (using 0.5 M HCl or 2 % citric acid), indicating its potential to serve as P rich soil amendment material (wherein the P would not be excessively soluble, i.e., in water alone) (Pap et al. 2020b)
- Future work is required (plant growth trials) to consider P uptake/availability in different soils/crops using the P-loaded CCM.

3.7 Demonstrator I6.2: P precipitation at small-scale WWTPs (downscaled Struvia™)

Authors: Joe Harrington, Denise Barnett, Niahm Power, Asif Siddiqui, Ciaran O'Donnell (MTU); Cédric Mebarki (Veolia)

The Struvia P-recovery Pilot Plant was installed at the Macroom Wastewater Treatment Plant (WWTP) in Ireland. This WWTP represents a typical Irish WWTP in terms of population served, influent type, and treatment processes. The plant has a design load of 5,230 PE, which is typical of many Irish WWTPs with PE ranges of 2,000 to 10,000. The WWTP process comprises of an extended aeration activated sludge plant with preliminary treatment, sludge thickening and dewatering. The WWTP process does not include any P-removal.

The Struvia Pilot Plant was installed to recover P from the treated effluent from the WWTP. The Pilot Plant operation commenced in November 2019 and included the stages of commissioning, steady state operation at a constant pH level, steady state operation at varying pH levels, steady state operation with hydrated lime replaced by recycled calcium products and decommissioning and shutdown in February 2021. The steady state operation at a constant pH was included COVID related pilot plant shutdown for a nine month period.

Detailed testing and analysis was undertaken as part of this work, including on the pilot plant, the influent to and effluent from the pilot plant and on the recovered product.

Full details of the Struvia P-recovery process and its installation and operation and the testing and analysis undertaken and results obtained are presented in detail in the Phos4You Project Technical Report.

The primary technical lessons learned from the operation at the Macroom WWTP may be summarised as follows:

1. Overall, this research has provided significant insight into the effectiveness and the limitations of the Struvia process through installation at the Macroom WWTP.
2. The primary benefits of the Struvia process are its simplicity and flexibility of application; lower demand for chemicals, production of recovered P from wastewater, reduction in P emissions and overall improvement to the environment.

3. The pilot plant operated most efficiently at a pH of 10.8 and less so in the range from 10 to 10.4.
4. The pilot plant has operated successfully at Macroom WWTP, reducing the wastewater PO_4^{3-} content from 4.28 mg/L to 1.70 mg/L, resulting in a removal efficiency of 60.26 %, as shown in the table below.
5. The removal and recovery of phosphorus led to a simultaneous reduction in total nitrogen and COD content of the effluent. The effluent from the pilot plant had an elevated pH and alkalinity, the broader effects of which will require further investigation.
6. The Struvia operation at the Macroom WWTP produced approximately 60 kg of dry recovered calcium phosphate.

Table 3.7.1: Summary of results at pH 10.8

Results	
PO_4^{3-} removal mg/l	2.58
PO_4^{3-} removal %	60.26 %
TN removal mg/l	3.67
TN removal %	17.60 %
Increase alkalinity mg/l	27.42
% increase in alkalinity	50.69 %
COD removal mg/l	34.12
COD removal %	38.72 %
TSS removal mg/l	7.50
TSS reduction	23.15 %
TSS (influent) mg/l	32.34
TSS (effluent) mg/l	24.49

7. A potential issue with the Struvia pilot plant is the lower sludge output, which may be attributed to the relatively low phosphorus content in the WWTP effluent.
8. The average pH of the effluent from the pilot plant was 10.37 (for a pilot plant pH of 10.8). This pH level exceeds the Macroom WWTP Emission Limit Value (pH from 6 to 9) and thus for a full-scale P-recovery plant pH correction would be required.
9. The scale up of the P-recovery process to the full WWTP would involve a total annual lime requirement of approximately 108 tonnes which at a lime cost of € 200 per tonne would yield a total annual lime cost of approximately € 21,500.
10. The results presented for the Struvia Pilot Plant operation at the Macroom WWTP indicate satisfactory pilot plant effluent parameter values (relative to the Emission Limit Values for the Macroom WWTP) for COD, TSS and PO_4^{3-} but not for pH. It

should be noted however that the WWTP influent P values are relatively low and that further test applications of this technology at WWTPs with higher influent P levels would be required prior to making more definitive conclusions on same.

11. Macroom WWTP discharges up to 800 kg of P to receiving waters annually, through effluent discharge. If it were possible to fully implement this recovery process at the Macroom WWTP, for example, it could lead to up to approximately 500 kg of recovered P product (this is presented for illustrative purposes only with a range of assumptions inherent to the estimate).
12. At a national level it is estimated that approximately 1,475 tonnes of P is discharged annually from Irish municipal WWTPs, the application of this technology, for example, at a national level would indicate the potential for P-recovery of over 900 tonnes of P (this is presented for illustrative purposes only and acknowledging that there are a wide range of assumptions inherent to the estimate).

3.8 LCA of phosphorus recovery technologies

Authors: Gaspard Chantrain, Sylvie Groslambert, Angélique Léonard (ULiège)

Throughout the project, life cycle assessments were carried out on the sewage sludge phosphorus recovery demonstrators. The purpose of the LCAs is to quantify the environmental impacts of the different recovery technologies.

The aim of the LCA of these demonstrators was to enable their eco-design by highlighting the most impactful stages of the different processes. Within the framework of this project, the LCAs also permitted a comparison of the environmental impacts of the different phosphorus recovery technologies with the "business as usual" (BAU) production of mineral phosphorus.

Life Cycle Assessment is ruled by the (ISO 14044:2006)and (ISO 14040:2006) standards. Four steps are mandatory: goal and scope definition, inventory analysis, impact assessment, and interpretation.

One of the specificities of the LCA of the demonstrators of the project consisted in the particular status of sewage sludge. Indeed, paper reviews showed that sludge is mainly considered as “waste” or “waste-to-product” sludge. This status allows the use of sewage sludge without any environmental impact, this is called the "zero burden assumption". However, with the development of sludge recovery technologies and the production of high value-added sludge-based materials, this status is being reconsidered. This questioning would lead to placing the status of the sludge between "product" sludge and "waste-to-product" sludge. This is because sludge can be considered as a raw material for the manufacture of sludge-based materials or for energy production. The "(co)product" sludge status would imply a share of the environmental burden of the WWTP between the treated water and the sludge (allocation). The development of such an allocation factor requires the knowledge of certain parameters specific to the treatment plant. These factors are therefore not applicable as a general rule, which is why this allocation method has been abandoned in the framework of a project such as Phos4You, which deals with the development of demonstrators, each of which has its own specificities and is applied to very different treatment plants. Several methodological approaches were used in order to include the sludge production by the wastewater treatment plant in the studied systems. The first is the system expansion method and the second is the avoided burden approach.

3.8.1 Initial methodological approach: system expansion

Initially, the system expansion approach was applied to evaluate environmental impacts of the EuPhoRe®, Struvia™, PARFORC and PULSE demonstrators, in addition to a reference scenario for comparison. This methodological approach considered the environmental impacts of sludge production by including the whole wastewater treatment plant in the system boundaries. The boundaries then included the wastewater treatment plant and the production of phosphorus fertiliser which implied that the whole system was multifunctional (treatment function coupled with phosphorus fertiliser production function). The functional unit of such a system included the treatment of the wastewater (100 m^3) and the production of 1 kg of P_2O_5 fertiliser (from P-recovery in Phos4You demonstrators and/or chemical route). The wastewater treatment is modelled by a large size Belgian WWTP (Liège-Oupeye). The treatment of 100 m^3 of wastewater generates a certain amount of sludge, and its valorisation to recover P is carried out using the Phos4You demonstrators. The valorisation of sewage sludge by the demonstrators produces a quantity of product rich in phosphorus lower than 0.8 kg of P_2O_5 and the complement to obtain 0.8 kg of P_2O_5 comes from the "BAU" P fertiliser production route (chemical). The conventional production of phosphorus fertiliser considered is the production of triple superphosphates (TSP) from phosphate rock attacked with phosphoric acid. This production was modelled using data from the Ecoinvent database. The reference system consisted in the incineration of the sludge together with the chemical production of the totality of the P fertiliser. The choice to consider incineration was motivated by the this practice is widely used in Germany and other countries where direct agricultural spreading of sludge is not allowed.

Remark: 0.8 kg of P_2O_5 fertiliser produced in the Phos4You demonstrators was considered as equivalent to 0.8 kg of P_2O_5 fertiliser produced by the "chemical" BAU route (no information of P bioavailability when the LCA is realised). Other nutriments included in the P-recovery products were also not taken into account because of the lack of data at this point.

The Figure 3.8.1 below illustrates the general boundaries of this first approach of system expansion.

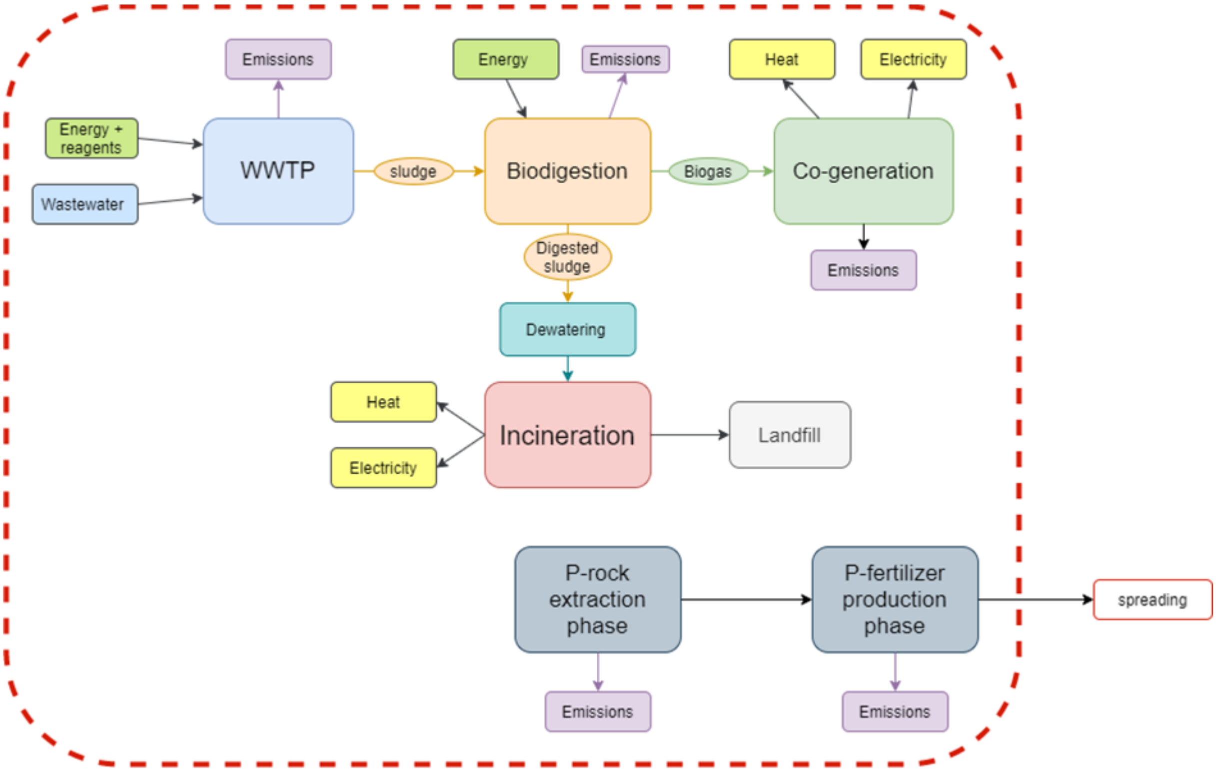


Figure 3.8.1: General boundaries for the LCA (system expansion approach) (Chantrain et al. 2021)

In this figure, the sludge management is replaced by the incineration in the reference case and by the recovery process in the case of the Phos4You process. The schematics illustrating the different cases can be seen in the technical report Phos4You (Chantrain et al. 2021).

Environmental impacts were evaluated with the ReCiPe 2016 method (Huijbregts et al. 2017). Generic data are from Ecoinvent 3.6 database (Wernet et al. 2016), as implemented in Simapro software 9.1 (edveloped by PRé Sustainaibility in the Netherlands).

The study of the environmental impacts according to this first approach made it possible to identify the most impacting stages for each system studied (the details of these analyses can be found in the technical report (Chantrain et al. 2021)). The most impactful elements from an environmental point of view were:

- For the WWTP: direct emissions (to air and to water), energy consumption, sludge treatment.
- For the EuPhoRe process: electricity, chemicals and natural gas (for the starting procedure). One of the specific points of this process is the large environmental benefits of heat recovery.

- For the Struvia process: electricity and flocculant (polymer).
- For the PARFORCE process: use of hydrochloric acid, electricity and heat.
- For PULSE process: process waste treatment, organic solvent regeneration and electricity consumption.

The results for each process are detailed in the project technical report LCA-LCC (Chantrain et al. 2021).

The conclusion for this first approach was that the P-recovery as performed in Phos4You demonstrators have an environmental advantage over the mineral resource depletion category. This advantage comes from the local production of phosphorus, which avoids the use of phosphate rock to produce phosphorus fertiliser. The results on the other environmental categories vary according to the processes studied. However, only the processes EuPhoRe® and Struvia™ were gave environmental benefits regarding the conventional chemical route to produce P fertilisers.

3.8.2 Evolution of the LCA methodological approach: avoided burden

In order to strengthen the robustness of the results and to confirm the conclusions obtained earlier, an environmental assessment was also performed using the avoided burden approach. This method allowed for the consideration of environmental impacts due to the production of sewage sludge. The application of this method consists of studying the impacts of a system including the treatment of a quantity of wastewater and the treatment of the sludge by a phosphorus recovery process and compare them with the impacts of the wastewater treatment coupled with traditional sludge management. The phosphorus-rich products of the different recovery processes are taken into account as avoided mineral fertilisers. The avoided burden is a chemical production of Triple Superphosphate (TSP) from phosphate rocks.

The functional unit of the systems studied was therefore the treatment of 100m³ of wastewater and the treatment of the sludge that is generated.

Figure 3.8.2 below describes the reference case schematically.

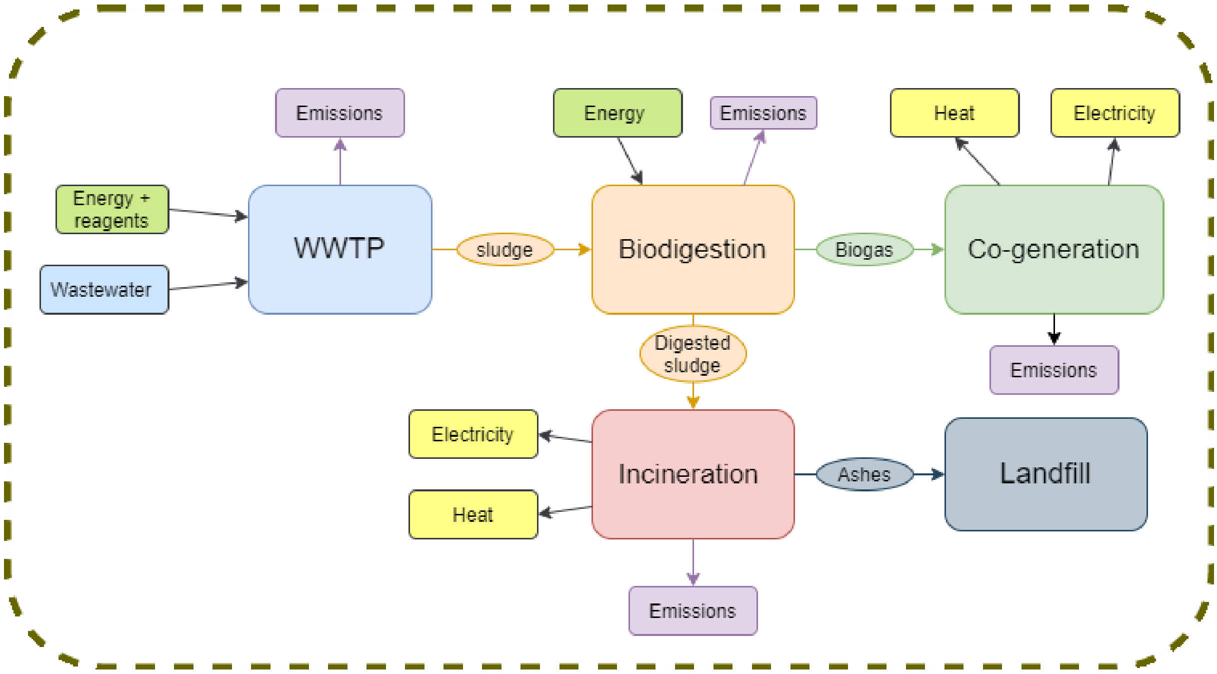


Figure 3.8.2: System boundaries for the reference case with the avoided burden approach (Chantrain et al. 2021)

As shown in the figure above, the reference case includes biodigestion of the sludge with biogas cogeneration and incineration of the digested sludge followed by landfilling of the incineration residues.

Other systems studied include a P-recovery process that is included in the sludge treatment line according to its specificities. The processes studied here are EuPhoRe®, Struvia™, Pulse and PARFORCE. Details of those processes and the systems studied can be found in the technical report of the project. As an example, Figure 3.8.3 shows a schematic description of the system including the EuPhoRe® process. This system replaces the incineration and landfill steps because of its nature (thermochemical treatment with recovery of directly usable P-rich ash).

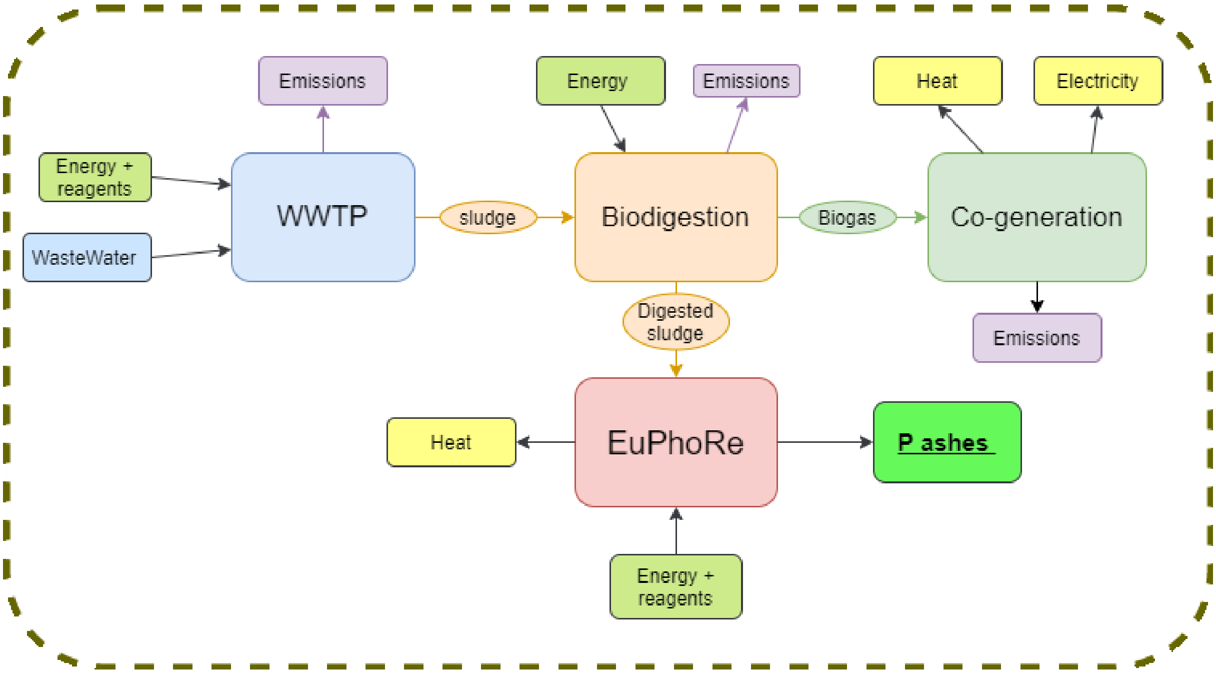


Figure 3.8.3: System boundaries for the EuPhoRe® system with the avoided burden approach (Chantrain et al. 2021)

The assessment of the environmental impacts of each system highlighted the most impactful stages for each recovery process. These stages were:

- For EuPhoRe®: significant environmental benefit due to heat recovery, and the detrimental effect of using electricity and natural gas.
- For Struvia™: negative effect of the use of electricity and polymer (for solid/liquid separation) and increase of the environmental benefit of cogeneration due to the addition of easily degradable co-products during biodigestion.
- For PARFORCE: significant detrimental effects of the use of additives (mainly acid), electricity and heat, and beneficial effect of road salt recovery.
- For Pulse: significant detrimental effects from the use of electricity (mainly for drying), and from the incineration of spent solvent.

This information allowed the formulation of eco-design advices focusing on the most impactful steps of the process. Those advices helped the developers of the demonstrators to identify the best ways to improve their processes from an environmental point of view.

Finally, two sensitivity analyses were performed on the studied demonstrators. The first one focuses on the influence of the electricity mix used for each scenario. Three electricity mixes of 2016 have been studied in this context: Germany, France and

Belgium. The second sensitivity analysis aims at studying the effect of a change in the phosphorus content of the sludge used by the demonstrators. The results of these two sensitivity analyses for each process are developed in the technical report of the project (Chantrain et al. 2021).

The results obtained with the avoided burden method are comparable to those obtained with the system expansion method. The environmental benefit on the category of mineral resources depletion has been shown for all the demonstrators studied. More generally, only the EuPhoRe® and Struvia™ demonstrators seem to have an environmental benefit. This advantage is due to the recovered heat for EuPhoRe® and the low impact of the process coupled with the increased cogeneration benefit for the Struvia™ process.

The environmental advantage provided by all the demonstrators studied on the category of mineral resources scarcity comes from the local production of P-material. This production from sewage sludge allows the avoidance of the exploitation of phosphate rock which is a non-renewable and non-infinite resource. This production also contributes to reduce Europe's dependence on phosphate rock importing countries.

4 Value chains for recovered P materials and their quality assessment

4.1 Possible value chains and business models

Author: Marie-Edith Ploteau (Lippeverband)

Using the processes demonstrated in Phos4You, five type of phosphorus materials have been recovered: sewage sludge ashes, phosphate salts, microalgae biomass, P-rich biomass and phosphoric acid. Possible routes to 'market' for each were identified and portrayed within information sheets (listed in Appendix A). The project focussed on the integration of the recovered materials into CE-marked fertilising products, according to the EU FPR 2019/1009. In addition, stakeholder mapping was included for each material.

Up until now, the recovery of phosphorus from wastewater has primarily been driven by the expectations that the wastewater sector will undertake mandatory P-recovery, and strengthened P-removal as well as by the circularity ambitions of the wastewater sector (see Introduction and EurEau 2021). During the project, a market for recovered materials was positively evaluated and detailed within the STRUBIAS report (Huygens et al. 2019, Chapter 7), but nevertheless, operators preparing the pathway for implementation of P-recovery face large uncertainties in the demand for their products and by-products. At the outset, the choice of a recovery technology needs to carefully consider the generated output materials.

Based on stakeholders' exchanges, the following criteria related to the output streams of a P-recovery technology were identified as essential:

- Diversity of output streams: these vary depending on the P-recovery technology, used i.e., only one entirely recyclable P material may be recovered (microalgae biomass) or several output streams may be generated (e.g. 1) P-salts and P-poor sewage sludge; 2) phosphoric acid, Fe/AL-salts, gypsum/road salts, SSA-residues; 3) SSA with bioavailable P and SSA residues);
- An identified market requirement for the products/by-products at an affordable transport cost: market assessment needs to include the evaluation of the material´s potential to substitute current supply sources, but also to estimate if the volume generated (especially of by-products) can be absorbed by the market;

- Volume produced: can it be used locally or is it valuable enough to be incorporated into a long value chain?
- Need for further transformation/processing steps;
- How easily can the products be stored and transported.

In addition, an analysis of stakeholder mapping is important to ensure the business model is strongly associated with the implementation of the P recycling. A high local variability in terms of key partners (strategic alliances) may be observed. This will directly influence the choice of centralized *versus* decentralised approaches. The risk associated with the choice of a recycling route, and the share of risk among the involved stakeholders, also need to be analysed before decisions are taken.

The following sections present recycling pathways for the phosphorus materials recovered with the processes demonstrated in the project, based on exchanges and experiences made during the Phos4You project.

4.1.1 Sewage sludge ashes

In case SSIP operators do not build their own P-recovery plant, they can contract with fertiliser stakeholders for integration of their sewage sludge ashes into the manufacturing processes of fertilisers. A high phosphorus content, a good bioavailability of the phosphorus, and a low level of contaminants in the sewage sludge ashes will in all cases be an advantage, facilitating post-treatment. Only one stream needs to be considered, which can be delivered to one or several "purchasers" (Figure 4.1.1).

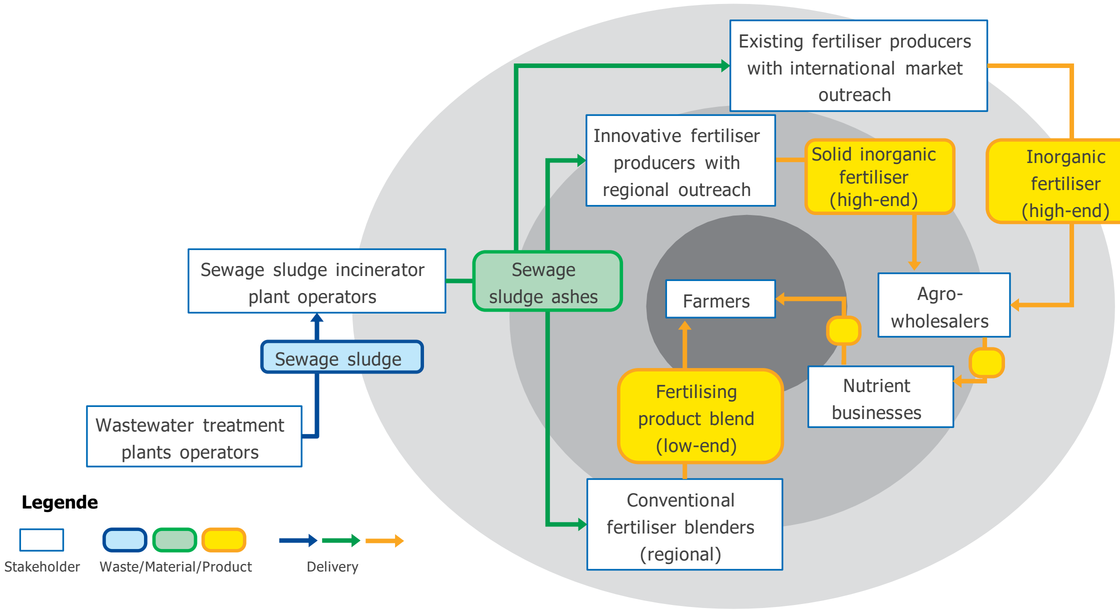


Figure 4.1.1: Stakeholder mapping for P-recycling from sewage sludge ashes (Klose et al. 2020)

Fertiliser stakeholders can make use of SSA for the regional market or for international trade activities. An analysis of the regional demand for phosphate fertilisers will help to define the capacity of that market to absorb the generated volume of ssa. If there is local capacity, it is worth pursuing entry to the short value chain. If not, it would be advisable to go for a business model with an outlet on the international market. This longer value chains involves more stakeholders (agro-wholesalers, nutrients businesses) before reaching the farmers as end-users.

In terms of substitution potential, sewage sludge ashes will only replace a part of mined rock phosphate [2] (Huygens et al. 2019). As a consequence, the risk of placing SSA on the market is only limited by the capacities offered by external providers.

Depending on its quality, and especially on the bioavailability of its phosphorus, the sewage sludge ashes can be either chemically processed or solely mechanically. In both cases, granulation into a high-end product is anticipated, e.g., as inorganic macronutrient fertiliser or as compound solid inorganic macronutrient fertiliser. Through mechanical processing, the SSA (so far considered as straight fertiliser in powder form) can also be simply blended with further products to manufacture a customised fertiliser, directly applicable on soil with usual machinery. Within the Phos4You project test were successfully undertaken with the sewage sludge ashes out of the EuPhoRe® process (Klein et al. 2021). With chemical processing, a constant and homogeneous supply (approx. 10,000 tonnes ssa/year) is necessary.

It is important for SSIP operators to check, before contracting, what the conditions are at the plant of the external provider: the capacity (tonnes of ashes) that can be continuously delivered (storage) and processed (technical readiness, storage, etc.); any ecological constraints; the types of stream accepted (waste, REACH registered product, material with end-of-waste status) and availability of corresponding permits (acceptance of waste or hazardous waste); and the means of disposal of wastewater and ash residues if required. The contract terms should define how the purchase prices or the gate fee are regulated, any tolerance on quality parameters, and details of how the SSA will be integrated if it does not reach the requirements of the fertiliser stakeholders. For international processing, certificates may be required from the countries of origin of the ssa. For example, German operators of SSIP will need to present their national authorities with a certificate stating the recovery of P from ssa; Dutch operators will

[2] "As a best estimate for the year 2030, the opening of the P-fertiliser market to STRUBIAS materials will result in a substitution effect of mined rock phosphate and processed P-fertilisers by fertilising products containing precipitated phosphate salts & derivates, and thermal oxidation materials & derivates of 17% to 31% (Huygens et al. 2019).

need a certificate of reuse of the residues from sludge incineration. It is also important to verify how the fertilising products, partly manufactured with ssa, will reach their target market (as CE mark fertilising products or as fertilising products according to national regulation and mutual recognition).

Furthermore, transport and storage aspects will play a key role. For short and longer distances, it is worth checking the different transport (truck, train, ship, pipeline) options that are available, and combination thereof. The required investment and the available areas for storage (handling warehouse), need to be evaluated. If the SSA is classified as a hazardous waste, and needs to be transported abroad, a notification procedure is required. For international transportation and delivery, the Incoterms® between SSA provider and purchaser needs to be agreed on, to clearly define the share of risk.

The addition of " thermal oxidation materials and derivates as component material categories (CMC 13) for fertilising products into the EU FPR 2019/1009 (European Commission 2020a) is a further step towards facilitating the entry to the market for sewage sludge ashes.

4.1.2 Phosphate salts

With P-recovery from sewage sludge, various phosphate salts can be produced. Depending on quality and quantity, four main target groups can be identified: fertiliser producers with international market outreach, conventional fertiliser blenders (usually acting at a regional level), producers of eco-friendly compounds for gardening and horticulture and farmers. As for sewage sludge ashes, only one stream needs to be considered, which can be delivered to one or several "purchasers" (Figure 4.1.2).

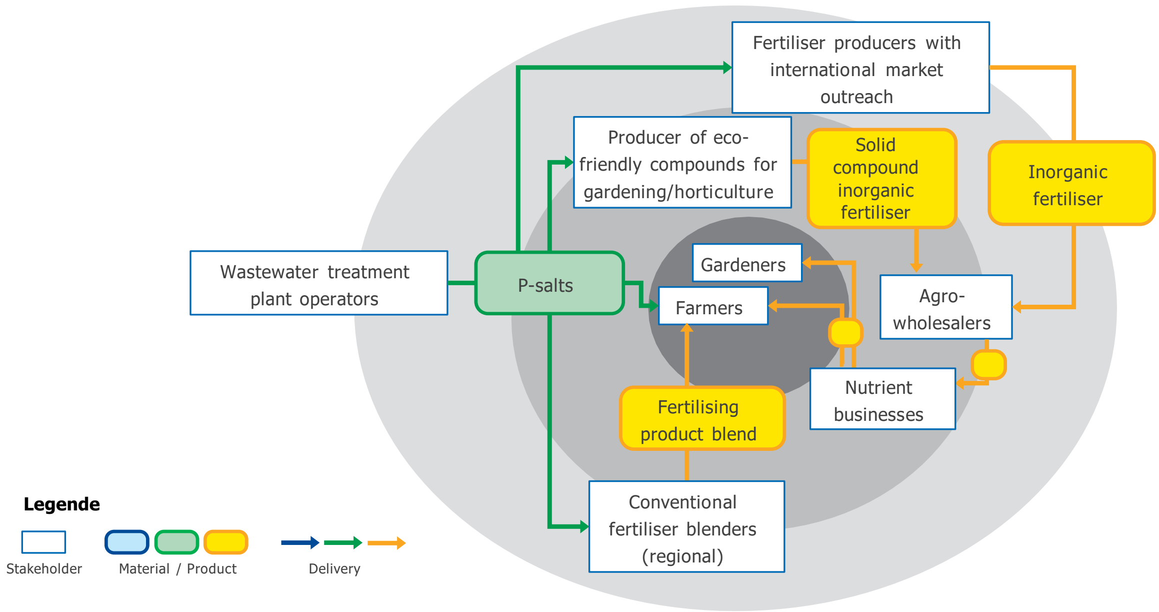


Figure 4.1.2: Stakeholder mapping for the recycling pathways of recovered phosphate salts (Mébarki et al. 2020)

The quantity of phosphate salts produced has a strong influence on whether production is derected at a local/regional market or whether it is made available for producers with an international market outreach. As with SSA above, an analysis of the regional demand for phosphate fertilisers will help to define the capacity of the market to absorb the generated volume of phosphate salts. This analysis should include the needs of the organic agriculture, in addition to conventional, as phosphate salts are likely to be added by delegated act under the EU Organic Regulation 2018/848 entering in force in 2022 (Expert Group for Technical Advice on Organic Production (EGTOP) 2016; Cuoco and Hermann 2020; OFR 2018/848). If sufficient local capacity is available, a short value chain can be selected. If not, co-operation with fertiliser stakeholders having a wider outreach should be pursued. As above, this longer value chain involves more stakeholders (agro-wholesalers, nutrients businesses) before reaching the farmers or gardeners as end-users.

Phosphate salts will only replace part of mined rock phosphate (Huygens et al. 2019). Consequently, the risk of placing this on the market is mainly dependent on the acceptance by “purchasers” of P recycled products.

Phosphate salts exist in different forms with variable availability of phosphorus. Also, within struvite samples that have similar P availability and plant biomass yields, a rather high variability of granule size and shape can be observed, depending on the substrate type the struvite was recovered from (Figure 4.1.3).

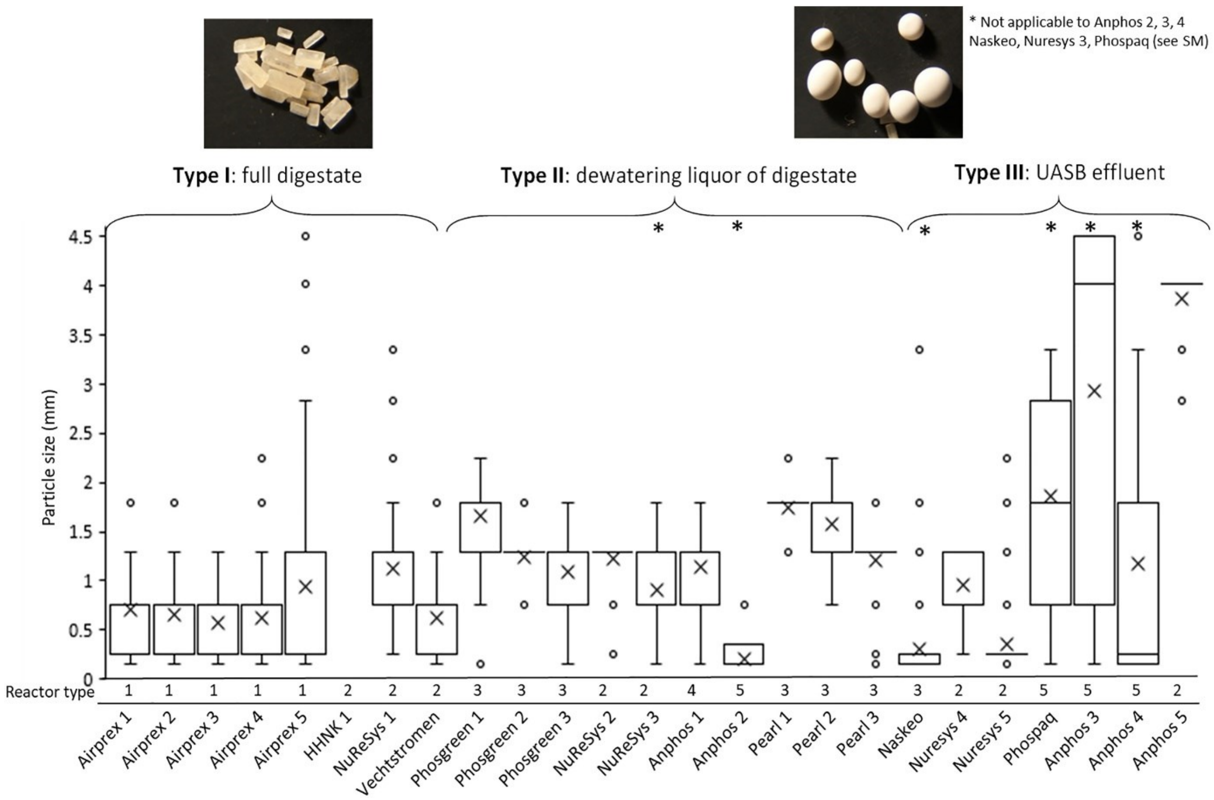


Figure 4.1.3: Mass fraction distribution per particle size for all analysed struvite samples. Crosses indicate the mean particle size (mm). Numbers indicate the reactor type as follows: 1 Airlift reactor, 2 Continues stirred tank reactor, 3 Fluidized bed reactor, 4 Tank aerated, 5 Tank mixed (Muys et al. 2021).

The works of Muys et al. (2021), but also tests made by Prayon as part of the project (Halleux 2021), further show that the physical properties of phosphate salts influence the selection of the most appropriate application routes. With a regular shape and a sufficient size of the grain, the phosphate salts can be directly blended in a compound fertiliser with customised N-P-K ratios or used for land spreading as compound solid inorganic macronutrient fertiliser. In case of irregular shape, or too small size of grain, reprocessing into water-soluble macronutrient fertiliser is the preferred routes.

For all routes described, a clear agreement should be made with the "purchasers" of the phosphate salts at the outset, to ensure consideration of situations when the phosphate salts may be beyond the defined tolerance on quality. Storage capacity for phosphate salts should also be agreed at the outset, in order to meet the requirements of the purchasers (e.g. storage until a minimum volume for processing into a larger manufacturing process is reached, or buffer storage to wait for appropriated schedule to spread fertilisers).

The addition of "precipitated phosphate salts and derivates" as component material categories (CMC 12) for fertilising products into the EU FPR 2019/1009 (European Commission 2021a) is a further step towards facilitating entry to the market for phosphate salts. However, the high level of requirements concerning sterilisation/ pasteurisation/ hygienisation of precipitated phosphate salts or derivates (applying when pathogens limits are exceeded) may restrict the penetration of phosphate salts into the market.

4.1.3 Microalgae biomass

The photobioreactor tested within Phos4You produced microalgae biomass as a result of the microalgae consuming the nutrients contained in wastewater. After separation, the biomass produced can be directly used in fertilising products.

Microalgae biomass meets a growing interest, as recognised in the EU algae initiative (European Commission 2021e, 2020b). The market for algal biomass is thus expected to grow, at both local and global levels.

Whilst considered here within the parameters of substitution for mined P rock fertilisers, the interest in algae biomass is related to its functional properties rather than for its nutrient content. Algal biomass is recognised for contributing to the increase of the organic carbon of soil, for enhancing the microbial activity and for improving the mineralisation of nutrients to make them plant available (Alobwede et al. 2019; Fu and Secundo 2016; Renuka et al. 2018).

Three main pathways for algal biomass were identified in Phos4You (Figure 4.1.4), based on the growth of *Chlamydomonas acidophila* in wastewater. As removed from the PBR, the microalgae biomass can be applied to soil by farmers or landscaping enterprises as a liquid soil improver. After a drying process, a longer value chain for the biomass is possible. This enables the further processing through e.g. producers of eco-friendly compounds for gardening or horticulture. The dried algal biomass can further be used as dried soil improver and as microbial plant biostimulant. Co-formulated with inorganics fertilisers, the algae biomass enters the composition of an organo-mineral fertiliser.

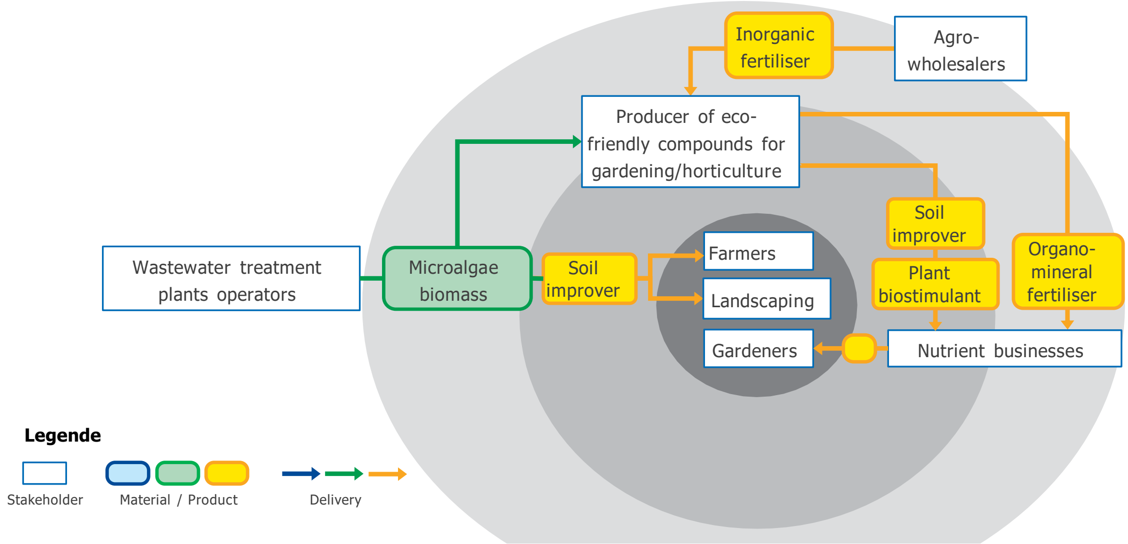


Figure 4.1.4: Stakeholder mapping for the use of micro algae recovered from wastewater (Escudero et al. 2020b)

A number of legislative issues still need to be clarified to enhance the reuse of the microalgae biomass obtained from algae growth on wastewater. The assessment of the EU End-of-Waste criteria for this stream could further facilitate its recycling (Joint letter to the European commission, DG Environment 2021).

4.1.4 P-rich biomass

Another source of P-rich biomass was produced from the wastewater effluent of small-scale treatment plant using an adsorbent material obtained from seafood waste. This product combines the properties of an abundant calcium rich material (from the shellfish) together with the phosphorus contained in the wastewater effluent.

Further work is required to identify whether stakeholders within the seafood industry might be interested in recycling waste shellfish products as part of this wastewater treatment process. Commitment to regular supply would be required. Clarification is also needed on who might undertake the step of the thermochemical activation of the raw crab carapace. In Figure 4.1.5 the mapping includes the possibility of an external enterprise dedicated to the task of thermochemical activation.

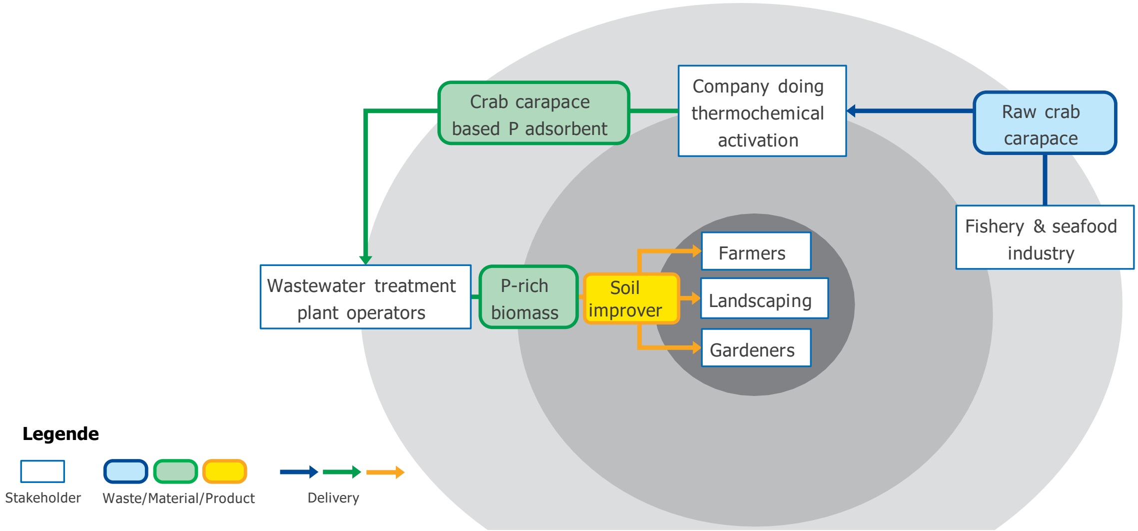


Figure 4.1.5: Stakeholder mapping for the value chains of P-rich biomass recovered with seafood waste (Pap et al. 2020c)

Due to the 'potential' small quantities of P-rich biomass generated per WWTP unit, a direct land application as soil improver for local farmers, landscaping or gardening businesses is favoured. Components such as $CaCO_3$, $MgCO_3$, potassium, chitin/chitosan proteins and lipids bring additional value to this biomass. The adsorbent has potential to increases soil organic matter content; improve soil physical properties (texture); supply essential plant nutrients; $CaCO_3$ content buffers against soil acidification caused by nitrogen application; chitin/chitosan has antibacterial properties – so may help rhizobial multiplication by biologically controlling root pathogenic organisms; possible replacement for costly inorganic fertilisers (Pap et al. 2020c).

The characteristics of the products allow for storage allowing land application to coincide with the production cycle. Common soil application machinery can be used.

4.1.5 Phosphoric acid and related streams

Phosphorus from sewage sludge ashes can be recovered in the form of phosphoric acid through wet-chemical processes. Production is accompanied by several by-products which differ according to the process implemented. These can be: gypsum, road salts, Fe/Al substances or Fe/Al solutions. In addition, leach residues, wastewater and precipitation residues are also generated. A reuse or a valorisation of all those streams needs to be considered, in addition to the recycling of the phosphoric acid itself. Therefore, all the concerned markets need to be carefully considered. The Figure 4.1.6 displays the complexity of stakeholders involved in the recycling pathways.

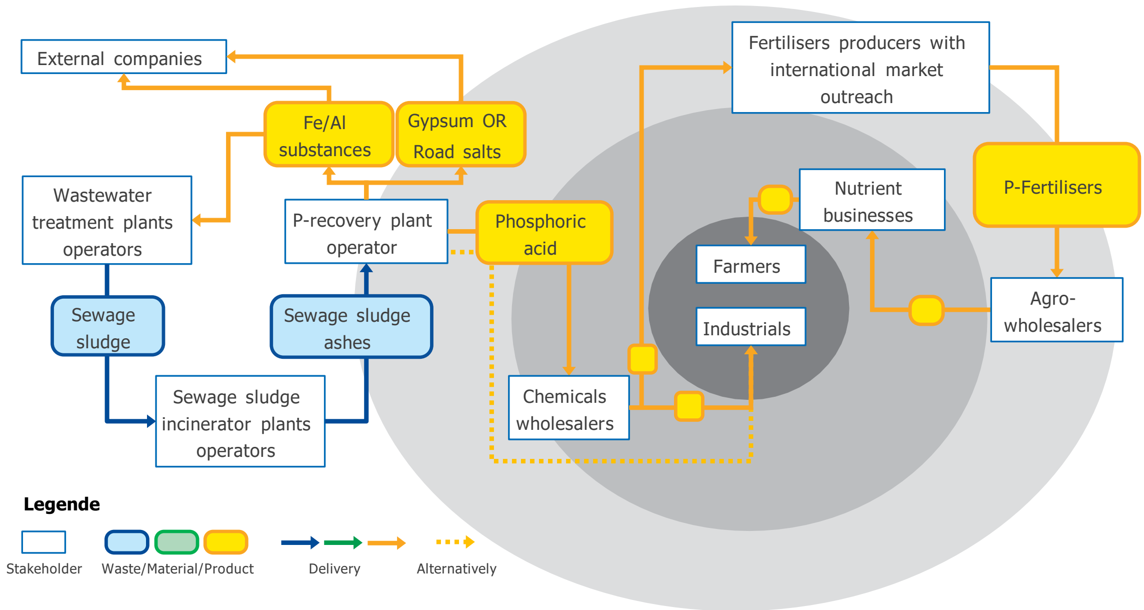


Figure 4.1.6: Stakeholder mapping for the recycling pathways of phosphoric acid and by-products (Blöhse et al. 2020)

The recovered phosphoric acid is aimed at reaching a technical grade in order to access markets with a higher added value. The uses of technical phosphoric acid in industrial application are manifold and globally important. Nevertheless, the size of the accessible market for the operators of a P-recovery plant might be limited, due to the specific quality requirements related with a particular application, or due to competition with existing suppliers and/or with potential further recovery plants. If the market of industrial grade phosphoric acid is not accessible, the recovered phosphoric acid might find application (at a lower selling value), in the manufacture of fertilisers. Merchant grade leads the global market for phosphoric acid, with about 85% of the phosphoric acid produced being used to make fertilisers (International Fertilizer Association 2021).

No less relevant is the analysis of regional markets for by-products, these having a variable added value. For recycled gypsum, the market opportunity is expected to rise (in Germany) because of the coal phase-out for energy. So far 55 % of the German need for gypsum has been supplied from flue gas desulphurisation plants (Portal EnBauSa.de 2020). For road salts, to have value, the volume produced will need to equate to regional needs, as the volume produced from the recovery plant could provide most of local requirements. The Fe/Al substances or Fe/Al solutions are often proposed by process owners to be reused at wastewater treatment plants for the chemical removal of phosphorus. One challenge might be to reach an equilibrium between the volume generated by the recovery process and the volume needed by the regional WWTP operators.

The valorisation of ash residues requires verification, to match recycling requirements in certain countries (e.g. through incorporation into building materials such as cinder or asphalt) or to enable landfilling at the best possible class (above or underground disposal).

On the whole, recovered phosphoric acid and related by-products have the potential to replace current supply sources, but the impact of the generated volumes on the accessible market needs to be checked thoroughly as part of process selection.

The storage and transport cost of those products is not negligible. The different transport options (truck, train, ship, pipeline) and combination of them, as well as the needs for storage investment, in accessible areas, will need to be checked as part of the management process for the various streams linked with the recovery of phosphoric acid from sewage sludge ashes (see 5.3.5).

4.2 Specificity of the quality assessment of phosphorus recovered materials

Authors: Aleksandra Bogdan, Ana Robles-Aguilar, Evi Michels, Erik Meers, (UGent); Mark Taggart, Szabolcs Pap (ERI); Marina Coquery (INRAE); Marina Le Guédard (ADERA – LEB Aquitaine); Joanne Roberts, Colin Hunter (GCU); Ciaran O'Donnell, Joe Harrington (MTU); Josien Ruijter (HVC)

4.2.1 Study framework

The selection of processes aimed to ensure the demonstration of a wide range of input sources for recovery of phosphorus (sewage sludge ashes, sewage sludge, sewage sludge liquor, wastewater) into valuable P fertilising materials (P-salts, ashes, microalgae, crab carapace phosphate) (Bogdan et al. [in press]; Ploteau et al. 2021). To allow the application of various recovered P fertilising materials on the market, it was necessary to assess their quality and define the optimal methods for its assessment. The quality assessment of the products was done in two batches.

Batch 1 was performed on five novel P fertilising materials provided by external companies (as the partners were still developing their technologies). These products were: two struvites (STRLQ and STRSL), two processed sewage sludge ashes (ASH1 and ASH2), and dried sludge iron phosphate (FeP). The results of Batch 1 were discussed in detail within the Phos4You partnership (Bogdan et al. 2020) and, to some extent, published in Bogdan et al. (2021).

After the first batch of analyses, the Phos4You partners demonstrated how phosphorus could be recovered from the following sources (Ploteau et al. 2021):

- sewage sludge with a thermal treatment (I1- EuPhoRe® process);
- sewage sludge with crystallisation after a chemical leaching (I3 - PULSE process);
- sewage sludge or liquor with crystallisation after a biological leaching (I6.1 - STRUVIA™ optimised with bio-acidification);
- sewage sludge ashes with a leaching process (I2 – REMONDIS TetraPhos® process).

In addition, complementarity between phosphorus removal and phosphorus recovery has been demonstrated:

- from wastewater at small scale wastewater treatment works with nature-based solutions (I4 – Microalgae *Chlamydomonas acidophilas*);
- from wastewater effluent of smallest scale wastewater treatment works with adsorption filter using innovative adsorbents (I5 – Filtraphos with chitosan-calcite adsorbent from fishery-food waste);
- from wastewater effluent of small-scale wastewater treatment works with crystallisation process (I6.2 – STRUVIA downscaled).

The resulting recovered P fertilising materials provided by the producers were investigated in the second batch (Batch 2) of the quality assessment analyses:

(1) a chemically leached phosphorus salt (Psalt3_CL) produced with the PULSE process from ULiège;
(2) a microalgae biomass (BioP1_MA) produced with a photobioreactor under the lead of Glasgow Caledonian University ;
(3) a crab carapace phosphate (BioP2_CCP) produced with the Filtraflo-P process of Veolia run by ERI;
(4) a sewage sludge ash (ASH2.2RK_PI) obtained by the partially implemented EuPhoRe® process (pyrolysis and incineration occured without the additive dosing) by the Emschergenossenschaft;
(5) two P-salts obtained with the Struvia™ process, applied once with biological acidification resulting in HAP (Psalt5_BL) and once at a small WWTP resulting in Ca-P (Psalt4_SL).

Additionally, a commercial mineral fertiliser, triple superphosphate (TSP), obtained from Pillaert Meststoffen NV (Belgium), was used as a control. The results are presented in (Bogdan et al. [in press]).

4.2.2 Study objectives

The objectives of this work package were:

1) to define the quality of the novel P fertilising materials recovered during the project from municipal wastewater;
2) to compare the different methodologies used during quality assessment of recovered P fertilising materials;
3) to provide recommendations towards a more standardised approach in assessment of the quality of recovered P fertilising materials.

Specifically, the following aspects are discussed:

- *Overall description of the analyses undertaken and methods used;*
- *Conclusions per type of products;*
- *Conclusions per type of analyses (in 7.3.1).*

4.2.3 Description of the analyses and methods used to assess the quality of novel fertiliser P products

Many chemical analyses were conducted at multiple laboratories, including inorganic (macronutrients, micronutrients and trace elements including heavy metals) and organic analyses (carbon, persistent organic pollutants, pharmaceuticals, and hormones). In addition, biological assays were extensively utilised, i.e., phosphorus availability tests (including pot trials, P lipid index test and field trials), ecotoxicity tests (Omega-3 index test and Triad approach test), and microbiological assays (i.e., aerobic plate growth, bacterial colony counting, and presence/absence of *Salmonella spp., Shigella spp., E. coli, coliforms* and *Enterococcus spp*.). The methods listed in Table 4.2.1 have been performed on all the Batch1 P fertilising materials (STRLQ, STRSL, FeP, ASH1 and ASH2). Based on the findings obtained from Batch1, the methods listed in Table 4.2.2 have been performed on all the Batch2 P fertilising materials (Psalt3_CL, Psalt4_Sl, Psalt5_BL, ASH2.2RK_Pl, ASH3_FB, BioP1_MA and BioP2_CCP). The only exception was Psalt5 BL, for which a reduced number of analyses was conducted due to the limited amount of sample available, and Ash3_FB, external fertilising P material (not developed within Phos4You, but used for comparison).

Table 4.2.1: Overview of the performed analyses on Batch 1 samples (STRLQ, STRSL, FeP, ASH1 and ASH2.) discussed in detail in (Bogdan et al. 2020)

Analysis	Parameter	Method		Partner
Carbon	Total Carbon	Total Carbon, Organic Carbon, Nitrogen and Sulphur dry combustion analysis (CNS)		IRSTEA
	Organic Carbon			
Inorganics	Macronutrients (N and S)	Total Carbon, Organic Carbon, Nitrogen and Sulphur dry combustion analysis (CNS)		IRSTEA
	Macronutrients (K, Ca, Mg, Na and S)	Solid-liquid extraction	Water extraction	ERI
			2 % citric acid	
	Micronutrients and heavy metals (Ni, Cu, Fe, Al, Mn, Zn, Pb, As, Cd)		*Aqua regia*	UGhent
	Heavy metal (Hg)	Total mercury analysis		IRSTEA
Organics	Persistent organic pollutants (POPs: OCBs, PAHs and PCBs)	WO262, GC-MS (NEN 6980)		HVC and UGhent
		WO271, GC-MS (NEN 6980)		
		WO271, GC-MS (NEN-ISO 18287)		
		P0962 Eurofin's procedure		
	Pharmaceuticals	Water extraction		ERI
		QuEChERS method		IRSTEA
	Untargeted analysis	Methanol and acetonitrile extraction		GCU
	Pesticides	QuEChERS method		IRSTEA
	Hormones			
Pathogens	*E. coli* CFU/g	Aerobic plate count		ERI
	Total coliforms CFU/g			
	Enterococcus spp. CFU/g			
	E.coli in 1g			
	Coliforms in 25 g			
	Salmonella spp. in 25 g			
	Shigella spp. in 25 g	Presence/Absence		
	Aerobic Plate Growth	Colony counting		
Phosphorus availability	P concentration	Chemical extractions	*Aqua regia* digestion (closed microwave)	UGhent
			Nitric acid digestion (closed microwave)	
			Mineral acids	
			Water soluble phosphorus	
			2 % citric acid	
			Neutral ammonium citrate	
			Ammonium lactate acetic acid buffer	
			Bray2	
			Olsen's	
			Mehlich3	
			0.01M Calcium chloride	
	Plant P uptake	Pot trial: P uptake		UGhent, External
	Plan P concentration			
	Plant dry matter			
	Residual P concentration in soil			
	Relative agronomical efficiency			
	Phosphorus use efficiency			
	Plan P concentration	Pot trial: Lipid P-index		LEB with IRSTEA
	Plant dry matter			
	Lipid P index			
	Plant dry matter	Pot trial: Effect of growing media		CIT
	Plant dry matter	Field trial		
	Residual soil P index			
Ecotox	Plan P concentration	Omega-3 index		LEB

	Plant dry matter		
	Omega-3 index		
	Total metal concentration		IRSTEA
	Earthworm avoidance	Triad approach	GCU
	Bioluminescence inhibition (microtox test)		

Table 4.2.2: Overview of the performed quality analyses on Batch 2 samples (Psalt3_CL, Psalt4_Sl, Psalt5_BL, ASH2.2RK_PI, ASH3_FB, BioP1_MA and BioP2_CCP) discussed in detail in (Bogdan et al. [in press])

<table>
<tr><th>Analysis</th><th>Parameter</th><th colspan="2">Method</th><th>Partner</th></tr>
<tr><td rowspan="2">Carbon</td><td>Total carbon</td><td colspan="2" rowspan="2">Total Carbon, Organic Carbon, Nitrogen and Sulphur dry combustion analysis (CNS)</td><td rowspan="2">INRAE</td></tr>
<tr><td>Organic carbon</td></tr>
<tr><td rowspan="6">Inorganics</td><td>Macronutrients (N and S)</td><td colspan="2">Total Carbon, Organic Carbon, Nitrogen and Sulphur dry combustion analysis (CNS)</td><td>INRAE</td></tr>
<tr><td>Macronutrients (K, Ca, Mg, Na and S)</td><td rowspan="4">Solid-liquid extractions</td><td>Water extraction</td><td rowspan="4">ERI</td></tr>
<tr><td rowspan="3">Micronutrients and metals
(Ni, Cu, Fe, Al, Mn, Zn, Pb, As, Cd)</td><td>2 % citric acid extraction</td></tr>
<tr><td>Nitric acid/peroxide extraction</td></tr>
<tr><td>Aqua regia</td></tr>
<tr><td>Heavy metal concentration (Hg)</td><td colspan="2">Total mercury analysis</td><td>INRAE</td></tr>
<tr><td rowspan="9">Organics</td><td rowspan="4">Persistent organic pollutants
(POPs: OCBs, PAHs and PCBs)</td><td colspan="2">WO262, GC-MS (NEN 6980)</td><td rowspan="4">HVC (and UGhent)</td></tr>
<tr><td colspan="2">WO271, GC-MS (NEN 6980)</td></tr>
<tr><td colspan="2">WO271, GC-MS (NEN-ISO 18287)</td></tr>
<tr><td colspan="2">P0962 Eurofin's procedure</td></tr>
<tr><td>Persistent organic pollutants (POPs: PFAS)</td><td colspan="2">QuECHERS method with acetonitrile as the organic solvent</td><td>GCU</td></tr>
<tr><td>Pharmaceuticals</td><td colspan="2">QuEChERS method</td><td>IRSTEA/INRAE</td></tr>
<tr><td>Untargeted analysis</td><td colspan="2">QuECHERS method with acetonitrile as the organic solvent</td><td>GCU</td></tr>
<tr><td>Pesticides</td><td colspan="2" rowspan="2">QuEChERS method</td><td rowspan="2">IRSTEA/INRAE</td></tr>
<tr><td>Hormones</td></tr>
<tr><td rowspan="9">Phosphorus availability</td><td>Plant P uptake</td><td colspan="2" rowspan="6">Pot trial: P uptake</td><td rowspan="6">UGhent</td></tr>
<tr><td>Plan P concentration</td></tr>
<tr><td>Plant dry matter</td></tr>
<tr><td>P concentration in substrate solution</td></tr>
<tr><td>Relative agronomical efficiency</td></tr>
<tr><td>Phosphorus use efficiency</td></tr>
<tr><td>Plan P concentration</td><td colspan="2" rowspan="2">Pot trial: Lipid P-index</td><td rowspan="2">LEB/INRAE</td></tr>
<tr><td>Lipid P index and other Lipid P biomarkers</td></tr>
<tr><td>Plant dry matter</td><td colspan="2">Pot trial: Effect of growing media</td><td>CIT</td></tr>
<tr><td rowspan="2">Ecotox</td><td>Omega-3 index</td><td colspan="2" rowspan="2">Omega-3 index</td><td rowspan="2">LEB/INRAE</td></tr>
<tr><td>Total metal concentration in plant</td></tr>
<tr><td rowspan="8">Pathogens</td><td>E. coli CFU/g</td><td colspan="2" rowspan="6">Aerobic plate count</td><td rowspan="8">ERI</td></tr>
<tr><td>Total coliforms CFU/g</td></tr>
<tr><td>Enterococcus spp. CFU/g</td></tr>
<tr><td>E.coli in 1g</td></tr>
<tr><td>Coliforms in 25 g</td></tr>
<tr><td>Salmonella spp. in 25 g</td></tr>
<tr><td>Shigella spp. in 25 g</td><td colspan="2">Presence/Absence</td></tr>
<tr><td>Aerobic Plate Growth</td><td colspan="2">Colony counting</td></tr>
</table>

4.2.4 Conclusions per type of product and P-recovery technology

4.2.4.1 Phosphate salts (P-salts)

In total, in Batch 1 two P salts (STRLQ and STRSL) (Bogdan et al. 2020) and in Batch 2 three more P-salts (P salt3_CL, P salt4_SL and P salt5_BL) (Bogdan et al. [in press]) were analysed.

All phosphate salts (P-salts) had sufficiently high P concentration and low organic carbon concentration as compared to the minimum required by the Fertilising Product Regulation 2019/1009 to be classified as an inorganic fertiliser (EU FPR 2019/1009). High amounts of magnesium were detected in all samples, and calcium in Batch 2 samples. Struvites also had relevant concentrations of nitrogen, while the other P-salts did not.

Their nutrient availability to plants was tested in several pot trials. For struvites, the release of P at the dose equivalent to 60 kg P_2O_5 ha^{-1} was defined as optimal, the lower early P availability was compensated within one season of plant growth and even result in enhanced supply of P compared to TSP (Bogdan et al. 2021).

In Batch 2, fast initial P release was observed for treatment with Psalt3_CL. Overall, this study showed that Psalt3_CL could be employed as P fertiliser, with similar fertiliser efficiencies as the TSP. The nutrient availability of Psalt4_SL was tested on three low P growing mediums (GM) developed within the project, and it proved to have fast P release and comparable shoot dry matter as TSP starting from the 1^{st} month on all 3 GMs.

Regarding inorganic contaminants, the two struvite materials (STRLQ and STRSL) tested in Batch1 were the purest products. The lowest concentrations of inorganic contaminants among the three examined P-salts (P Salt3_CL, Psalt4_SL and Psalt5_BL) tested in Batch 2 were measured in Psalt5_BL. This is most likely a consequence of differences in the source of wastewater used and P-recovery technology applied.

In terms of organic contaminants, no (or little) organochlorine (OC) pesticides, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) were generally detected in P-salts (not analysed on Psalt5_BL). In case of P salt 3_ CL, traces of PCB 53 and one Per/poly fluorinated substance (PFAS) were found in the sample, 3 PFAS were detected in P salt 4 SL (note: Psalt5_BL was not analysed on POPs). A few more polymers were detected in Psalt3_CL compared to TSP, most likely coming from the wastewater than the P-recovery technology. Hormones, androstenedione and epitestosterone, were detected only in Psalt4_SL, while four different pharmaceuticals were also seen in Psalt4_SL and Psalt3_CL. Several pharmaceuticals were detected in all

P-salts but at relatively low concentrations. Some traces of pharmaceuticals were also detected in struvites using Quick, Easy, Cheap, Effective, Rugged, and Safe (QuEChERS) method, but not in water extracts, while few hormones were quantified using both methods.

The presence of several microbial communities was also detected in Psalt4_SL, indicating that more precautions should be taken if the P-salts are made from organic rich waste streams using this specific P-recovery technology.

In addition, based on ecotoxicity tests, attention should be paid to the P dose of struvites and Psalt4_SL to avoid possible adverse effects by overdosing.

4.2.4.2 Ashes

In total, in Batch 1 two ashes (ASH1 and ASH2) (Bogdan et al. 2020) and in Batch 2 two more ashes (ASH2.2RK_PI (same technology as for ASH2, but different source of sludge) and ASH3_FB) (Bogdan et al. [in press]) were analysed.

Thermally recovered P fertilising materials (ASH1, ASH2.2RK_PI and ASH3_FB), had low organic carbon concentration typical of inorganic fertilising products, while ASH2 had a high organic carbon concentration similar to organo-mineral fertilising products. The atypical high organic carbon concentration in ASH2 was caused by use of mixed industrial and municipal wastewater sludge as inlet to the P-recovery plant and not municipal wastewater sludge alone. All ashes were found to have sufficiently high concentration of P compared to the minimum required by the Fertilising Product Regulation 2019/1009 to be considered as an inorganic P fertiliser (EU FPR 2019/1009). In addition, all ashes except ASH3_FB (ash treated with KOH to result in PK fertiliser) had a low concentration of potassium (K) but high amounts of magnesium and calcium.

The P availability of ashes could be affected significantly by the sewage sludge source and P technology (Lemming et al. 2017; Nanzer et al. 2014). In the Batch 1 study, ASH1 (processed with Na_2SO_4) was found to be similar to TSP, while ASH2 was less efficient than TSP, but better than the unfertilized control (Bogdan et al. 2021).

For ASH1, the mid P dose (eqv. to 60 kg P_2O_5 ha^{-1}) has proven sufficient for optimum plant growth, although the relative agronomic efficiency (RAE) may indicate that more P can be delivered to the plant at the highest P dose (eqv. 90 kg P_2O_5 ha^{-1}) (at which the nutrient ratios most likely became more favourable for this product). In terms of ASH2, more efficient P uptake in shoots was achieved at the highest P dose (eqv. 90 kg P_2O_5 ha^{-1}) applied (Bogdan et al. 2021).

In the ASH2.2RK_PI. (same technology, different sludge) P release was improved. In addition, the treatment with ASH3_FB gave comparable shoot P concentrations through time as ASH2.2RK_PI, which was expected as their chemical composition in relation to P concentration was comparable (e.g. Fe:P, Zn:P ratio).

The concentrations of potential inorganic contaminants in all examined ashes proved to be below the legislative limit of the EU FPR 2019/1009, except for ASH2.2RK_PI, which showed higher copper (Cu) and zinc (Zn) concentrations than the other fertilisers. However, these elements may be considered as micronutrients if applied at a dose that corresponds to plant requirements needs and corresponding soil deposits.

Furthermore, ashes were found to be safe in terms of organic contaminants. Some PAHs (Naphthalene and Phenanthrene) were detected in ASH3_FB, and no POPs were detected in Ash2.2RK_PI (except one PFAS at extremely low concentration) and ASH1. POPs were not analysed in ASH2. Similarly, no hormones, pharmaceuticals nor pathogens were observed (except in ASH1, discussed in Bogdan et al. (2020)).

In terms of risk assessment, the ecotox Triad earthworm avoidance test indicated that ASH1 had an effect even at lower P doses. This test should be considered for use in assessment of other types of ashes. Unfortunately the COVID pandemic jeopardised further testings).

4.2.4.3 Bio-phosphates

The two novel bio-phosphates, BioP1_MA and BioP2_CCP were analysed in Batch 2 (Bogdan et al. [in press]).

According to fertilising product category limits, as defined in EU FPR 2019/1009, BioP1_MA can be considered as an organic P fertiliser and BioP2_CCP as an organo-mineral P fertiliser having sufficient concentration of P/ higher than the minimum required. Besides, BioP1_MA had the highest amount of total nitrogen. High amounts of magnesium and calcium were also detected in BioP1_MA and BioP2_CCP.

The availability of P from both BioP1_MA and BioP2_CCP to plants was strongly affected by the substrate type. For BioP1_MA, a comparable shoot P uptake to TSP was observed on an acidic/neutral substrate, but lower on alkali substrate.

Treatment with BioP2_CCP achieved lower shoot P uptake than the commercial TSP treatment, but higher compared to the unfertilised treatment (ZeroP).

In terms of inorganics contaminants, of those tested BioP2_CCP was the purest product (better than TSP). On the other hand, BioP1_MA contained higher concentrations of contaminants than TSP, but within legislative limits (except for copper).

Several organic pollutants were detected in the products that had high carbon concentrations - BioP2_CCP and BioP1_MA. Concentrations of persistent organic pollutants (POPs), pharmaceuticals and one polymer were detected in BioP1_MA, however these were very low - present at parts per billion levels (i.e. low µg/kg dry matter). While growth of gram variable rod-shaped bacteria was detected in BioP1_MA, both products were free from *Salmonella spp*., *E.coli*, coliforms and *Enterococcus spp*. In addition, ecotoxicity tests indicated that BioP2_CCP was suitable for use at normal application levels.

A precautionary approach would indicate that end-users should review potential toxin risks if there were plans to use much higher application quantities than normal.

5 Prepared territorial deployments of P-recycling in urban context

Within the project Phos4You, the pathway to deployment of P-recycling in urban areas has been prepared or showcased. The following sections outline the status of regional developments in Switzerland, The Netherlands and Germany.

5.1 Scenarios for implementing the mandatory phosphorus recovery in Switzerland

Authors: Anders Nättorp, Matthias Mahler, Dario Cairoli, Maurice Jutz (FHNW)

5.1.1 Background

Swiss regulation ADWO (Swiss Federal Council 12/4/2015)[3] requires a recovery of phosphorus from meat and bone meal and from sewage sludge (200,000 t dry matter). The resource potential is about 6,000 t P/year in sewage sludge (Mehr et al. 2018) and about 1,500 t P/year in meat and bone meal (MBM), that is currently landfilled or incorporated in cement. The implementation guideline of the regulation requires a recovery of 50 % from 2026 with a final target of 75 % suggested for 2036 (Bundesamt für Umwelt BAFU Abteilung Abfall und Rohstoffe 2021; FOEN Federal Office for the Environment 2020).

The new Minrec category in the Swiss fertiliser regulation (DüV) (Schweizerische Eidgenossenschaft 2001, 2019) specifies mineral fertilising compounds from phosphorus recycling. These compounds are subject to very strict contaminant limits (ORRChem) (Swiss Federal Council 5/18/2005) that are a factor 2 to 5 lower than those of the EU FPR 2019/1009.

[3] especially the amendment in force since 1 Jan. 2019 that relates to a specification of Art. 15 which states: "When recovering phosphorus from waste in accordance with paragraph 1 or 2, the pollutants in the waste must be removed according to the state of the art. If the phosphorus recovered is used to manufacture a fertiliser, the requirements of Annex 2.6 Number 2.2.4 ORRChem must also be met."

Contribution of Phos4You

The activities leading to the Swiss scenarios are outlined in Figure 5.1.1. As part of Phos4You the FHNW made an inventory of the state of the art of Swiss sludge disposal (Cairoli et al. 2021; Nättorp and Scheidegger 2019) with support of the respective stakeholders and their organisation VBSA. Furthermore, previous data on technologies from the «PNRW» project (Antakyali n.d.) were adapted to Swiss conditions and complemented with Swiss experience. FHNW developed scenarios and criteria for their evaluation with representatives from the Cantons and sludge disposal operators of Northwestern Switzerland. Draft scenarios, as well as the finished scenarios, were discussed and validated in two workshops with the abovementioned stakeholders. The report on the scenarios contains the following: i) an analysis of regional sewage sludge volumes and disposal capacity, ii) multicriteria characterisation of location independent recovery-disposal scenarios using a set of recovery technologies suitable for Switzerland, and iii) analysis of further aspects that are mainly related to the choice of location (Nättorp et al. 2021). FHNW coordinated the development of the scenarios with the SwissPhosphor project of the FOEN, which also supports the implementation of phosphorus recovery in Switzerland (More info in German: https://pxch.ch/aktuelles.html).

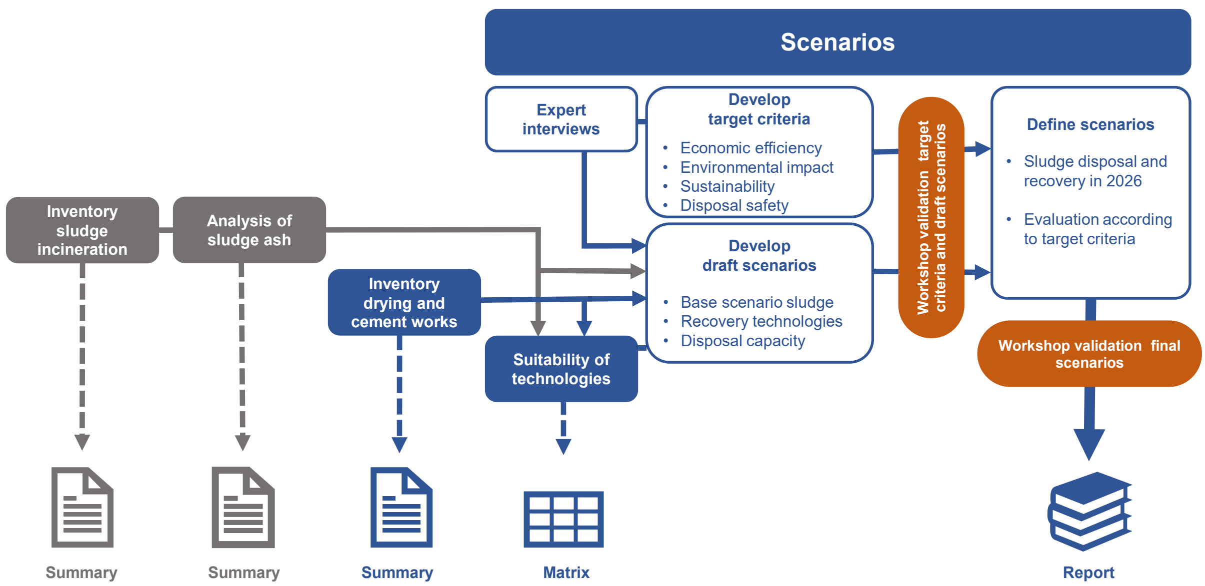


Figure 5.1.1: Description of how sludge disposal and phosphorus recovery scenarios in Switzerland were developed in Phos4You

Nationwide implementation

Northwestern Switzerland consists of four Cantons: Argovia (AG), Basel city (BS), Basel country (BL), and Solothurn (SO). The Canton of Jura is also sometimes included in the area but was not part of this study. The region has 1,450,000 inhabitants on an area of 2,750 km². This is 17 % of the Swiss population and 7 % of the Swiss area.

The scenarios developed would also be valid for nationwide implementation. The general conditions and legislation to be considered regarding sewage sludge generation and disposal would be the same, although the quantities would be about four times larger. For other regions of Switzerland, the export scenario could be less advantageous. The environmental and economic impact of sludge transport are a comparatively small component in Northwestern Switzerland but would be more significant in more rural regions.

5.1.2 Analysis of sludge origin and disposal

A sewage sludge balance was prepared based on the cantonal statistics on sewage sludge produced, and its disposal, using the methodology of VBSA (Gaussen-Freidl 2019). A total of 98 WWTPs are currently operated in Northwestern Switzerland. In 2019, a total of 43,000 t DM of sewage sludge was produced (30 kg DM/(cap*a)).

The distribution of sewage sludge and the remaining capacity of the various disposal plants in Northwestern Switzerland are shown in Figure 5.1.2. The pie charts refer to 100 % of the capacity of the respective plant. The size of the diagrams increases proportional to the plant's capacity. The pie charts show the shares of disposed sewage sludge of the investigated regions.

The total capacity for the disposal of sewage sludge in Northwestern Switzerland is 94,000 t DM/a. The disposal plants include four sludge incineration plants (SIP) with a total capacity of 59,000 t DM/a (63 %), two municipal solid waste incinerations (MSWI) with a capacity of 11,700 t DM/a (12 %), and two cement works with a capacity of 23,500 t DM/a (25 %). In addition to the 43,000 t DM/a of sewage sludge from Northwestern Switzerland, 24,000 t DM/a of external sludge are also disposed of in plants in Northwestern Switzerland. The average capacity utilisation of the plants in Northwestern Switzerland is thus 70 %, such that the region is able to dispose of all of its sludge in its own plants.

Two plants indicate that they intend to cease sewage sludge disposal in the next few years (KEBAG, RENI). The remaining sludge incineration plants (ARA Rhein, Prorheno, erzo) have a capacity of 52,000 t DM per year. The cement works and the Turgi MSWI have a capacity of 25,000 t DM per year. Thus, the remaining sludge incineration plants can dispose of all sewage sludge from the region (43,000 t DM/a). With the cement plants and Turgi MSWI there is an additional capacity. These regional plants could dispose of 180 % of the sewage sludge produced in Northwestern Switzerland.

For reasons of age, SIP ProRheno and ARA Rhein will have to be shut down by about 2035 and erzo also anticipates a replacement of the SIP.

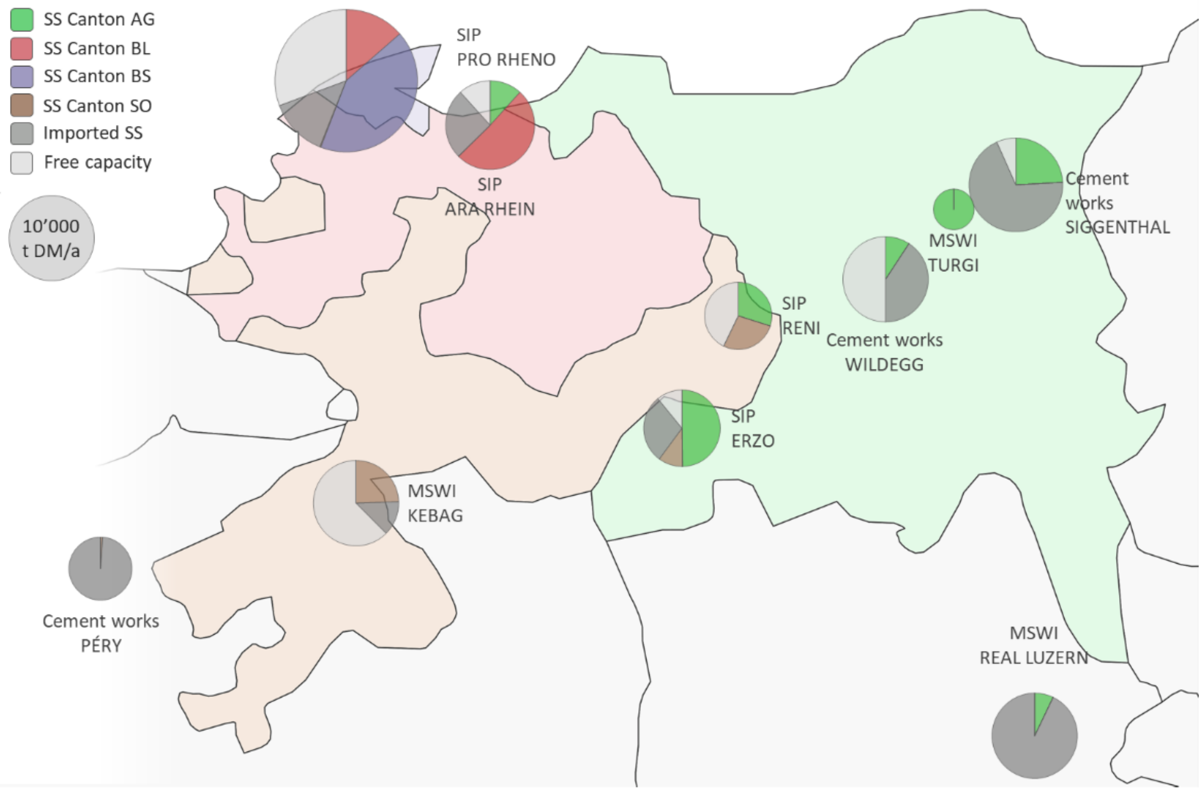


Figure 5.1.2: Amount of sewage sludge (SS) disposed of broken down by disposal facility and canton. Data from 2019 (Cairoli et al. 2021; Nättorp and Scheidegger 2019)

5.1.3 Scenarios for recovery and sludge disposal

Since the applicable recovery is dependent on the disposal solution, integrated scenarios that combine recovery and sludge disposal were developed.

Description of the technologies

The recovery technologies in this study were mostly investigated in the PNRW project. They were selected because they have a sufficient TRL, active supplier and operational experience in Europe. Some of the technologies of the PNRW project are not suitable for Switzerland: direct struvite precipitation without a previous solubilization step has insufficient yield, and technologies with limited removal of pollutants cannot fulfil the particularly strict Swiss contamination limits. Two additional technologies were added based on Swiss experience: REALphos and ZAB/Phos4Green. In the end the following nine technologies are applicable for Swiss scenarios:

The EcoPhos®, PARFORCE, Phos4Life and REALphos processes leach sewage sludge ash with mineral acids and purify the resulting phosphoric acid for use as a fertiliser or for technical applications. EcoPhos®, PARFORCE and Phos4Life also produce other products such as coagulants road salt and dilute hydrochloric acid (Scenario 2a, 2b, 2c; Figure 5.1.3).

EuPhoRe® and Pyrophos integrate disposal and recovery in a thermal process with reducing and oxidizing conditions to remove parts of the heavy metal and produce an ash as a fertilising compound. Pyrophos also uses a potassium additive to achieve high plant availability (Scenario 3a, Euphore® also 2c).

The ZAB/PHOS4green increases plant availability by adding acid to a mixture of meat and bone meal and sewage sludge ash (Scenario 3b).

PhosForce and Stuttgarter process enable phosphorus recovery from wet sewage sludge. PhosForce uses acidification by microorganisms before digestion, whereas Stuttgarter uses mineral acid after sludge digestion. After the subsequent dewatering step phosphorus is precipitated from the liquid phase, typically in the form of struvite (Scenario 4).

Description of the scenarios

Together with the stakeholders, realistic site-independent implementation scenarios were defined (Figure 5.1.3; Table 5.1.1). These combine the existing options for mineralization[4] and phosphorus recovery.

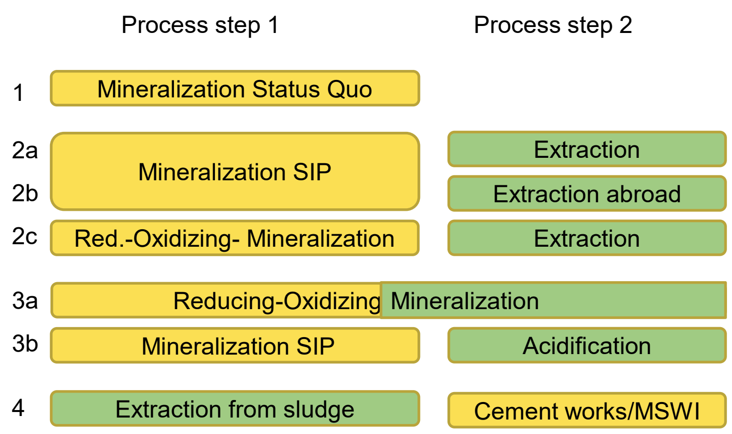


Figure 5.1.3: Illustration of scenarios for 2026 consisting of combinations of sewage sludge mineralization in yellow and phosphorus recovery in green

5.1.4 Evaluation of the scenarios (details in full report)

Four scenarios (2a, 3a, 3b, 4) were evaluated, with eleven criteria in the following four groups:

- Economic efficiency: Investment costs, OPEX and Revenue from process output
- Environmental impact: Carbon footprint, Removal of pollutants and Amount of waste
- Sustainability: Recovery rate, Contribution to closing the P cycle in Switzerland and in agriculture, Solubility of output
- Disposal safety: Technological Readiness level (TRL), Experience in Swiss projects

Each scenario was evaluated for all the possible technologies and the result was strongly influenced by the chosen technology (Table 5.1.1). Overall tendencies for all the seven scenarios are summarized in Table 5.1.2. Detailed results are available in the German report (Nättorp et al. 2021).

[4] Mineralization denotes technologies for complete oxidation: incineration in sludge incineration plant, SIP, incineration in municipal solid waste incineration plant MSWI, incineration in cement plant or oxidizing-reducing treatment with processes such as Euphore® or Pyrophos.

Table 5.1.1: Evaluation of scenarios 2a, 3a, 3b, 4 with different technologies. Eleven different criteria. More info in Nättorp et al. (2021)

	Mineralization in SIP and extraction of P from the ash				Reducing-oxidizing mineralization or acidification to increase plant availability			Extraction from sludge Mineralization in cement plant or MSWI (or SIP)	
	T1	T2	T3	T4	T5	T6	T7	T8	T9
Investment costs	●●●	●●●	●○○	●●○	●●○	●●○	●○○	●●○	●●○
Operating costs	●●○	●●○	●○○	●●○	●●●	●○○	●●●	●●○	●○○
Revenue process output	●●○	●●○	●●●	●○○	●○○	●●●	●●○	●○○	●○○
Carbon footprint of phosphorus recovery process	●●○	●○○	●●○	●●○	●●●	●●●	●●○	●●●	●○○
Removal of pollutants (heavy metals)	●●○	●●●	●●●	●●○	●●○	●○○	●●○	●●●	●●●
Waste quantity landfill category B	●●○	●●○	●○○	●○○	●●●	●●●	●●●	●●●	●●●
Waste quantity heavy metal concentrate	●●○	●●●	●●○	●●○	●○○	●●○	●○○	●●●	●●●
Recovery rate	●●●	●●○	●●●	●●○	●●●	●●●	●●●	●○○	●○○
Contribution to closing the P cycle in Switzerland and in agriculture	●●●	●●●	●●●	●●●	●○○	●●○	●○○	●●○	●●○
Phosphate solubility in neutral ammonium citrate (NAC)	●●●	no fertilizer	no fertilizer	●●●	●○○	●●●	●●○	●●●	●●●
Technology Readiness Level (TRL)	●○○	●○○	●●○	●○○	●●●	●●●	●○○	●●○	●●○
Experience in Swiss project	●○○	●○○	●●○	●●○	●●●	●●○	●●○	●○○	●○○

Table 5.1.2: Description, characteristics, main advantages, and main disadvantages of the seven scenarios

Description	Characteristics	Analysis
Scenario 1: Mineralization status quo and phosphorus recovery open until 2026	The decision on the process for phosphorus recovery will only be made after 2026. Until then different options will be evaluated through piloting and contacts with other actors. Mineralization will not yet be adapted with regard to phosphorus recovery.	Late movers: + have less cost with later implementation + have more technology experience available on market + can combine recovery with upcoming NW Switzerland disposal renewal next 10-15 years - have less partners for cooperation
Scenario 2a: Mineralization in SIP with subsequent extraction of phosphorus from the ash	Mineralization in a SIP is usually carried out with sewage sludge alone or with support fuels that generate little but concentrated ash. The ash produced is then processed as a raw material by one of several possible extraction processes.	+ high removal of pollutants + high recovery rate and plant availability + closure of phosphorus loop in Switzerland and in agriculture - complex processes with likely difficulties for first movers - limited Swiss experience
Scenario 2b: …extraction abroad	The phosphorus in ash produced by mineralization in SIP is extracted abroad instead of domestically.	Requires stable cooperation partners. German market provides additional potentially better options. Comparable cost.
Scenario 2c: Reducing-Oxidizing mineralization followed by Ash Extraction	Mineralization by thermal treatment in reductive atmosphere (pyrolysis) followed by complete oxidation replaces mineralization in SIP as in scenario 2a.	Today less experience and thus more risk than with SPI. No known advantages in cost or environmental impact.
Scenario 3a: Reducing-oxidizing mineralization or (3b) acidification to increase of plant availability	With the right raw material mixture/input material, a low-pollutant output is produced. In contrast to scenario 2, no extraction of phosphorus from the matrix takes place, but the plant availability of phosphorus is more or less increased.	+ relatively simple processes with rather positive warming potential + little landfilling + high recovery rate - closing of phosphorus loop difficult in Switzerland because of diluted fertiliser product - challenging to procure a low contaminant input mix including for example MBM to fulfil Swiss contaminant limits.
Scenario 4: Extraction from sludge with subsequent mineralization in cement plant or MSWI (or SIP)	Phosphorus is extracted from the sewage sludge. The sludge is then incinerated directly in a MSWI, or dried and incinerated in a cement plant. Subsequent incineration in a SIP is also possible.	+ high removal of pollutants + no landfill needed if combined with cement works - low recovery rate and low output revenue - no (positive) Swiss experience

5.1.5 Discussion

Data quality

The underlying sewage sludge data are up to date and, as comparison with the recent VBSA balance shows, reasonably constant over time. The disposal infrastructure has been recorded by the FHNW in two inventories, and with access to the latest developments at most of the providers in Northwestern Switzerland. Only for the cement industry are the plant condition, future expected development and the quantities disposed of partly unknown.

The recovery technology data are up to date. These were collected and validated with the technology providers in 2019-2020. However, some of the technologies are evolving rapidly. Phos4Life, for example, has gained more knowledge since the technology was originally described. It has probably become more expensive and there is now a slimmed-down version as an alternative (erzo ZAB Geocycle Holcim ZAR ARA Thunersee 11/6/2020).

The cost data (investment, operating resources, personnel) for most processes were taken from studies for Germany and converted using the so-called BigMac index (2021). This is a simplification and will result in deviations compared to the actual implementation in Switzerland. However, there is a larger amount of cost data for Germany and the EU area, respectively, which is why comparisons with these data are also advantageous. For the costs of mineralization (sludge incineration, drying, transport, landfill) Swiss prices were used.

Results

Northwestern Switzerland has ten regionally distributed plants for sewage sludge drying and disposal, with a capacity of 180 % of the sewage sludge volume. Over the next 10 - 15 years all sludge incineration plants are expected to be decommissioned. Thus, there is opportunity to:

- Introduce integrated recovery and disposal solutions while optimising the overall capacity.
- Select suitable sites which consider transport distance and synergies with infrastructure and facilities for integration of raw material supply, heat supply and output sales.

Seven scenarios for phosphorus recovery and mineralization of sewage sludge were assessed. A total of nine phosphorus recovery processes could be considered under these scenarios. These allow for either, 1. recovery from ash (after mineralization), 2.

integrated mineralization and phosphorus recovery, or 3. recovery from sludge (before mineralization). In the scenarios, either mineralization in SIP, reductive-oxidative mineralization, co-incineration in MWSI, or incineration in a cement kiln can be used as the disposal solution.

Depending on the criterion and scenario, economic viability and environmental impacts can vary widely (see Table 5.1.3). Thus, the potential influence of some of these variables on the implementation of phosphorus recovery in Switzerland is also large.

5.1.6 Conclusion and outlook

Based on the above analysis, no scenario stands out. All have advantages and disadvantages in the categories of economic efficiency, future viability, disposal safety and environmental impact. These seem balanced and the choice of each scenario can be justified, depending on the weighting of the criteria. The weighting of the necessary criteria for such an overall assessment would have to be negotiated among the stakeholders. Although there is no obvious scenario that performs better than the others, we also show that the choice of scenario has large consequences. The scenarios are a contribution to the implementation of phosphorus recovery by 2026 as required by the ADWO. In a next step, priorities can be defined, and the selected scenarios can be concretized in preliminary projects.

Table 5.1.3: Median and range between maximum and minimum values for some quantitative criteria from Table 5.1.1 and the corresponding potential if implemented for the total amount of sewage sludge in Northwestern (NW) Switzerland.

Criterion	Median	Range between maximum and minimum value	Potential NW Switzerland (170,000 t dewSS/ a, 1,500 P/a)
Investment cost P-recovery[5]	260 CHF/t/a dewSS	600 CHF/t/a dewSS	100 MCHF
OPEX	180 CHF/t dewSS	150 CHF/t dewSS	26 MCHF/a
Revenue process output	18 CHF/t dewSS	60 CHF/t dewSS	10 MCHF/a
CO_2 emissions[6]	0.05 t CO_2 eq/t dewSS	0.17 t CO_2 eq/t dewSS	28,000 t CO_2eq
Landfill volume[7]	0 t/t dewSS	0.23 t/t dewSS	40,000 t/a
Phosphorus recovery yield	90 %	45 %	700 t P/a
Phosphorus solubility in neutral ammonium citrate	90 %	45 %	700 t P/a

[5] The investment in reductive-oxidative mineralization includes both mineralization and P-recovery.
[6] One outlier was discarded.
[7] This is the amount of inert material generated, typically leaching residue. Also smaller amounts of heavy metal concentrates are generated by some technologies.

5.2 Sewage sludge incineration plants´ operators on the way to recycle phosphorus from sewage sludge ashes in The Netherlands

Authors: Ruijter, Josien (HVC); Sijstermans, Luc (SNB); Wubben, Jeroen (HHSK)

For many years HVC and SNB along with their 13 shareholding water authorities have been assessing ways to recover phosphorus from sewage sludge ashes. Sewage sludge ashes in The Netherlands contain a high P_2O_5 content, just slightly lower than the P-content in phosphate-rock. Several scenarios have been studied aiming to allow development of feasible business cases in which the highest efficiency of P-yield is reached while maintaining the most sustainable technical approach that fits the business model of HVC and SNB. Cooperation within the water and sludge 'chain' with the water authorities, a collective approach and combined ambitions on energy and resource are the basis for the framework. The conditions under which P-recovery is most feasible are: no (or limited) additional P-recovery from sludge to maintain a high content of P in the SSA; valorisation of the ash residue and metals salts; prolonged life time of the mono-incinerator of HVC/SNB to guarantee at least 15 years of SSA-production; and no tax on the incineration of sludge (as is the case with incineration of municipal waste). Furthermore, P-recovery needs to be more sustainable than the current conditions in which the SSA is completely reused as a filling material in asphalt, concrete tiles or in salt mines (in Germany) to avoid surface subsidence. In the Netherlands it is not allowed to use the sewage sludge ashes, and the remaining residue after P-recovery in landfilling.

To put this in context: In The Netherlands 1,400,000 tonnes of dewatered sewage sludge is available, coming from municipal waste water treatment plants. More than 50 % of the sludge is already digested. From this total amount of sewage sludge almost 40 % is mono-incinerated by HVC and SNB, resulting in, currently, about 60,000 tonnes of ashes with 20-28 % of P_2O_5. The other 60 % is treated via drying installations or biological composting after which the dried sludge is co-incinerated in waste-to-energy plants in The Netherlands or in cement factories (mainly in Germany).

Sewage sludge from all orange regions in Figure 5.2.1 has been mono-incinerated by HVC and SNB since 1993/1995. In the pink regions, sewage sludge is composted, while sludge from the yellow regions is dried prior to co-incineration.

Figure 5.2.1: Sewage sludge treatment in The Netherlands (orange = incineration; pink = composting; yellow and green =drying and co-incineration) (©SNB)

5.2.1 Quality of sewage sludge ashes

Over the last 20 years a decrease in cadmium (25-50 %), lead (33-50 %) and mercury (50 %) can be seen in the sludge processed by HVC and SNB. Other heavy metals do not show a clear decrease. In recent years the nitrogen in the sludge increased (+20 %) due to an increasing in digesting. These developments can also be seen in the produced ashes. The P_2O_5 content in the SSA of HVC (approx. 28 %) and SNB (approx. 20 %) sludge has been relatively stable (Ruijter et al. 2021) as can be seen in Figure 5.2.2. A dedicated report on the composition of the ashes (Ruijter et al. 2021) was completed under the Phos4You programme.

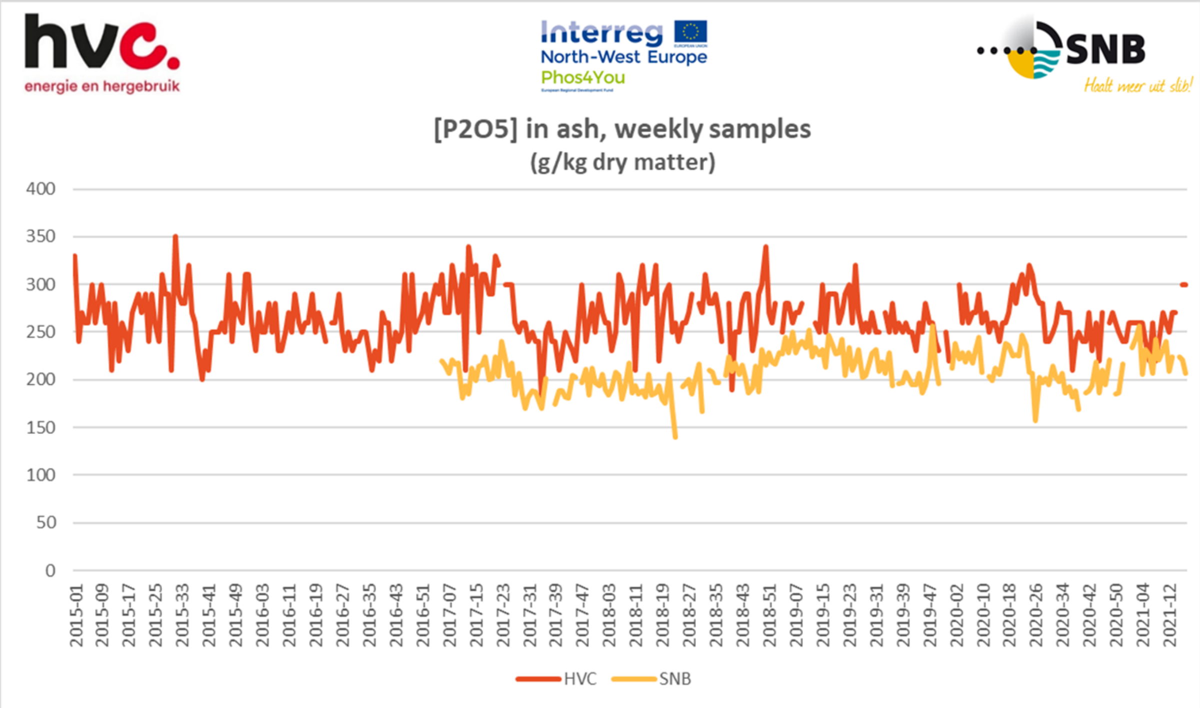


Figure 5.2.2: P_2O_5 content in sewage sludge ashes of HVC and SNB (Ruijter et al. 2021)

5.2.2 Scenarios for P-recovery

All 21 water authorities in The Netherlands have a high ambition to recover phosphorus. It is not possible/ permitted to directly apply sewage sludge in agricultural land. Unlike Germany, in The Netherlands phosphate recovery is not obliged by law (see part 1.1).

In this part, the following draft scenarios for large scale P-recovery that were, and are still considered, are presented:

- Dunkerque/France, ash delivery contract (wet chemical leaching)
- Direct ash delivery to fertilising industry (blending process) in The Netherlands
- Co-participation with a technology provider (wet chemical leaching) in The Netherlands

5.2.2.1 Scenario 1: Dunkerque (France) - ash delivery

This scenario focussed on a location that is characterised by two main advantages: The location was very near to an industrial site that produced hydrochloric acid (HCl), which is needed for a wet-chemical leaching process that enables more than 80 % of P-recovery from sewage sludge ashes. The second advantage was the proximity of the sea, which made disposal (which was allowed in the past) of the by-product of CaCl permittable.

The scenario comprised the following key aspects:

- All the sewage sludge incineration ashes that are currently available in The Netherlands, about 60,000 tonnes;
- Technology based on wet leaching process with hydrochloric acid and phosphoric acid;
- Production of technical or merchant grade phosphoric acid;
- A cooperation model that was based on a supply contract for ashes. The fertiliser plant was intended to be responsible for the sales of end-product;
- The fertiliser-company would invest;
- Issues/challenges: the valorisation of the residual ash after P-recovery remained a problem as the fertiliser plant had less experience with this material, while the ash-producers had no hands-on influence and market in France. Currently, ash applications as a filling material in asphalt or in concrete tiles require a dry product (which is not the case with the ash residue coming out of a wet-chemical P-recovery process). Cross border transport is an important disadvantage because of the additional required administration.

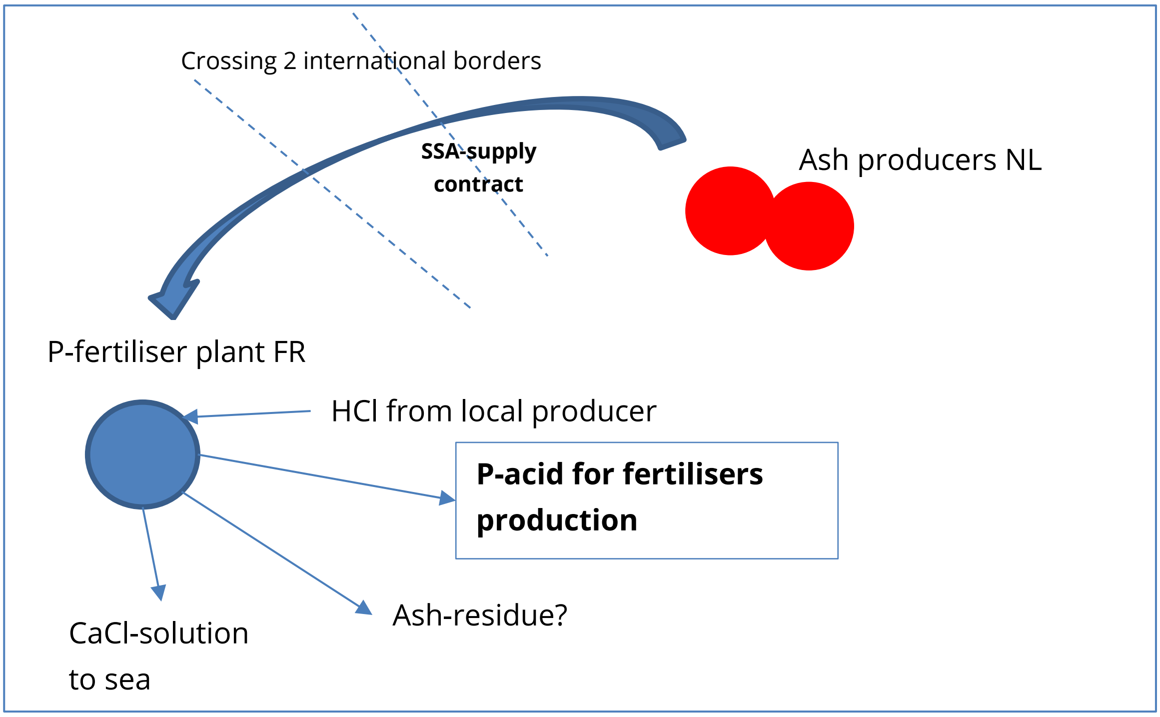


Figure 5.2.3: Schematic representation of the scenario "sewage sludge ash delivery from The Netherlands to a plant of an external provider located in France

The scenario as represented in Figure 5.2.3 came to a halt, due to the bankruptcy of the phosphate company Ecophos, the provider. With the same type of technology, the Dunkerque site however, is still an attractive location. Prayon bought the Intellectual Property of the Ecophos technology and pilot plant research facilities in Varna (Bulgaria) (Prayon 5/6/2020) and is looking at options to continue this scenario.

5.2.2.2 Scenario 2: Direct ash delivery to a fertilising industry in The Netherlands

This scenario was characterised by the fact that sewages sludge ash was supplied directly to the fertilising industry, and no ash-residue remains after the process. This made it less complicated for ash-producers. However, concerns about heavy metals in the end-product need to be taken into account.

If the ash supplier and the fertiliser producer ICL are both located in The Netherlands no transboundary regulation has to be fulfilled. The quality of the ashes is being monitored by HVC/SNB by taking representative samples and analysing several components as contractually agreed. The final fertiliser product must comply with the new Fertilising Regulation. If the fertilising industry is outside the Netherlands, then transboundary regulation has to be met. Transboundary transport complicates the logistics due to the additional required administration.

The scenario comprised the following key aspects:

- ± 20 % of the sewage sludge ashes of HVC and SNB are currently available for this route;
- Technology was based on blending SSA, acids and P-rock, while no specific separation of heavy metals took place. To comply to fertiliser regulation, just a small ratio of SSA could be used;
- As an advantage no separate residual waste stream was produced;
- A cooperation model that was based on a supply contract for ashes. The fertiliser plant was responsible for the quality and the sales of the end product;
- The fertiliser company managed the investment and operation of the plant. No co-investment by ash-producers was required;
- Issues/challenges:
    - The fertilising company needed to have a waste permit to be able to accept the required ashes (specified by Eural waste codes Eural 19.01.14).
    - A new fertiliser product would be produced. REACH requirements applied to the end-product. Technically challenging was the physical blending process which, on a full-scale installation, appeared to react differently than was expected.

- If SSA did not meet acceptance requirements, an alternative take-off had to be arranged (e.g. as filling material). Such companies, however, require a constant off take of fly ash (amount, quality) to be able to maintain the required installation and products/markets in which the ash is being reused. If transboundary transport was required, the transport and destination had to be arranged three days before. If the fertilising industry requires sampling and quality assessment of each truckload this would complicate transport.
- According to the Dutch regulation (Landelijk Afval Plan, Ministry of Infrastructure and Water Management (2019)) recovery of phosphate should not lead to an increase of landfilled material.

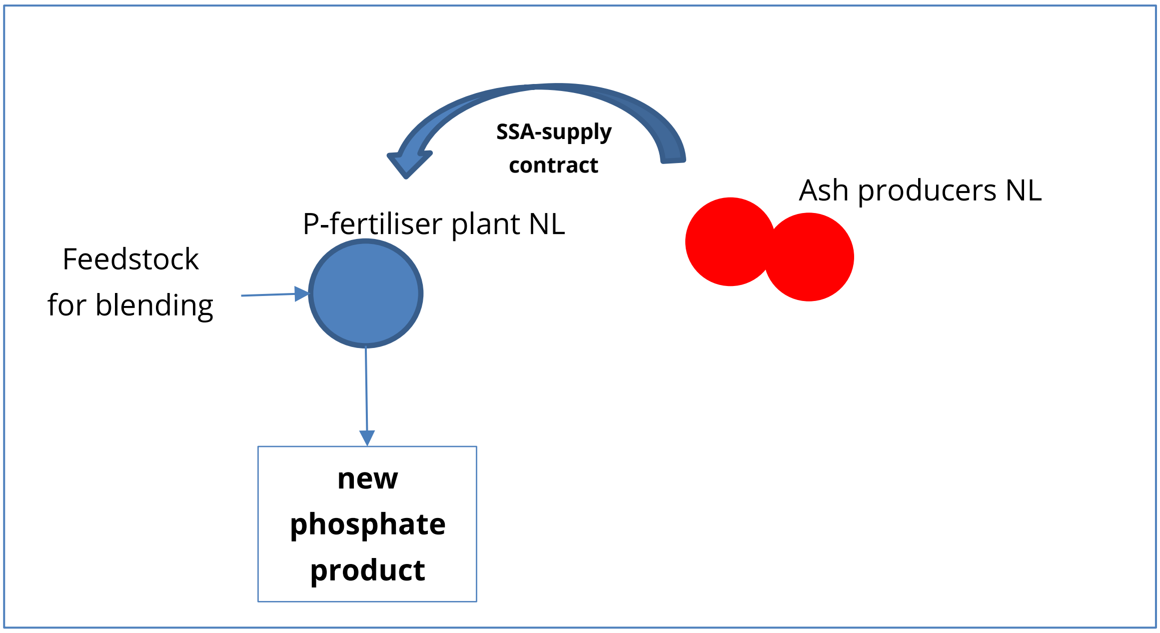


Figure 5.2.4: Schematic representation of the scenario "sewage sludge ash delivery from The Netherlands to a plant of an external provider located in The Netherlands"

The scenario as represented in Figure 5.2.4 was contractually agreed upon in 2019. Up to 2021 however only marginal amounts of SSA were ordered by ICL. ICL mentioned problems with pelletizing quality and REACH clarification. Furthermore, high Fe and Al content in the ashes make it expensive to extract the phosphorus.

Since mid-August 2021, one truck load a week has been delivered, indicating that slowly the process is becoming stable.

5.2.2.3 Scenario 3: Co-participation with a technology provider in The Netherlands

Although contracts for full scale delivery were signed, the previous mentioned scenarios have not yet developed into a realisation phase for large scale P-recovery. Therefore, the last scenario focussed on a close cooperation with all parties: ash suppliers, technology provider (Remondis Aqua B.V.) and water authorities. The final P-product would be a bulk chemical (P-acid) that can be relatively easily adopted by the market. The location would be in The Netherlands, so that disadvantages of cross-border logistics were avoided, and advantages of shared responsibility with regard to by-products could be organised between partners that are already natural cooperation partners.

This scenario comprised the following key characteristics:

- Technology based on wet–leaching with high P-recovery yield, wastewater stream was limited due to lower salt content;
- The technology included the recovery of metal salts, to be used by water authorities for use at the WWTPs;
- Assessed locations, of which Moerdijk seemed the most promising due to the proximity of ash-producers, chemicals and waste water facilities (permitting);
- Co-investment by SSA-producers and technology providers, managed in a joint venture company;
- Issues/challenges:
    - Valorisation of the ash-residue after P-recovery in order to comply with the Dutch requirements (see chapter 1.1);
    - Lower grade metal salts compared to mainstream metal salts (coagulants), so that efforts at WWTP level need to be in place and additional transport costs to be considered. This is further topic for investigation.
    - Co-investing and participation in a phosphorus plant, would imply a technical life span of about 20 years. This would mean that the lifetime of HVC's and SNB mono-incinerators would need to be prolonged. It would mean continuing with sludge incineration while potentially new regulations or technologies might emerge which might give encouragement to reduce incineration (and with that CO_2 emissions!).

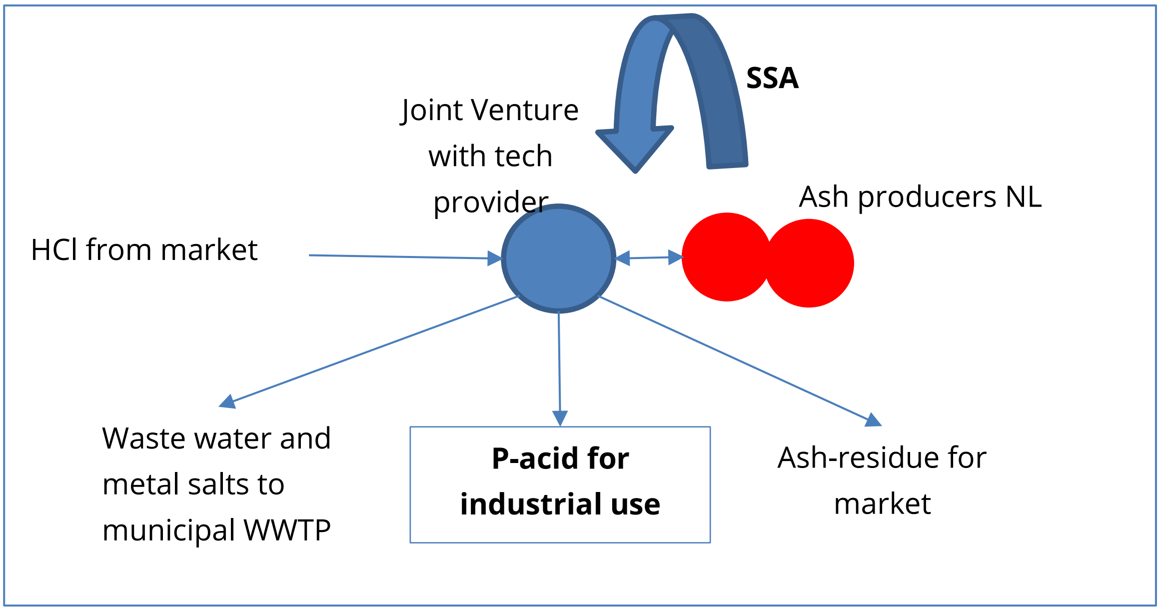


Figure 5.2.5: Schematic representation of the scenario "co-investment in P-recovery facilities to produce phosphoric acid out of sewage sludge ashes"

Pre-industrial tests of the Dutch ashes with the Remondis TetraPhos process confirmed the feasibility of the scenario represented in Figure 5.2.5 (REMONDIS Aqua Industrie GmbH & Co. KG 2021). In the next phase HVC, SNB and Remondis are investigating a further cooperation with the aim to have a running installation in 2025. The investigations comprise several aspects: 1) the reuse of all by-products from the TetraPhos process, 2) a feasible business case 3) a governance model acceptable for all parties in which risks are evenly spread amongst the parties. Another crucial pre-condition for decision making at shareholders level of HVC and SNB is that the TetraPhos-plant in Hamburg should be in operation.

5.2.3 Conclusion and outlook

Currently no decisions have been taken yet on the final choice for the best technology in combination with a governance model. However, a clear set of conditions were determined by HVC and SNB as to accelerate the selection and decision progress:

- P-recovery with a yield of > 80 %;
- A proven technology, and a first plant need to be in operation;
- A limited time to realisation;
- Full-scale installation permittable at or close to the site of SSA–producer in The Netherlands;
- Financial commitment by the technology provider.

This leads to the conclusion that TetraPhos technology of Remondis is the preferred main route to a full-scale plant with a capacity of around 60,000 tonnes of sewage sludge ashes.

Besides the large-scale phosphorus recovery process using SSA, smaller scale struvite production took place at several waste water treatment plants. This is mainly done to improve the operations of the WWTP rather than for nutrient recovery. However, struvite is nowadays a well-known fertiliser, albeit a niche in the market (Boer et al. 2018). If the P content in the SSA increases, more P-product can be produced and therefore the business-case of P-recovery from SSA will improve. Increasing the P content in the sludge by returning the struvite to it is one option to improve the business-case of P-recovery from ashes. However, the production and selling of the struvite does not always have to lead to a lower P content in the sludge if the P concentration in the effluent of the WWTP is reduced as was the case at WWTP Land van Cuijk. Depending on struvite prices and the P product from SSA, the overall profitability can be assessed.

Several institutions, for example Wetsus in Leeuwarden, The Netherlands, are also researching the potential of vivianite (iron phosphate) to be magnetically recovered from the sludge phase (e.g. in the Horizon2020 ViviMag project). The technology however is not yet applied on an industrial scale. Also, other thermochemical processes and leaching process are being piloted. For smaller amounts of ashes, new technologies, such as the Susphos technology (P-acid for fire retardants) are promising. Especially for HVC's 3 new shareholder water authorities, a feasibility study will be set up in order to select the most promising technology for smaller scale applications after 2025.

Overall, the available technologies for recovering P do not yet seem to lead to significant lower sludge disposal costs despite the recovery of the phosphate. During the development phase of new technology prospects are favourable and associated problems tend to be underestimated by the developers. Rightfully so as otherwise no new technology would ever be developed! However, as there is no P-recovery obligation in the Netherlands and therefore no deadline to implement P-recovery, these (too) positive expectations of new technologies lead to a tendency to postpone investments whilst awaiting for the possibility of more profitable technologies.

5.3 Strategical options for recycling phosphorus from wastewater in the Emscher-Lippe region

Authors: Dennis Blöhse, Dirk Bogaczyk, Marie-Edith Ploteau, Issa Nafo (Lippeverband)

5.3.1 Framework and possible recycling routes

The Emscher-Lippe region is located in North Rhine-Westphalia and includes the central and northern part of the "Ruhr area" (Ruhrgebiet), one of the largest agglomerations in Germany. The catchment area is essentially formed by several large cities that have grown together and achieved their present structure with industrialisation and mining in the 19th and 20th centuries. It owes its name to the two rivers Emscher and Lippe.

Emschergenossenschaft (EG) is a water management association largely responsible for the treatment of the wastewater produced in the Emscher basin. Together with Lippeverband (LV), which is responsible for wastewater treatment north of the Ruhr area (Lippe basin), both jointly operate a total of 59 wastewater treatment plants as an administrative community. The size of the plants ranges between 1,500 and 2.4 million PE. The total capacity amounts to 7.1 million PE. Currently, around 730 million m^3 of wastewater per year is treated in the WWTPs. The sewage sludge (SS) produced is digested and mainly dewatered in centralised dewatering structures, located in WWTP at larger facilities. These plants produce an average of more than 300,000 tonnes of dewatered sewage sludge per year.

In 2020, a mixed utilisation of sewage sludge took place. This consisted mainly of mono-incineration (80%) and, a small proportion of co-incineration (20%). In the future, all sludge will be fed to mono-incineration. For this purpose, EG operates its own incineration plant in Bottrop. A second incineration plant is available in Lünen, operated by its subsidiaries (BETREM/Innovatherm). At the Bottrop site, the largest worldwide solar-thermal drying plant is currently (2021) going into operation (Knake et al. 2020). A drying plant is also being planned and built at the Lünen site. The existing incineration capacities for municipal sludge will expand because the previously used high-calorific-value industrial sludges and waste can be dispensed with. In the future, it is planned to primarily recycle external municipal sludge in addition to EGLV sludges. The total incineration capacity of both plants will be up to 170,000 tonnes DM after completion of the new drying facilities.

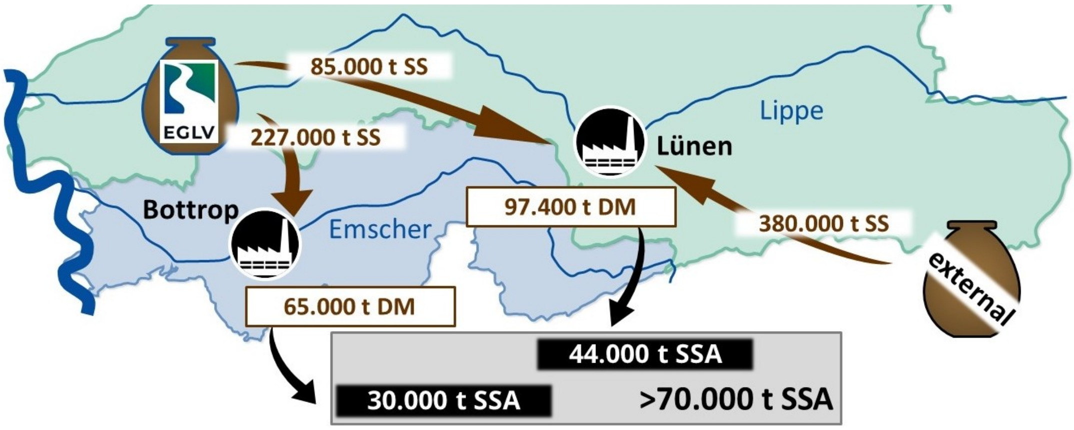


Figure 5.3.1 Perspective of the SS flows and the SSA produced at the sites of EG (Bottrop) and Innovatherm (Lünen) in 2029 (planning basis) (Blöhse et al. 2021)

The requirements for sludge disposal in Germany are established in the Sewage Sludge Ordinance (AbfKlärV) which bans land application of sewage sludge by 2029 for large facilities (> 100,000 PE) or 2032 for small facilities (> 50,000 PE), and requires the recovery of phosphorus from sludge if the P-content is higher than 2 % of dry matter.

There are two main issues to be considered for the future obligation to recover P in Germany:

- No recovery is necessary for sewage sludge with < 2 % P per DM - in principle, it can be recycled in power plants, waste incineration plants or in the cement industry (so-called co-incineration).
- If sewage sludges with < 2 % P per DM are recycled in a mixture together (in this case mono-incineration) with other sewage sludges which contain more than 2 % P per DM (thus concerned by the obligation), the P-recovery from the entire incineration ash produced will be necessary.

The sewage sludge from EGLV is above the limit value in all cases. Only decentralised P-recovery in the sludge treatment plants can produce sewage sludge with < 2 % P and then enable the use of the resulting sewage sludge in co-incineration.

In principle, this results in three routes, which are shown in Figure 5.3.2.

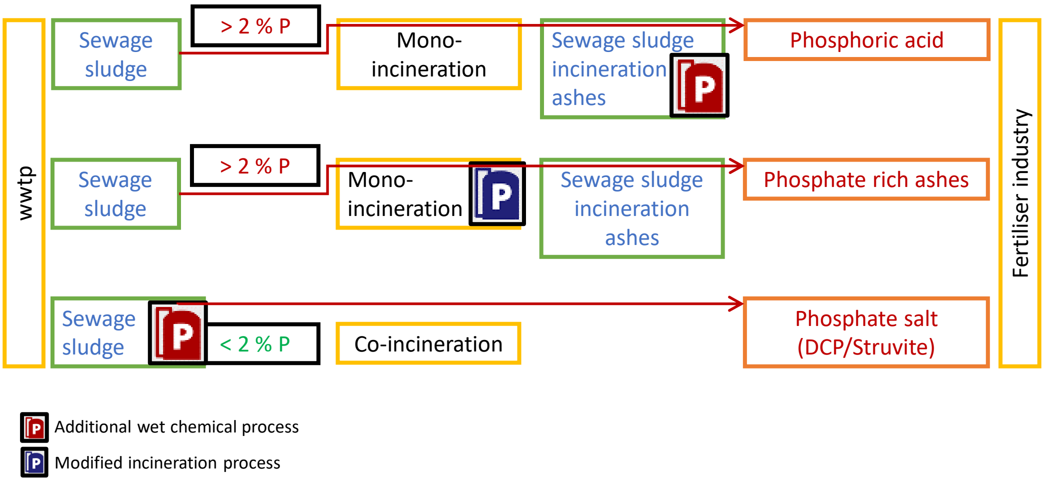


Figure 5.3.2: Possible P-Recovery routes

A possible decentralised P-recovery at the WWTP via extraction from the sewage sludge, and subsequent P precipitation, is ignored during the scenarios choice and only considered as a complementary route (co-incineration), due to the number of sludge treatment facilities, as well as the (internal) requirements to make use of the existing incinerators to capacity.

Based on the presented infrastructure with existing incinerators, phosphorus recovery from sewage sludge incineration ash (SSA) is focused on. For the year 2029, it can be expected that > 70,000 tonnes of incineration ashes will have to be treated for mandatory P-recovery (Figure 5.3.1). In this process, a substantial amount of external sewage sludge is also recycled in the incineration plant in Lünen. The obligation to recover phosphorus is in this case transferred to the operator of the incineration plant.

Against this background, EGLV have intensively considered two possible routes with their own work as part of Phos4You:

1. incineration of sewage sludge in fluidised bed furnaces (mono incineration) with subsequent recovery of phosphorus from the incineration ashes (wet chemical P-recovery);
2. alternative: modified incineration according to the EuPhoRe® process with production of fertiliser-compliant incineration ash (thermochemical P-recovery).

Results of this investigations are published in Blöhse and Nafo (2021).

5.3.2 Business models

Regardless of the scenarios investigated, one question water authorities face is how to get organised for the implementation of phosphorus recycling.

In relation to the entire value chain of P-recycling (Figure 5.3.3), the following questions play a role in the selection of a business model:

1. should the statutory tasks of EGLV be expanded to include P-recycling so that the P-recyclates can ultimately be marketed in-house?
2. should the marketing of the P-recyclates be carried out by existing distribution structures of third parties?
3. should all P-recycling activities be outsourced?
4. should a subsidiary be established with or without the participation of private companies (PPP) to fulfil the task of P-recycling?

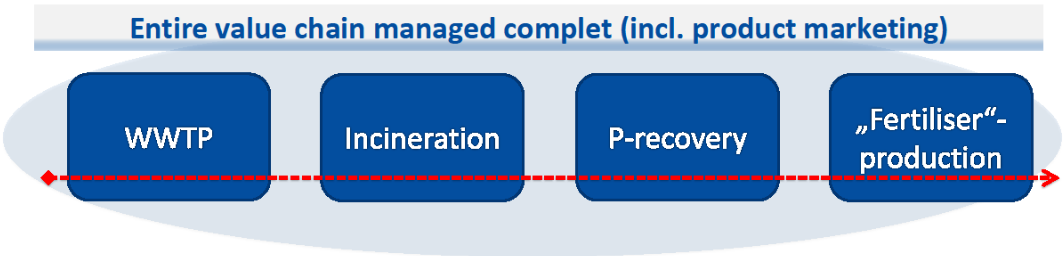


Figure 5.3.3: Value chain of P-recycling including a sewage sludge incineration stage (Blöhse and Bogaczyk 2019)

Since the production of a marketable fertiliser (as well as distribution and marketing) involve considerable additional effort, this task should be passed to existing third parties (chemical wholesaler and fertiliser producers). In addition, complete outsourcing is conceivable if third parties set up appropriate structures for P-recycling from sewage sludge incineration ash.

However, joint cooperation with private companies in the sense of public-private partnerships is viewed critically. The integration of private companies tends to be questioned critically, since water management is generally carried out under public law.

Based on those considerations, three general options for a business approach for implementing P-recycling at EGLV can be established (Figure 5.3.4):

1. Integration of P-recovery into the core business (in-house model)
2. Implementation of P-recovery within a public cooperation (cooperation model)
3. Tendering of P-recovery as a service (outsourcing)

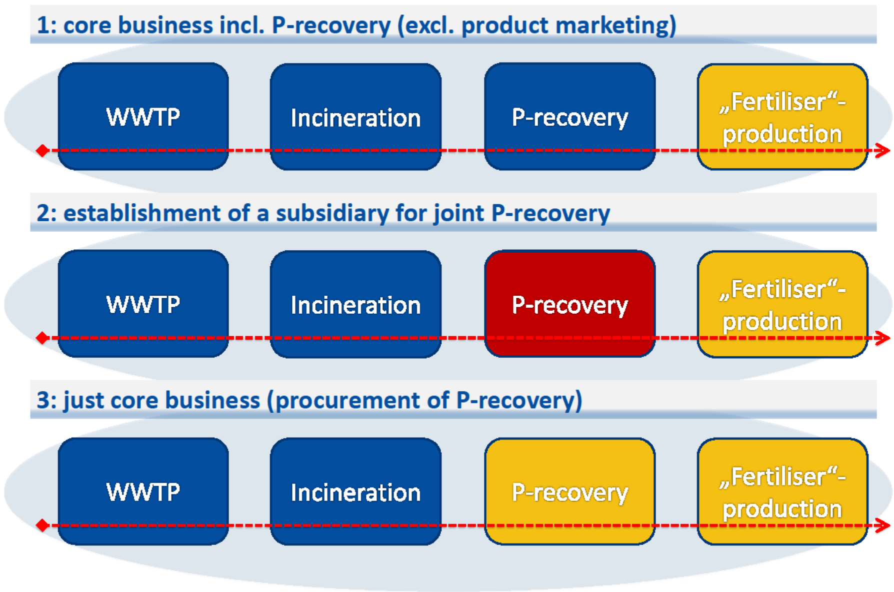


Figure 5.3.4: Options for a business approach for implementing P-recycling at EGLV (Blöhse and Bogaczyk 2019)

5.3.3 Location

As shown in Figure 5.3.1, two central operating sites with incineration plants are located in the catchment area of the EGLV. A large amount of incineration ash will be produced centrally. Therefore, these sites are suitable for P-recovery from incineration ash. Given a wet-chemical process with a high demand for operating materials (e.g. chemicals) then, an external site (for example chemical parks) may offer advantages. This is further considered in the following.

5.3.4 Scenarios choice

Scenarios can be based on different time horizons and can be designed both centrally and decentrally. The scenarios primarily considered here are based on the boundary conditions currently targeted by EGLV's sewage sludge strategy for the next 10 years. As listed above, the initial priority P-recycling route is considered with wet chemical P-recovery from incineration ash. The so-called sewage sludge management is not considered for the time being, except in one sub-variant.

In addition, the following scenarios are based on the three business model options shown above. The implemented variants are based on different location options as listed before.

5.3.4.1 In-house model

In the selected scenarios, basically two different site options are considered. In option 1), the ashes are treated directly at the point of origin (decentralised), i.e. at each incineration site. In option 2), the ashes are treated centrally at a common site.

The centralised site could be a) at the wastewater treatment plant in Bottrop (incineration site) b) at the incineration plant in Lünen (Innovatherm) or c) at an external site (e.g. a chemical park).

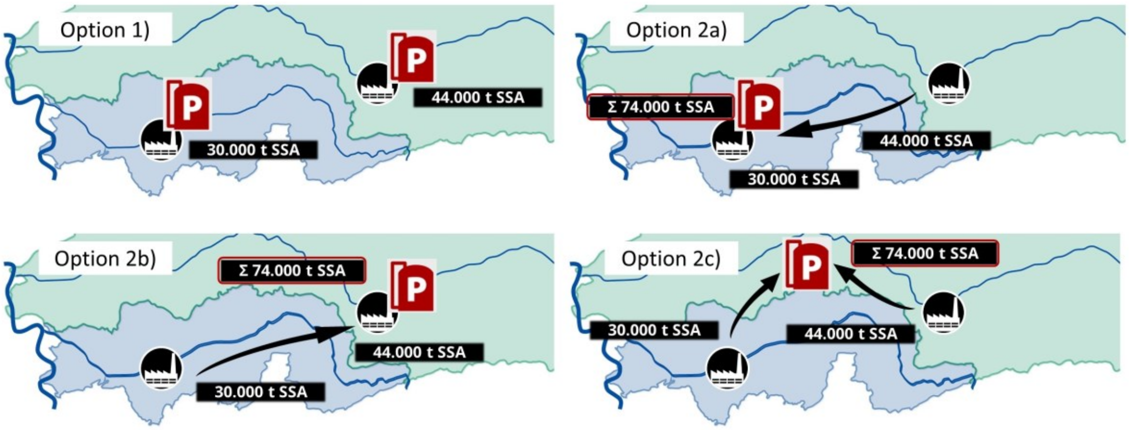


Figure 5.3.5: Schematic illustration of the in-house model implementing a wet-chemical P-recovery (Blöhse et al. 2021)

The decentralised option 1 would allow for further variants through the implementation of a thermo-chemical P-recovery (here EuPhoRe® technology). One variant considered is that a plant with a capacity of approx. 85,000 tonnes SS is built at an additional site and operated by the LV (Figure 5.3.6). At this site, sludge that has a low load of heavy metals (e.g. Ni, Cu) can be directly processed into a fertiliser material (EuPhoRe® ash) and used regionally. The produced ash at the Bottrop and Lünen sites, would still be processed into P-recovery using a wet-chemical process.

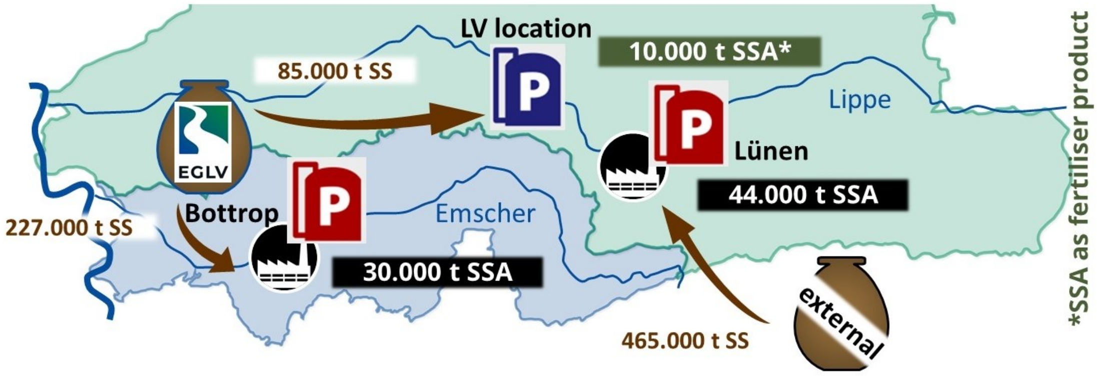


Figure 5.3.6: Schematic illustration of a possible extension of the in-house model implementing both, a wet-chemical recovery and a thermochemical P-recovery (Blöhse et al. 2021)

5.3.4.2 Cooperation model

The above-mentioned central treatment of incineration ash (Option 2a, b, c) could be expanded through possible inter-municipal cooperation. In this case, an increase in throughput at a central treatment plant through the co-treatment of incineration ashes from third parties is included as a variant. In the scenario of inter-municipal expansion, existing as well as planned incineration plants in the region were included. A total mass of ash of approx. 120,000 tonnes per year is produced and is jointly treated at a central location (Figure 5.3.7).

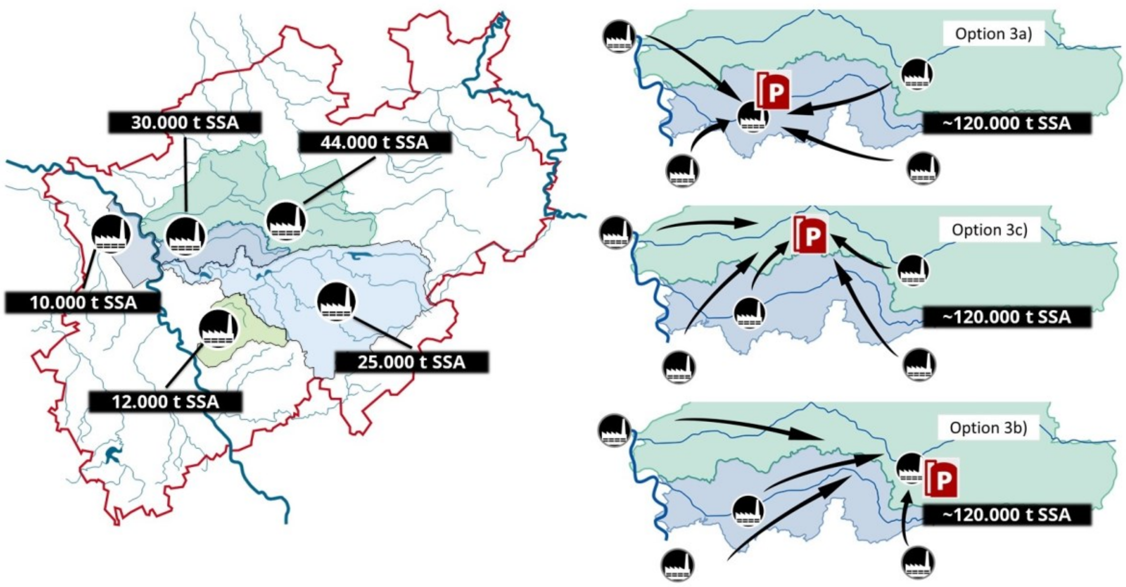


Figure 5.3.7: Schematic illustration of possible extension for a model of cooperate with waterboards (Blöhse et al. 2021)

This central location – similar to the in-house model – could be a) at the WWTP in Bottrop (incineration site) b) at the incineration plant in Lünen (Innovatherm) or c) at an external site (e.g. a chemical park).

This scenario was investigated in a complementary project in a joint concept phase. Five waterboards have joined forces to develop a sewage sludge and SSA management system for the region, together with further partners. For the implementation within the pilot project, a public subsidiary PhosRec Phosphor-Recycling Ltd was founded. The AMPHORE project (funded by the German Federal Ministry of Education and Research - BMBF) started in 2020 and has a duration of 5 years (German Federal Ministry of Education and Research 2021). This regional SSA-based approach for large-scale technology implementation is thus further consolidated in this specific cooperation model. Potentially, such a large-scale implementation could foresee capacities to carry out the P-recovery of additional external sewage sludge.

5.3.4.3 Outsourcing model

The third option considered is to have external parties carrying out the P-recovery. This requires, for example, that large fertiliser manufacturers integrate SSA into existing processes by means of appropriate pre-treatment or P-recovery. International stakeholders with large fertilisers manufacturing plants were identified in the Netherlands (ICL), in Norway (Yara), in Belgium (Prayon), in Spain (Fertiberia) and also in Serbia (Elixir group).

The use of waterway infrastructure (in North-Rhine-Westphalia) and transport by ship are particularly interesting for longer distances. With existing inland harbours, it would be possible to make the accumulating ash masses available for cross-border transport. With regard to the provision and storage, as well as to the requirements of the external suppliers, many detailed aspects need to be clarified, as explained in the following.

5.3.5 Results of the case studies

As part of the Phos4You project, the necessary information was gathered to enable case studies to be prepared on the basis of the outlined scenarios. Various location factors, such as space, provision of energy (if necessary through surplus energy), the availability of operating resources, and the potential for integration into existing infrastructure, need particular consideration. The corresponding investing and operating cost have been estimated for all the points mentioned.

In addition, logistical aspects were included. Potential value chains and associated stakeholders were discussed and the identification of sites for the use of the residual materials and by-products was determined.

5.3.5.1 *Technology*

Based on the results of the work in the demonstrations of thermochemical process (I1) and wet-chemical processes (I2) (Klein et al. 2021; Blöhse and Nafo 2021), the necessary investments and the consumption of operating resources can be considered. It became clear that a cost-covering implementation cannot be expected on the basis of the existing conditions at EGLV. As well as the economic challenges, there are also technical issues that prevent an implementation before 2029.

In addition, the quality and quantity of products, by-products and residual materials were identified. In comparison with literature data, factors were determined that illustrate the logistical challenges that arise.

Table 5.3.1: Transport goods depending on the annual throughput of a P-recovery plant with wet-chemical process (Blöhse et al. 2021; Ploteau et al. 2020, modified)

Goods in transit	Factor per tonne SSA	Capacity of P-recovery plant			
SSA*	1.0	30,000	70,000	120,000	
Chemical demand	0.5 – 1.5	15,000-45,000	35,000-105,000	60,000-180,000	
H_3PO_4 (75 %)	0.2	6,000	14,000	24,000	
Ca-By-product	0.3 – 0.4	9,000-12,000	21,000-28,000	36,000-48,000	tonnes/a
Fe/Al-By-product	1.0 – 2.0	30,000-60,000	70,000-140,000	120,000-240,000	
Residues	1.0 – 1.2	30,000-36,000	70,000-84,000	120,000-144,000	
Total (min-max)	**2.5 – 3.8**	**120,000-189,000**	**280,000-441,000**	**636,000-756,000**	

*minus the SSA arising at the location of the P-recovery plant

In a scenario with additional ash from third parties, treatment capacities of, for example, more than 100,000 tonnes ash/a may be necessary. With the factor of 3 described above, up to 400,000 tonnes of goods would have to be transported, resulting in approximately 16,000 trucks on the roads in Germany's largest agglomeration. Therefore, it makes sense to deal with logistical issues at an early stage.

5.3.5.2 Logistics and operation site

Against this background, the Phos4You project examined future logistics concepts for the scenarios outlined. A concrete value chain was set up and the necessary stakeholders identified. The following approaches were taken when considering logistical challenges:

- Implementation of alternative transport by ship and/or train
- Calculation of transport costs and emission (Supply, staff and energy costs)
- Cost estimates for infra- and superstructure
- Consideration of different locations
    - Two operation sites of EG (Bottrop) and Innovatherm (Lünen)
    - Three externals (2 different chemical parks, 1 industrial area - chemical wholesaler)

Despite relatively short distances between the selected locations of the recycling plant and their customers and suppliers, there were economic as well as ecological advantages in the use of alternative modes of transport, such as rail and ship. However, it also became clear that high investments in infra- and superstructure are necessary for this. The general conditions at the various locations are very different. The sites were evaluated on the basis of the following criteria:

- Land availability
- Right of approval
- Modality
- Investment needs
- Logistics costs
- Other location factors
    - Suppliers/customers - on site/or not
    - Disposal or utilisation opportunities - on site/or not
    - Energy surplus (electricity/heat) - on site/or not

In conclusion, all sites have advantages and disadvantages. For example, a chemical park has the advantage of chemical provision, but with regard to any residual materials, the proximity to corresponding recyclers and disposal companies also need to be evaluated positively. The same applies to the connection to a wastewater treatment plant for the recycling of metal solutions or for any wastewater disposal that may be necessary. To obtain answers to the locational question, concrete examples with detailed information must be examined, as it was done in the case study.

5.3.5.3 Requirements of externalisation

In addition to the logistical issues involved in the regional implementation of P-recycling, the transport requirements for the outsourcing model were also considered. Due to the relatively long distances, there are clear advantages for transport by ship. However, high investment costs, especially for storage and shipment, as well as corresponding land availability must be considered. The administrative effort involved in international waste shipments should also not be underestimated, especially in the case of hazardous waste.

The necessary framework conditions must be clarified or created by the service provider to ensure reliable disposal for the water authority who remains responsible for a compliant SSA-disposal. Processes must be adapted to ensure necessary capacity to accommodate waste-based secondary raw materials, including the corresponding permits for the reception and processing of the waste. Furthermore, acceptance criteria for the quality of the SSA (and consequences if not) must be defined. Finally, a certificate will be required to certify to the competent authority in Germany that P-recovery has occurred.

5.3.5.4 Summarized evaluation of the scenarios

In summary, the options established with the scenarios can be evaluated as follows:

1. In-house model → Directly implementable, but P-recovery is not expected to be cost-covering and technology readiness is still "rather low“;
2. Cooperation model → Joint cooperation provides many possible synergies (economy of scope/scale), but also challenges (high space and resource requirements). Investigation with new R&D project participation (AMPHORE);
3. Outsourcing model → High provider engagement is required and there are a lot of open questions which need to be investigated.

EGLV and subsidiaries are broadly positioned with their activities. Within Phos4You technical solutions were identified and good network with stakeholders at national and international level was created.

In the next steps EGLV will continue to track and promote technology development and evaluate detailed aspects of implementation (location/logistics/customers/suppliers). The presented options must be continuously reviewed and adjusted against new developments.

5.3.6 Résumé

Once a decision has been made on technology, and when statements can be met with a certain degree of probability about the occurrence, quality and quality fluctuations of the products, by-products and residual materials, then stakeholder discussions can be intensified to define the value chain (establishment of customer and supplier relationships).

The same applies to the choice of location. Here, the organisational orientation of the implementation with regard to cooperation models is decisive, because this also determines the plant size and any site-specific restrictions.

Thus, it will be necessary to validate and refine previous findings. Involvement of EGLV in R&D projects, with large-scale implementation of wet-chemical P-recovery from SSA, will bring about necessary operational experience. On this basis, the case studies can be validated and lead to further decisions.

6 Prepared territorial deployments of P-recycling in Remote, Rural & Island (RRI) context

Whereas P-recycling technology in some urban areas in North-West Europe is being actively progressed by forward thinking operators, the deployment of P-recycling in Remote, Rural & Island (RRI) context requires a phase of stakeholders' engagement. On the basis that two NWE-countries have large RRI areas, i.e. Scotland and Ireland, stakeholders´ initiatives were carried out within the project Phos4You. A decision support tool using a geographic information system was also developed, with the aim of supporting stakeholder engagement and the decision process related to the P-recycling. The main findings of those works are presented here.

6.1 Stakeholders engagement initiatives and dynamics based on Scottish and Irish experiences

In order to engage with stakeholders on the P-challenge, the Scottish and Irish partners of Phos4You mainly went through the following steps (Figure 6.1.1): a launch event (in Edinburgh, 2017 involving all Scottish Partners; and in Portlaoise - County Laois, 2018 organised by MTU); a stakeholders analysis including interviews with key stakeholders; dissemination events and site visits of pilot plants; a questionnaire; a wrap-up event (online, November 2021).

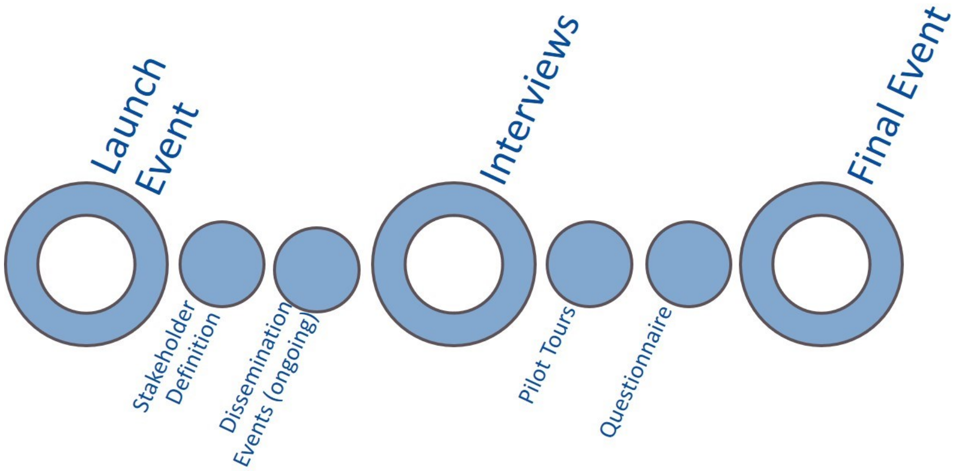


Figure 6.1.1: Engagement timeline applied by Scottish and Irish partners (Kennedy 2021, modified)

6.1.1 Stakeholders analysis in Scotland

Authors: Karin Helwig, Paul Teedon, Ania Escudero, Ole Pahl (GCU)

This part presents parts of the “Phos4You Scottish Stakeholder Analysis” (Helwig et al. [in press]). GCU’s analysis for the understanding of the stakeholder field relating to phosphorus recovery in Scotland is based on data gathered in two phases. The first phase consisted of a workshop (launch event, 2017) attended by 27 stakeholders from academia, government, SMEs, the Water Industry, the regulator, consultancy and a professional body (CIWEM). The second phase consisted of 15 semi-structured interviews with key stakeholders (experts from industry, agronomy, government and the regulator), targeted to follow up on the findings in phase 1. The resulting data enabled the team to map stakeholders’ role and influence in the ‘P-recovery cycle’, and to understand the factors that determined their level of interest in and their attitudes toward P-recovery. In this ‘phosphorus recovery cycle’, four key ‘locations’ of P are distinguished and it is the progression through these locations that enables the flow of the cycle and thus sustainable, circular P use: P in recovered product, P application to land, P in food chain and P in sewage (Figure 6.1.2).

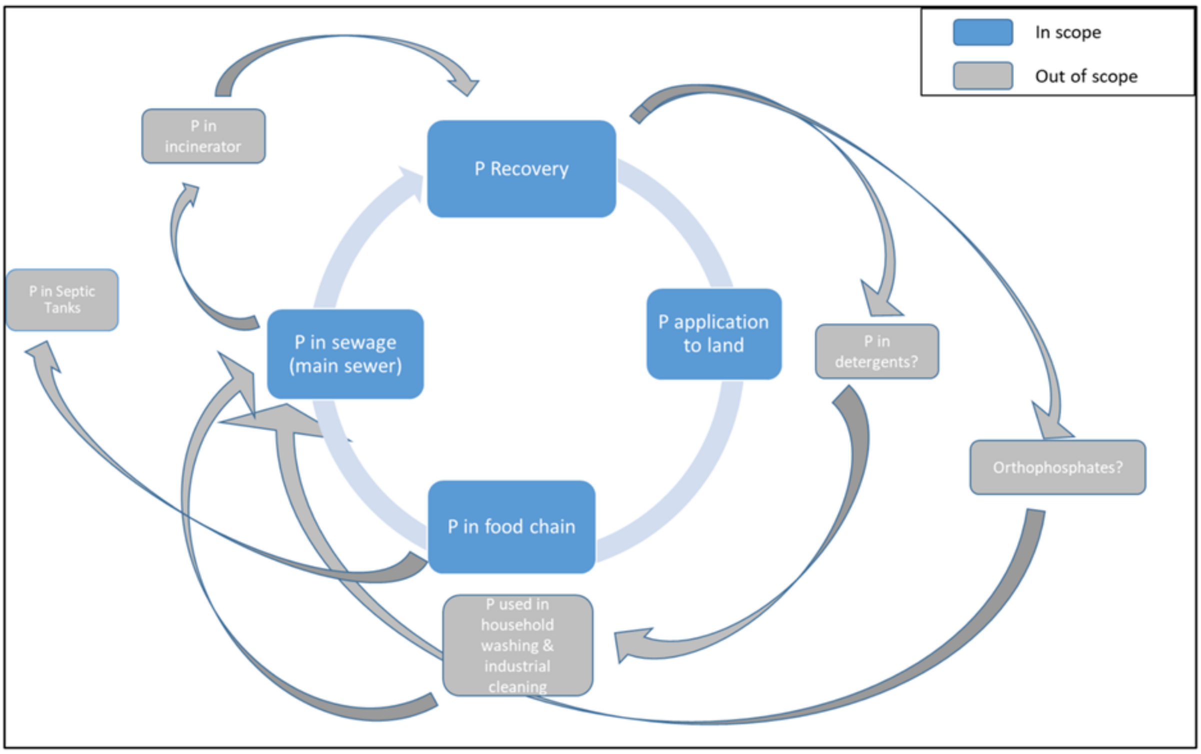


Figure 6.1.2: The phosphorus recovery cycle

6.1.1.1 Progression 1: P-recovery

In this stage, two separate processes need to happen: the technology needs to be (1) brought to market and (2) implemented.

The first process, developing the technology, takes place in negotiation between academic partners and technology companies. Funders influence this sphere (but are considered outside this study´s scope). Key negotiated considerations are the match with prior research interests, innovation value, price, and (perceived) future marketability or demand.

In the second process, the move towards implementation of the technology, the most important stakeholder is the WWTP operator, in Scotland usually Scottish Water (SW). Without their involvement, P-recovery will never be realised to a significant extent (in terms of total amount of P in wastewater) as they have direct or indirect control over the majority of wastewater. Their interest and attitude are determined by the organisation's appetite for innovation and business values, but also by negotiated factors. The negotiation between technology company and WWTP operator is predominantly about performance, price, product, and operational issues. On the other hand, the WWTP may be influenced by the regulator e.g. through regulatory target values, subsidies, and 'soft' encouragement.

From the interview data, it emerged that P is one of the most important compliance issues for the water industry, but one respondent also reported that an agreement is in place between SW and SEPA to consider where it is possible to go beyond compliance. It also emerged that there is considerable local variation in the need for intervention and any regulatory thresholds that may be applied.

At the stakeholder event, it was felt that in the early stages of the technology P-recovery may not be commercially viable, but the power of the regulator to drive change via subsidies or regulation was widely recognised. From the interviews, it is clear that the regulator maintains a 'democratic stakeholder' approach and considers a wide range of stakeholders and objectives: in Scotland, in most locations the water quality is not so poor that a price increase to the consumer is merited. On the other hand, the principle of P-recovery is supported, as the regulator's vision is that of 'One Planet Living'.

6.1.1.2 Progression 2: P application to land

In this section of the recovered P cycle, farmers are largely the gatekeepers, as they take the decision whether or not to apply recovered P. This section contains initial findings only, for which in particular the agronomists' interviews were very informative.

At the launch event, concerns were raised by stakeholders about contaminants in recovered P. In interviews, some thought that public opinion would be an important factor for farmers in their decision-making on whether or not to use recovered P. By contrast, others thought a 'green' image achieved through recovered P use might give farming businesses a market-edge.

Agronomists considered that various quality assurance schemes prescribed precisely what fertilisers should be applied to a crop, in particular for arable crops, and could put constraints on this e.g. with regards to sewage sludge application. It was thought that quality assurance organisations might also be concerned about public perception. This finding requires further exploration with farmers and with quality assurance organisations.

The quality and physical form of the P product were considered important, but ultimately outweighed by price: one agronomist gave an example of a P product recovered from animal waste that had poor physical form, but was made available at an attractive price, and had been taken up widely by farmers.

Agronomists advised farmers on P management and bioavailability, risk and long-term sustainability. One agronomist considered that products derived from waste should not present an additional cost to farmers. Farmers' decisions were also thought to depend on (perceived) long-term sustainability, appetite for innovation and core values such as adherence to tradition. Farm-specific factors were thought to include farm type (livestock or arable), crop type, and intensiveness of farming.

6.1.1.3 Progression 3: P in food

The significance of this progression is that many respondents felt that improvements in P efficiency was a more logical solution to both 'problems' (as defined at the stakeholder event) – eutrophication and scarcity of the P resource – than P-recovery. This could be an important reason why some stakeholders, whilst influential and positive towards P-recovery, do not perceive a great urgency or motivation to act.

Respondents felt that efficiencies in P uptake could be much improved: it was thought that P is commonly over-applied, resulting in unnecessary use of P as a scarce resource and in eutrophication where excess P reaches the water environment.

There were numerous remarks about inefficient application methods and potential improvements, in particular about the potential of Nutrient Management Plans. Currently, these are primarily formulated around nitrogen. Interviewees thought N-P-K ratios in fertiliser are not commonly targeted to suit the soil, which in any case can vary from field to field. Agronomists estimated that perhaps half of all farmers take regular soil samples.

Farmers' decision-making on the use of technologies to improve efficiencies in P application – such as precision-application of fertilisers – was mainly thought to depend on appetite for innovation and intensiveness of farming.

6.1.1.4 Interim conclusion

Based on the stakeholder engagement activities thus far, most stakeholders are moderately positive about recovered P, but see no great urgency either to recover it or to apply it. This relates directly to the most common problem definitions held by stakeholders, which relate to eutrophication of surface waters and the need to preserve P as a scarce resource: for both of these problems, P efficiency improvements are seen as a more promising solution than P-recovery.

Nevertheless, there appears to be support for P-recovery, which would align with the desire amongst policy makers and the water industry to go 'beyond compliance'. It is however seen as important that it does not lead to rising costs for the public, which would not be justified by the relatively good current surface water quality. It was expected that in the future, the price of phosphate rock may go up due to global population growth and changing consumption patterns. In addition, respondents thought that awareness of P as a scarce resource, as one of our planetary boundaries, was rising gradually.

Other future drivers might include cheaper and faster soil tests which could aid better Nutrient Management, increased demand for sustainable products from dairy buyers and supermarkets, and a desire for reduced reliance on imports in government circles.

This led some to believe that the interest in recovered P might well rise in the future – the question, though, is when.

6.1.2 Outcomes of the survey on P-recovery in Ireland

Authors: Dr. Aoife Egan, Dr. Niamh Power, Denise Barnett, Dr. Joe Harrington (MTU); Barbara Bremner (ERI)

This part gives the summary and highlights of the reported results of the stakeholders´ survey carried out in Ireland in 2021 (Egan et al. 2021).

6.1.2.1 Summary of results

"This […] study aimed to survey rural and urban Irish participants to assess their reasons for and the importance of recovering P and their concerns, awareness and opinions of using P from recovered sources such as wastewater. In addition, their opinion of the future use of recovered P was also determined. […].

The respondents had good insight into the importance of recovering P from waste sources and suggested that the cost of fertilisers and water contamination would be the main drivers that influence them to recover P from wastewater. Overall, the respondents had a very good understanding of the contribution mineral fertiliser, agricultural run-off and animal manure have on P emissions in rural waterways and the effects they have on water quality and eutrophication.

Participants, in general, were very familiar with a wide variety of P-recovery technologies from wastewater; however, they were most aware of chemical recovery technologies. Their preferred solution for P-recovery was the development of a range of new P-recovery technologies and building new infrastructure, as they shared their concerns for the Irish WWTP capacity and availability of technology.

Again, the respondents were aware of the present usage of P in Ireland suggesting that the main sources of P were artificial fertilisers and animal manure. They also indicated that the product cost was the main factor in land operators' decisions when selecting a fertiliser and fertiliser cost would be the main condition to consider when using P from recovered sources.

In terms of the future use of P and its demand in Ireland, the participants were aware that recovering P from a rural wastewater source would improve environmental protection and would help achieve a good water status. In addition, the participants were optimistic about P-recovery in the future, suggesting it was likely to change in Ireland in the medium term and very likely in the long term.

To promote the development of P-recovery technologies and to encourage the uptake of recovered P from wastewater and other recycled sources, the stakeholders' concerns highlighted in this survey must be taken into consideration. The respondents’ awareness of the importance of finding alternative recycled sources of P is highlighted in the survey and the next step from a developer’s point of view is to implement these changes, therefore actively contributing to the circular economy.” (Egan et al. 2021).

The survey carried out in March 2021 included rural stakeholders in Scotland and the general findings concur with stakeholder response in Ireland. However, the response rate in Scotland was low due to issues with cyber security at North Highland College at the time of the survey so only qualitative comment may be drawn from findings.

6.1.2.2 Irish survey highlights

The Main Concerns Regarding Wastewater Effluent in Ireland

The Irish respondents' main concerns regarding wastewater effluent, assessed with an open-ended question (Figure 6.1.3) included:

- Contamination (31% of respondents), in particular the presence of excess nutrients in the wastewater was an issue, such as P in freshwaters and lakes. The respondents were also concerned about heavy metals and chemicals in the wastewater effluent and the presence of microorganisms.
- Impact on water quality (30% of respondents), in particular they were concerned about water quality, especially eutrophication.
- Wastewater treatment plant capacity/ technology (25% of respondents), with some indicating that wastewater effluent is inadequately treated.

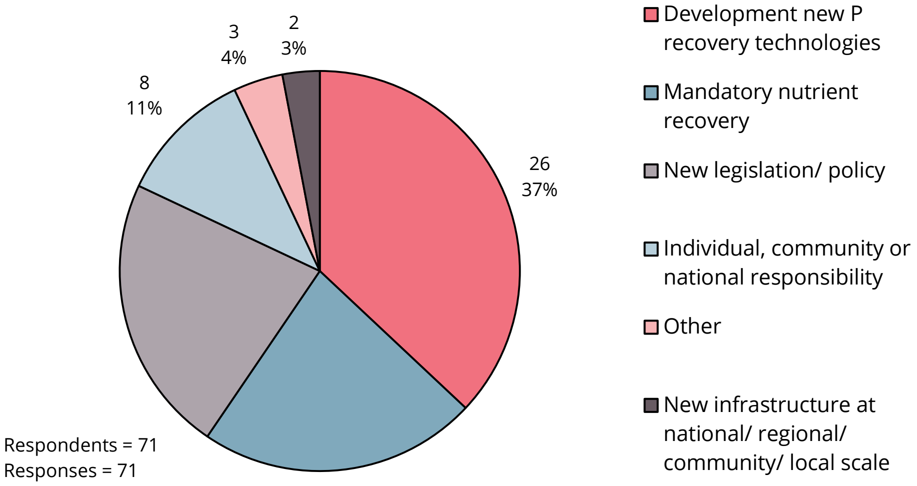
Respondents = 73
Word count = 665

Figure 6.1.3: Word cloud produced from the most commonly occurring words in the open-ended question, on the main concerns regarding wastewater effluent or other waste streams (Egan et al. 2021)

Preferred solution for Urban/rural P-recovery in Ireland

The participants preferred solution for urban/rural P-recovery was explored with a single answer question; where the participants had a choice of five different solution options to choose from.

- The respondents preferred solution was the development of new P-recovery technologies (Figure 6.1.4), including those appropriate for small-scale wastewater treatment systems.
- However, they also preferred mandatory nutrient recovery and new legislation/ policy as a solution for P-recovery.



The number of responses and the percentage of the survey responses is indicated in the figure.

Figure 6.1.4: Overall distribution of respondents' preferred solution for urban/rural P-recovery (Egan et al. 2021)

Main considerations regarding using P from recovered sources in Ireland

The respondents' main considerations regarding using P from recovered sources were explored using a ranking question (Figure 6.1.5). An overview of the ranked conditions to consider when using P from recovered sources include:

- That participants indicated that the quality of P from recovered sources, and the price of the fertiliser were the most important considerations when using P from recovered sources respectively.
- They also indicated that the availability of P as a fertiliser/ the security of supply was the next most important consideration.

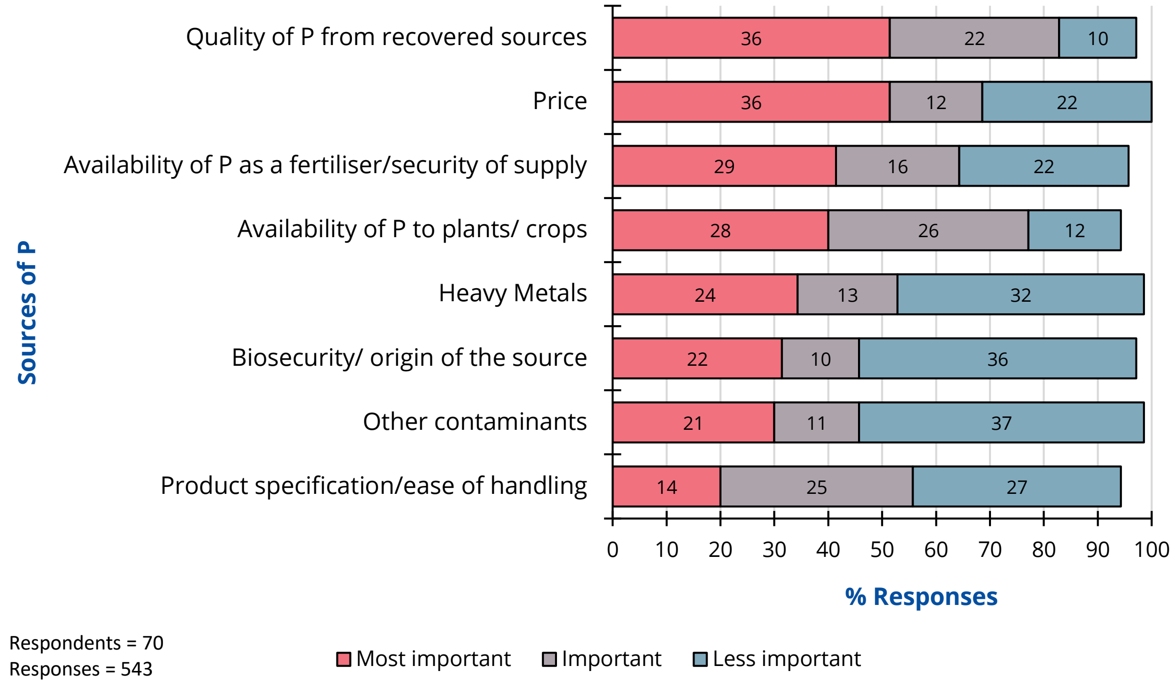
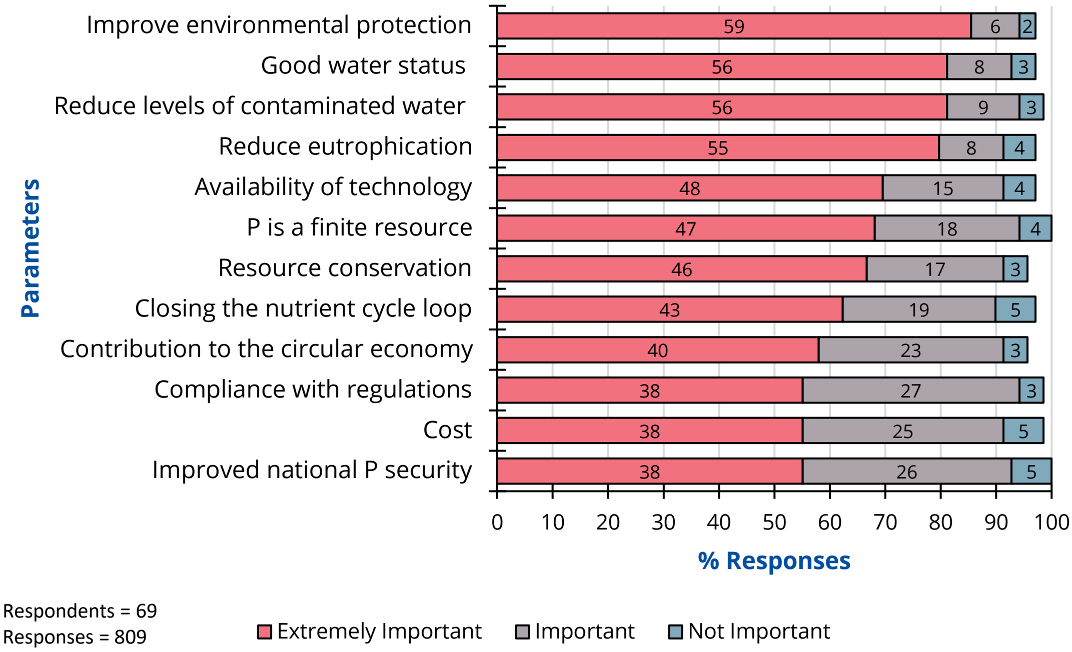


Figure 6.1.5: Overall distribution of the conditions to consider when using P from recovered sources (Egan et al. 2021)

Parameters to consider in the decision-making process when recovering P from a rural wastewater source in Ireland

An overview of the ranked parameters to consider in the decision-making process when recovering P from a rural wastewater source include:

- Participants consider recovering P from a rural wastewater source will improve environmental protection. This was an extremely important parameter (Figure 6.1.6).
- Reduced levels of contaminated water and good water status, respectively, were extremely important as they were ranked joint 2nd.
- In addition, reducing eutrophication was also extremely important as it was ranked 3rd.



The number of responses and the percentage of the survey responses is indicated in the figure.

Figure 6.1.6: Overall distribution of the parameters to consider in the decision-making process when recovering P from a rural wastewater source (Egan et al. 2021)

6.2 Findings made out of the GIS-based decision support tool

Authors: Pierre Thiriet, Thierry Bioteau (INRAE)

To support the decision-making processes by developing P-recovery strategies, a decision support tool (DST) was developed within the Phos4You project. The GIS-based DST is presented in this section.

The goal of the DST is to provide *relevant information* to stakeholders to identify the *potential application of P-recovery solutions* at the scale of EU countries. To that end, the tool is designed to identify the 'optimal' treatment plant according to their characteristics and their local context. These criteria can be used to search plants suitable for the specific constraint of a given P-recovery solution. The tool specifications were defined during the first consultation phase. The key characteristics selected were the following:

- The tool should make available information for all the project partners and potentially for a wider audience.
- The tool should provide a treatment plant explorer including their location.
- The tool should allow areas (administrative, watersheds, etc.) exploration regarding their sewage sludge treatment profile.
- The tool should display a series of spatial datasets related to sewage sludge and phosphorus recovery.

A web map tool appeared to be the best DST shape to overcome the availability constraints, the needs of interactivity, and the spatial nature of the data. It was decided to ground the application on a *PostgreSQL/PostGIS* server. This server hosts not only the spatial data but also any other tabular data such as settings table.

The DST now exists: https://dst.p4y.web-maps.fr/ and offers two approaches to the user. The main one is based on the UWWTPs as an entry point. The second approach uses areas (administrative areas, watersheds, or regular grid) to interact with databases.

6.2.1 Treatment plants approach

The *treatment plants approach* is based on two essential components, summarized in Figure 6.2.1.

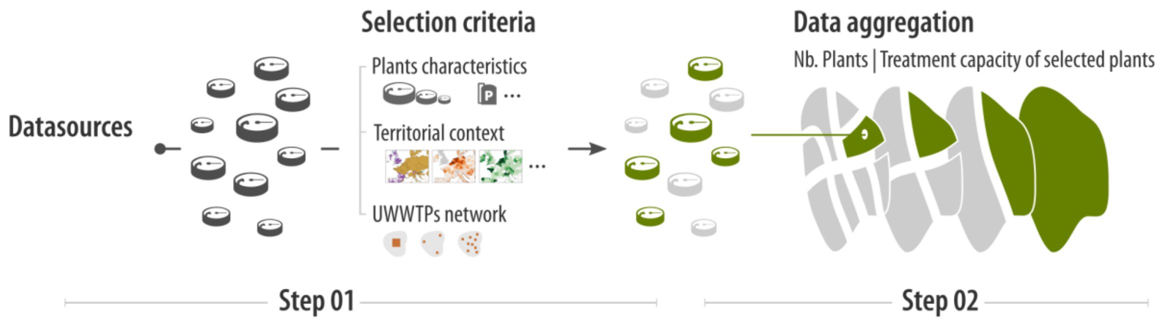


Figure 6.2.1: Schema of the "treatment plants" approach of the DST (Thiriet and Bioteau 2020)

The selection of treatment plants

The website provides a user-friendly tool for exploring wastewater treatment data in multiple dimensions. The underlying database contains information for both UWWTPs and incinerators. For UWWTPs, several data sources are available to combine spatial coverage and data accuracy. The parameters for filtering the data are gathered in three groups: *UWWTPs characteristics*, the *territorial context*, and the *UWWTPs network.*

Table 6.2.1: List of criteria used in the DST to filter UWWTPs data

Topic	Description	Criteria
UWWTPs characteristics	Main characteristics of the UWWTPs	· Treatment capacity (PE) · Phosphorus removal · Phosphorus removal performance
Territorial context	Regulation and eco-environmental local or regional context of the UWWTPs and their discharge points	· P-recovery obligation · Sensitive areas for phosphorus · Ecological water quality of watersheds · Livestock density (nuts 2)
UWWTPs network	Spatial organisation of the UWWTPs network based on their proximity for cluster identification or isolated plants	· Number of plants located within a specific radius distance of each plant · Sum of capacities of the plants located within a specific radius distance of each plant

The data aggregation

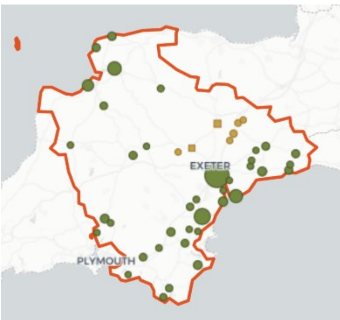
By default, the DST returns a simple map of the location of the plants selected. An additional aggregation step allows summarizing information at a different spatial scale and with different variables. The DST provides three groups of spatial aggregation further divided into several scale level:

- *Administrative limit*: Nuts 0, 1, 2, 3
- *Watershed from Ecrins*[8]: Basins districts and sub-basins
- *Regular grid*: 50km hexagonal grid

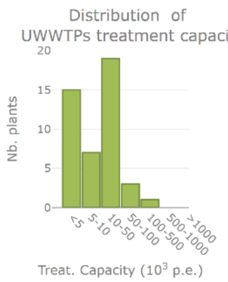
6.2.2 Area approach

The *area approach* aims at providing an overview of target territories and providing a simple synthetic profile of their UWWTPs system. It provides an interactive tool for the exploration of the UWWTPs of specific areas. Several type or size of areas can be selected: *administrative limit* (Nuts 1, 2, 3), *watershed* from Ecrins (Basins districts and sub-basins) and *regular grid* (50 km hexagonal grid).

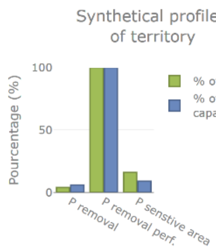
The tool returns 3 types of information for a selected area Figure 6.2.2



Map of a target area with location and characteristics of the UWWTPs



Histogram of UWWTPs treatment capacity



Complementary info about UWWTPs

Figure 6.2.2: Outputs of the "areas approach" (Thiriet and Bioteau 2020)

In addition, other relevant datasets, such as census data, livestock density, protected areas were added as complementary information.

6.2.3 Scotland scenario

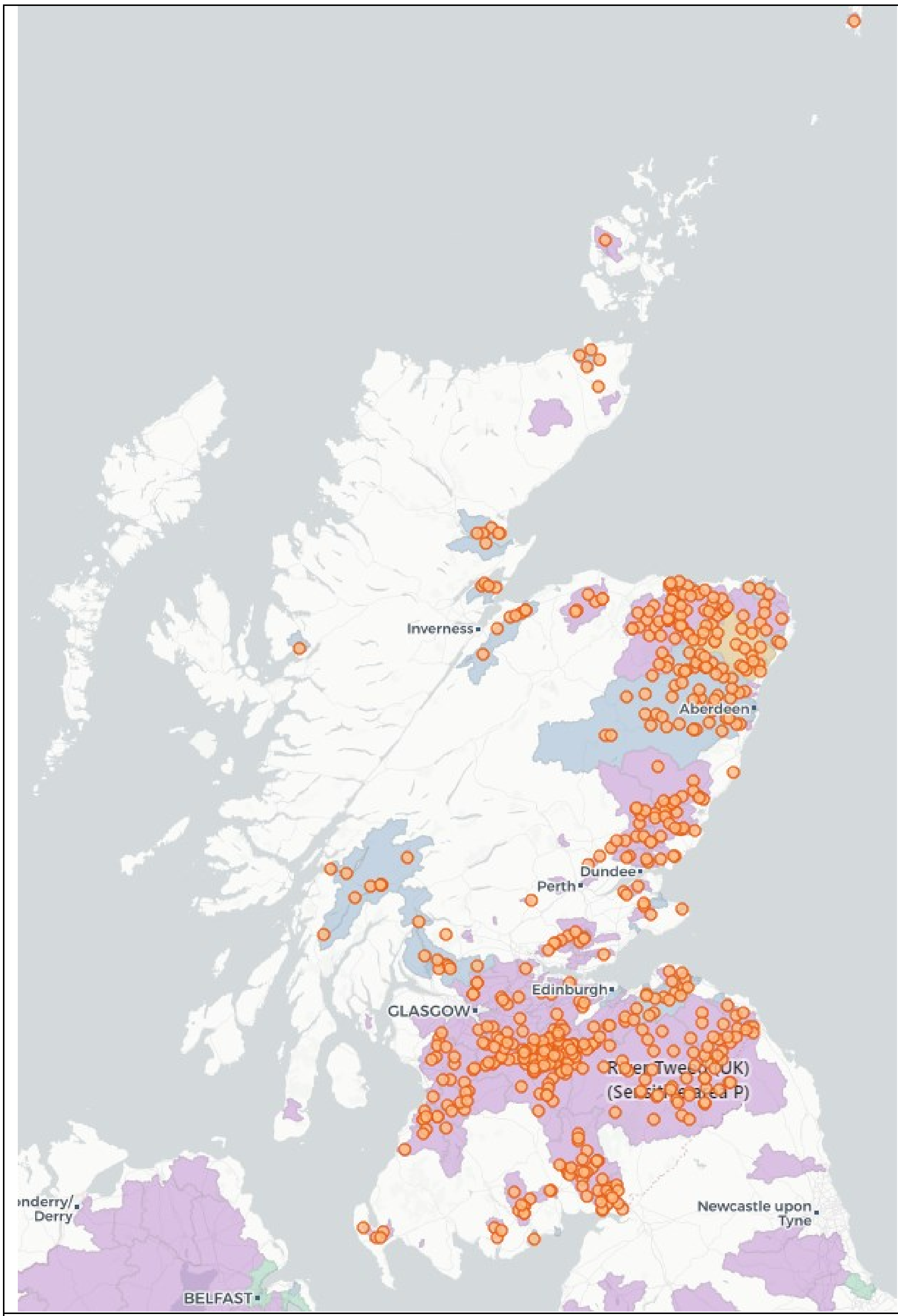
Thanks to the DST, the results of the scenario described below can be obtained in a few minutes.

[8] European catchments and Rivers network system (Ecrins): https://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network

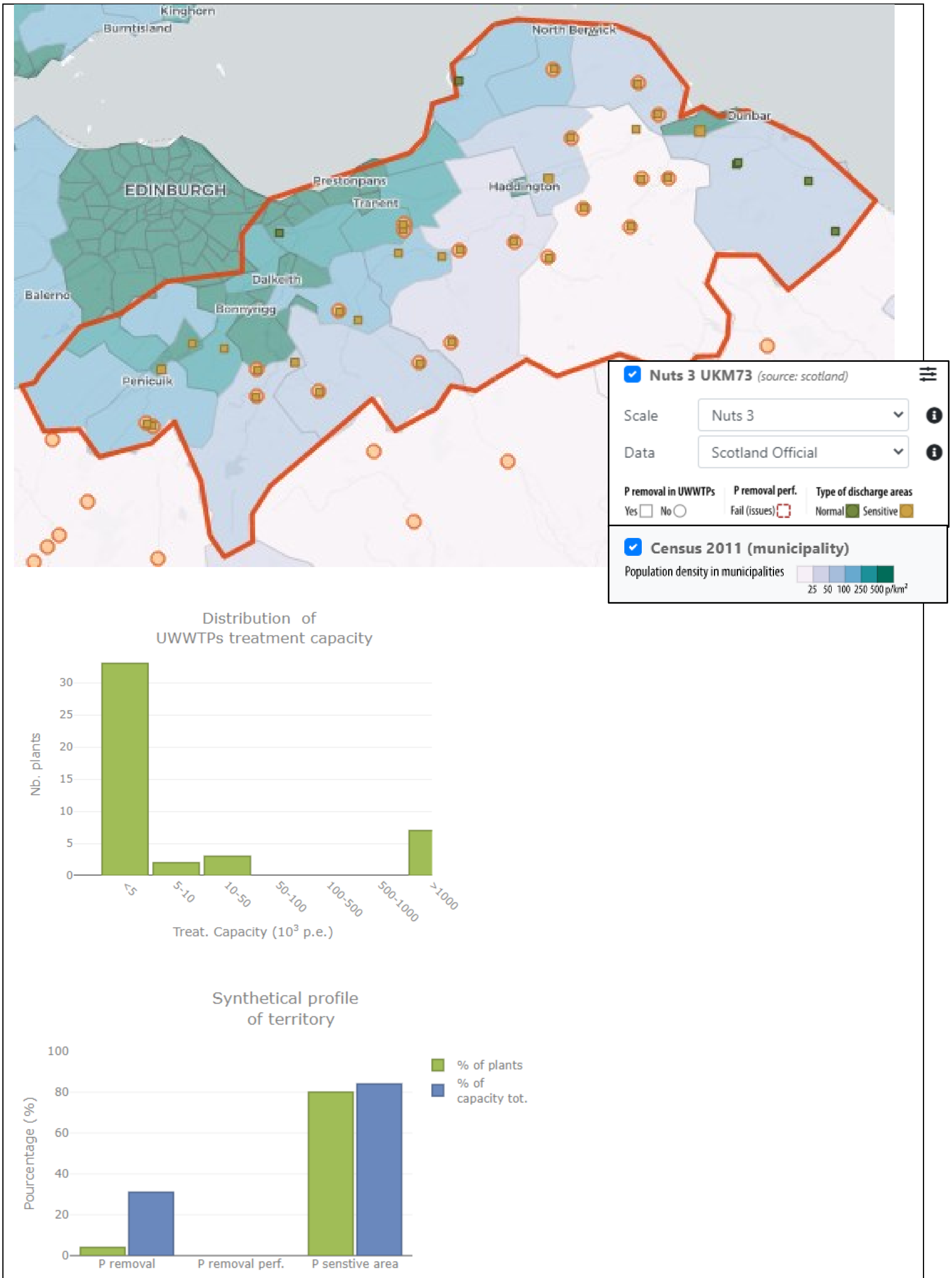
In a first approach, the user wants to have a preview of all the UWWTPS less than 1000 PE in Scotland and only located in sensitive areas.

In a second approach, the user wants to focus on the district of East Lothian and Midlothian (Nuts 3 code: UKM73) in combination with the population density and display charts with the main characteristics.

The different maps and data of the result obtained are described in the figure below:



UWWTPs < 1000 PE in sensitive areas



Detail information on the district of East Lothian and Midlothian

Figure 6.2.3: Results of a Scottish scenario.

As a commentary on this scenario focusing on East Lothian and Midlothian, it is observed that the majority of the UWWTPs are less than 5000 PE and mainly located in sensitive areas. A suitable P solution for small-scale wastewater treatment might be implemented in areas with very low population density, for instance in the south of the city of Haddington. Thanks to the additional data available on the website, the livestock density appears to be very low. In addition, the East Lothian lowland plain is one of the largest areas of high yielding farmland in Scotland (East Lothian Antiquarians and Field Naturalists Society 1998). While the phosphorus application rate in Scotland has decreased since the mid-2000 in farmland, the agricultural needs remain high, about 46 kt of P_2O_5 in 2019 (The British Survey of Fertiliser Practice 2021).

Thus, a low livestock density combined with intensive cropping suggests local needs for phosphate fertilisation that could be partially satisfied from the recovery of phosphorus from UWWTPs - allowing use on neighbouring farms which currently have to buy phosphate fertilisers.

As a global comment, the DST shaped in the form of a web map tool could be useful for different stakeholders. All the data included in the DST can be found independently but the force of the website is to gather in the same tool all the useful data to allow dedicated spatial combinations and aggregations. Because it displays a series of spatial datasets related to sewage sludge, the base of different scenarios can be built in few minutes regarding various phosphorus recovery solutions.

6.3 Conclusion and outlook

Authors: Anna Baran, Tamsyn Kennedy (Scottish Water)

The potential for phosphorus recovery from RRI (Remote, Rural and Island) locations is high, however it is unlikely to be realised in the foreseeable future. The majority of rural wastewater treatment works (or septic tanks) offer basic treatment, with bioresource taken away to local STC's (Bioresource Treatment Centres) for further processing, then recycled to land.

This activity is regulated under either "The Sludge (Use in Agriculture) Regulations (1989) (Sludge Regs) or the "Waste Management Licensing (Scotland) Regulations (2011) (WML Regs) depending on the material applied and its purpose. Any materials have to be applied at a beneficial rate to the soil and comply with the standards set out in the appropriate regulation. As biosolids can be used as fertiliser in Scotland phosphorus is fully recovered from those materials.

Therefore, without change in regulations and major investment in current wastewater treatment technology in RRI locations, the use of phosphorus material technically recovered from wastewater treatment process will hardly occur.

During the Phos4You final workshop for Scotland, 24th November 2021, the status quo of phosphorus recovery and the future perspective for Scotland was discussed with relevant stakeholders from Scottish government, the Scottish Environment Protection Agency, Scottish enterprises and research institutes.

From the survey that was undertaken amongst Scottish stakeholders (section 6.1.1) the response to the perceived problem about phosphorus as a scarce resource included the request to increase phosphorus efficiency. Stakeholders discussed that, although this is not an argument for phosphorus recovery, the controlled slow-release characteristics often offered by phosphorus recycling materials can directly contribute to enhance the phosphorus efficiency use, by avoiding P-accumulation in soils.

The land application of sewage sludge in Scotland is evaluated to have great sustainability, agronomic and environmental benefits, where the suitability in P supply balances against risks associated with the potential of soil contamination, losses to water, crop/food contamination and GhG emissions (Stutter et al. 2021). Stakeholders nevertheless identified multiple benefits from potential use of phosphorus recovered materials: the reduction of antibiotics or other micropollutants transferred to soils in comparison with direct land application of sewage sludge; potentially better quality in comparison with phosphate rock sourced fertilisers in terms of undesirable contents such as cadmium or uranium; possibly better availability of phosphorus in comparison with the sewage sludge; the additional characteristics as organic soil improver/ plant biostimulants compared to single chemical P fertiliser. Also, the distribution of the phosphorus contained in wastewater over wider distances might be facilitated when the phosphorus has been recovered in form of e.g. struvite rather than being transported with the sewage sludge (Stutter et al. 2021). All those aspects can be highlighted to foster the market for phosphorus recovered materials in RRI locations.

To overcome regulatory barriers for the use of recycled phosphorus fertilisers on land, stakeholders identified a need to elaborate further the end-of-waste status. The Scottish Environment Agency is able to act with respect to the environment in Scotland; beyond that the UK government is invited to undergo a UK certification scheme.

Finally, the following subjects for future investigation have been identified:

- Chemical assessment and further analyses to provide data that will underline arguments identifying the multiple benefits of phosphorus recycling materials;
- Investigation into the market needs for phosphorus in Scotland, including price assessment;
- Research in phosphorus recovery technologies including LCA;
- Cooperation with organic farmers and industry to identify a targeted (local) market.

7 Conclusions and recommendations

The project Phos4You was thoroughly implemented in the seven partner countries of the North-West Europe area between 2016 and 2021. Through the implementation of phosphorus recovery technologies under real life conditions, seven possibilities of how phosphorus (currently lost through incineration of sewage sludge or in wastewater effluent) can be technically recovered and recycled in existing or innovative value chains were demonstrated. The LCA of the processes concluded on a beneficial environmental impact for technical recovery of phosphorus from wastewater compared to production of mineral fertilisers from mined phosphate under the category of mineral resource scarcity, but not always on other categories such as climate change and fossil fuel depletion. The quality assessment of the products concluded on a positive agronomical value of the recovered materials and on their global safety. Actions plans for further implementation of the phosphorus recovery were developed for urban areas in The Netherlands, in Switzerland and in the Emscher-Lippe Region in Germany. Further implementation in Scotland and Ireland were also prepared, although here the stakeholders engagement initiatives were largely affected by the COVID pandemic related restrictions.

Based on key-findings and experiences of the partnership, some recommendations for policy makers at European and national levels, for investors, and standardisation bodies and towards research and education funding programme have been proposed as follows.

7.1 Recommendations towards policy makers at EU level

Large-scale implementation of P-recovery plants is difficult. There are still many uncertainties for investors (reliability of the technologies, market opportunities for the phosphorus materials, financing…). Also, for initial developments, the price of recovered materials can hardly compete with the price of phosphate rock even when it fluctuates. Therefore, suitable policy to support implementation is required.

7.1.1 EU rules for production and labelling of organic products

The European rules for the production of organic products (currently Regulation (EC) 834/2007 replaced by OFR 2018/848 from 2022 on) include a restrictive list of authorised products and substances which may be used in organic farming as fertilisers, soil conditioners or nutrients.

It is recommended to add the following materials to this restrictive list (currently integrated in annex I of Regulation (EC) 889/2008):

a) Phosphate salts, as defined in the regulation (EU) 2019/1009 on fertilising products;
b) Renewable calcinated phosphate as defined in regulation (EU) 2019/1009 on fertilising products;
c) Algae and microalgae biomass grown on wastewater;
d) P-rich biomass obtained after P adsorption on chitosan/chitin material adsorbent from seafood waste.

Justification:

"Organic farming in its current state relies largely on phosphate rock for its P supply, either directly or by import of conventional animal manure. […] The principle of ecology states that the production is to be based on ecological processes and recycling. […] This principle calls for a decreased dependency on phosphate rock in organic farming" (Möller et al. 2018). On this basis, sources of phosphorus for use in organic agriculture that emerge from wastewater treatment streams, after assessment of risk, are welcomed by the organic farming sector (Expert Group for Technical Advice on Organic Production (EGTOP) 2016). The list of the products proposed rely on the analyses done during Phos4You (Ploteau et al. 2021) whereby the categories a) and b) were already suggested by the Expert Group for Technical Advice on Organic Production (EGTOP) (2016) and their detailed integration in the organic farming regulation has been proposed by IFOAM and the ESPP (Cuoco and Hermann 2020).

7.1.2 Regulation (EU) 2019/1009 on fertilising products

The recent regulation on EU fertilising products (EU FPR 2019/1009) lays down rules on the making available on the market of CE marked fertilising products. Criteria are given for material belonging to Component Material Category (CMC) that enters in the composition of fertilising products defined according to several Product Function Categories (PFC).

It is recommended to:

a) Get the Regulation (EU) 2019/1009 recognised and implemented in the United Kingdom;
b) Apply harmonised limit values for cadmium content in phosphate fertilisers at Union level and for all members states, based on the lowest existing national values in the EU;

c) Add the *Chlamydomonas* family to the positive list of micro-organisms in CMC 7 that can be used, if they have undergone no other processing than drying or freeze-drying, as microbial plant biostimulant (PFC 6(A));
d) Reconsider the difference of the copper limits between the PFC 1(A), PFC 1(B) and PFC 6;
e) Set up limits for copper and zinc based on their ratio to P.
f) Authorise liquid soil improver in PFC 3;
g) Consider the addition of the citric acid as solubility criteria in Annex II –Part II (Product specific labelling requirements).

Justification:

A recognition and implementation of the Regulation (EU) 2019/1009 in UK is required to ease the market movement of fertilising products with stakeholders acting in the UK.

Adoption of a harmonised value of cadmium limit for all Member States, based on the most stringent value applied would be the most efficient way to avoid arbitrary discrimination, a disguised restriction on trade or an obstacle to the functioning of the internal market, and ensure the highest level of protection of the environment.

The microalgae biomass obtained by the growth of *Chlamydomonas* on wastewater improves the plant nutrition to which it is applied (Bogdan et al. [in press]). This biomass could meet the further requirements for a CE marked microbial plant biostimulant as long as the *Chlamydomonas* family is added to the list of micro-organisms authorised under CMC 7.

When a material fits for different PFCs, it is difficult to understand why different copper limits are applicable - in Phos4You, PFC 1(A) and PFC 6 are relevant. The copper content in an organic fertiliser must not exceed 300 mg/kg whereas in a plant biostimulant it must not exceed 600 mg/kg. For both, the same material may be used (in this case algae biomass, on one hand under CMC 2 and at the other hand under CMC7 – provided *Chlamydomonas* is included in the positive list). Therefore, the invitation is given to reconsider the different limit values set up for copper.

Furthermore, as reported in Bogdan et al. (2021), "when the secondary P fertilizers are applied to pots, heavy metals become related to P ratio rather than fertilizer dry weight and should be rather limited as such (in terms of ratio to P), unless P concentration of all secondary P fertilisers is first standardised (defined P concentration range) and the contaminant limits are adjusted accordingly."

At the moment, soil improvers are only accepted in dry form in the EU FPR 2019/1009. In the case experimented in Phos4You with the microalgae biomass, the easiest application as soil improver was in liquid form. A drying step improves the handling of the product but not quality of the product, especially for the application as soil improver. A liquid soil improver might surely be used more locally to avoid transport of water, but still could be included to facilitate transboundary transport.

In the current version of the EU FPR 2019/1009, an inorganic fertiliser can be labelled as a “mineral fertiliser” only if it fulfil among others a minimum solubility either in water, in neutral ammonium citrate (NAC) or in formic acid (only for soft rock phosphate). This limited list of solubility methods selected in the regulation prevents some inorganic fertilisers having a very low organic content (C*org*<1%) to be recognised as “mineral fertiliser” (e.g. EuPhoRe-SSA, wood-ashes). Historically, solubilities methods have been developed to rapidly characterise the type of fertiliser, according to the type of P-compound present in the fertilisers (Wollmann et al. 2018). To characterise fertiliser with high CaO content such as Thomas-fertilisers, the 2% citric acid (CA) method has been recognised as appropriate method and inscribed for years in the EC 2003. Thomas-fertilisers are not being produced anymore (as already described in 2003 by Walter) and the citric acid is not included in the EU FPR 2019/1009. For phosphate ashes produced thermochemically from SSA treated with the Ash-Dec process (applied with Na-additive), the alkali/P ratio required to achieve sufficient P_{NAC}-solubilities varied depending on the type of alkali additive used and a high P_{NAC}-solubility > 85% was achieved with Na_2SO_4, Na_2CO_3 and NaOH at molar Na/P ratios > 1.75 (Herzel et al. 2016). Further, P-$_{NAC}$ correlated better than P-$_{CA}$ with plant availability in neutral soil for a range of recycling fertilisers tested, including SSA treated with Ash-Dec (Wilken et al. 2015). For phosphate ashes produced thermochemically from dewatered sewage sludge treated with the EuPhoRe process (applied with Mg-additive), a high P-$_{CA}$ solubility (ranging from 70 % to 90 %) was constantly higher than the P-$_{NAC}$ solubility (see analytic of the EuPhoRe ashes (LUFA Nord-West 2020-2021; Klose 2018)). Parallelly, P-$_{CA}$ correlated highly (and similarly than P-$_{NAC}$) with plant availability in slightly acidic soil (pH=6.66 ±0.12) for a range of recycling fertilisers tested, including SSA treated with EuPhoRe (Bogdan et al. [in press]). In the EuPhoRe process, a pyrolysis of sewage sludge followed by their incineration occur. The additive dosing with alkaline earth metals, especially with magnesium has been identified as ideal whereas an additive dosing with alkali metals as not suitable (glazing, slag formation) (IBU-tec advanced materials AG 2014). Therefore, it seems that the conclusion made for the AshDec process (obtaining ashes with a better plant availability with Na-additive rather than Mg-additive, analogously to the Rhenania phosphate process (Herzel et al. 2016)) are not transferable to the EuPhoRe process (producing SSA similar to Thomas-fertilisers with Mg-additive). To create a level-playing field for recycling fertilisers similar to Thomas-fertilisers, it does make sense to consider the addition of the P solubility in 2% citric acid as an appropriate method to characterise a mineral fertiliser into the EU FPR 2019/1009. Here it is important to point out that the assessment of the solubility of a fertiliser through a chemical extraction method has its interest in its standardisation and reproducibility which is fully relevant for conformity monitoring. However, the correlation between a chemical extraction method and the plant P uptake and dry mass is often only moderate (BMEL 2020).

7.1.3 Common Agricultural Policy

For the common agricultural policy 2021-2027 (start pushed back to 1 January 2023[9]), the reform has introduced the elaboration of CAP strategic plans at the Member states level, including the instrument of the Eco-schemes. The CAP reform aims to significantly contribute to the achievement of the target of the EU Green Deal, including the common objective of the Farm to Fork Strategy and the Biodiversity Strategy (May 2020) to: “reduce nutrient losses by at least 50 % while ensuring no deterioration in soil fertility; this will reduce use of fertilisers by at least 20 % by 2030”. A list of agricultural practices that eco-schemes could support has been published (European Commission 2021c).

It is recommended that Member States:

a) Integrate as agricultural practice, into the eco-schemes developed within their CAP strategic plans, the introduction and use of P-recyclates by farmers as part of their production chain.

Justification:

Based on the conclusion of the LCA works done in Phos4You, the production of fertilising products originating from recovered phosphorus material has a positive impact on mineral resource depletion, and possibly also a beneficial effect on global warming, according to the implemented technology (Chantrain et al. 2021). An integration of the use of the P-recyclates in the eco-schemes would be a strong instrument to encourage demand. Farmers could receive compensation for additional costs, or additional payment to basic income support to make use of the P-recyclates. The recovered P materials should be sourced from technology having a positive global environmental impact.

[9] According to the Regulation 2020/2220 on transitional provisions for 2021-2022 (The European Parliament and the Council of the European Union 2020.)

7.1.4 Directive 86/287/EEC on sewage sludge

The European Commission has been considering the revision of the directive on sewage sludge (The Council of the European Communities 1986) since mid-2020. The aim is to check how effective the law on sewage sludge management in farming is, whether protects the environment, and in particular soil, when sewage sludge is used in agriculture.

It is recommended that the EU COM, by revision of the directive 86/287/EEC on sewage sludge:

a) Adds the obligation to recover phosphorus contained in sewage sludge (through land application or technical recovery) at EU level;
b) Aligns the land spreading of sewage sludge to the nutrient availability for the plant cover;
c) Prohibits or reduces temporary storage of SSA for later P-recovery;
d) Harmonises the legal framework for co-digestion at EU level, i.e. authorise co-treatment of sewage sludge with further substrates to optimise efficiency of recovery processes.

Justification:

Following the ambition set up in the different initiatives and action plan of the EU, nutrient losses should be avoided. Nutrients sequestered in sewage sludge, and especially phosphorus which are on the list of the critical materials in the EU, should no longer be disposed to land fill. Recycling either through direct spreading on agricultural land or through a technological recycling will allow for reduction in nutrient losses.

Having said this, it is important to underline that it has been long recognized that the plant availability of phosphorus in sludge varies widely according, among others, to the types of treatment made at the wastewater plant (Agence de l'environnement et de la maîtrise de l'énergie et al. 1996; Morel et al. 2003; Morel 2017; Möller et al. 2018). As a consequence, the spreading of sewage sludge with low bioavailable fraction of P on soils will continue to increase the long-term accumulation of phosphorus in agricultural soils (van Dijk et al. 2016). This phosphorus is not immediately accessible for the plants, but only uncontrolled after a long time, the stable pool of phosphorus serving as a slow-release buffer to replenish the labile pool of phosphorus (Ringeval et al. 2014). Aligning land spreading of sludge to its controlled availability of phosphorus is in line with a sound management of nutrients.

By the recovery of phosphorus from sewage sludge ashes, an option is available in some countries with mandatory recovery of phosphorus to store sewage sludge ashes in separate long- term land fill for later P-recovery. The construction, operation and dismantling costs of such landfill sites results in an increased financial cost which is difficult to predict and which has a high impact on the economics of phosphorus recovery. This approach is supported by the German phosphorus platform (Knickel et al. 2020).

The directive focusses so far on the use of the sewage sludge in agriculture and does not give any indication on conditions for anaerobic digestion. Besides the increase of biogas yield, the co-digestion of organic wastes together with sewage sludge is expected to increase the phosphorus concentration of the digestate (Wickham et al. 2016). This would enable for a phosphorus richer input at the phosphorus recovery unit, thus enhancing the phosphorus concentration in the output stream. Such initiatives are followed e.g. in Switzerland (Heiniger 2011; Nättorp and Jutz 2021). Such approaches are nevertheless constrained by the rules on co-digestion (restricted list of materials allowed, complex waste classification issues). The differences of the rules between the Member States suggest that a harmonisation, potentially within a revision of the EU Directive on sewage sludge, would contribute to enhance the frameworks for co-digestion of sewage sludge with further materials to achieve a better energy and phosphorus recovery.

7.1.5 Directive 91/271/EEC on Urban Waste Water Treatment

Based on the shortcomings and new societal needs identified in the evaluation of the EU Directive 91/271/EEC (UWWTD 91/271/EEC), the European Commission prepares 2021 a proposal for a revised directive (European Commission 2021f).

It is recommended that the EU COM by revision of the UWWTD:

a) Considers the reduction of the lower limit of 2,000 PE to 500 PE or below, thus reinforcing the implementation of phosphorus removal and recovery from small WWTP.

Justification:

Within the evaluation of the directive, it was found that small agglomerations or non-connected dwellings not completely covered by the Directive constitute a significant pressure on 11 % of the EU's surface water bodies (Pistocchi et al. 2019). Technologies demonstrated in Phos4You showed potential for affordable and robust solutions to improve the treatment of wastewater at small scale. Nature based (i.e. microalgae) and physico-chemical solutions can combine nutrient removal with nutrient valorisation via recovered nutrient-rich materials (Bogdan et al. [in press]; Ploteau et al. 2021). This supports the introduction of nutrient removal and recovery requirements for small-scale WWTP plants.

7.1.6 INMAP

The European Commission develops an Integrated Nutrient Management Action Plan (timeline 2022) as announced in the EU Farm-to-Fork and Biodiversity strategies (COM(2020) 381 final; COM(2020) 380 final), with a view to ensuring more sustainable application of nutrients and stimulating the markets for recovered nutrients as elaborated in the new circular economy action plan for Europe (COM(2020) 98 final).

It is recommended that the EU COM enables the INMAP to:

a) Support knowledge and innovation transfer towards farmers, regarding nutrient and healthy soil management, especially in relation to recovered nutrients.

Justification:

To achieve the ambition of the EU Green Deal on nutrient management, changes in farm practices are needed. The fertiliser and scientific communities are very active in the field of nutrient and soil management, e.g. regarding the assessment of the specific properties of new recovered nutrients. An adequate level of support is required to transfer the findings to the farmers in order to foster the uptake of improved practices and guarantee an optimal introduction and sustainable use of new nutrient products on the soils.

7.1.7 Further incentives schemes/policies

The European fertiliser sector is traditionally widely involved in circular economy. Waste and by-products out of industrial processes are commonly used in the production of fertilisers (Fertilizers Europe [2019]). The fertiliser sector also accepts the challenge to reduce nutrient losses for resilient food system - but point out difficulty to achieve it in the given timeframe (Fertilizers Europe 5/20/2020).

It is recommended that:

a) The European Commission requests the blending of a quota of recovered phosphorus from wastewater streams into the composition of fertilising products.

Justification:

Currently, there is no legal incentive to substitute mined phosphate rock by recovered phosphorus materials in the manufacturing of fertilisers or feed phosphates. This leads to the fact that the recovered phosphorus materials are competing with mined phosphate rock only on a price basis. To create a level-playing field in the market for the recovered products, a political action, such as a quota system is required.

7.2 Recommendations towards operators/investors

The investment in a full-scale phosphorus recovery unit is linked with rather high risks. Near to the associated elevated costs, the outlet of the generated streams (recovered phosphorus products, and possibly by-products and waste) is not yet established on the market. Further the reliability and the diversity of the recovery technologies still need improvements.

It is recommended that:

c) the stakeholders making use of the recovered P materials (mostly from the fertiliser sector), share the risks linked with the P-recycling together with the operators of sewage sludge incinerations plants or wastewater treatment plants;
d) Stakeholder's engagement actions get reinforced, e.g. through contracting.

Justification:

As long as the integration of recovered phosphorus is not established on the market, the risks of investing in phosphorus recovery full-scale plant will remain high. Thus, sharing the risks between the owner of the source of phosphorus (in this case, the SSIP or the WWTP operators) and the users of the recovered phosphorus (usually, the fertiliser industry or the players from the sector of phosphoric acid with technical grade) is seen as an acceptable way forward, especially because public money is concerned. The way to share the risk does not necessary rhyme with a public-private investment but can take other forms (contracting, engagement on prices…).

Considering circularity of the economy, the engagement with regional stakeholders is essential in case the created streams are better adapted to a local consumption. Confidence and adjustment of requirements are possible through synergies between engaged stakeholders. This would support implementation of recovery solutions.

7.3 Recommendations towards standardisation bodies

7.3.1 EU-Standard to assess quality of products

Authors: Ana Alejandra Robles-Aguilar, Aleksandra Bogdan, Evi Michels, Erik Meers, (UGent); Mark Taggart, Szabolcs Pap (ERI); Marina Coquery (INRAE); Marina Le Guédard (ADERA – LEB Aquitaine); Joanne Roberts, Colin Hunter (GCU); Ciaran O'Donnell, Joe Harrington (MTU); Josien Ruijter (HVC)

The proposed recommendations addressed all relevant legislative bodies, soon to be notifying bodies as well as fertiliser industry, water bodies, research institutes and laboratories that deal with recycled P materials.

The methods defined in the Fertiliser Regulation 2003/2003 (EC 2003) were developed several decades ago, while the analytical methods and instruments have progressed significantly since then. A crucial step towards reform of the quality assessment of P fertilisers was made via publication of the novel Fertiliser Product Regulation (EU FPR 2019/1009) but no standardised methods for quality assessment of fertilising products have been yet defined.

Thus, within the Phos4You project several methods for measuring inorganics (especially P availability), organics and ecotoxicity were compared.

In Phos4You, the quality assessment of P fertilising products recovered from municipal wastewater was organised in two batches. In the first batch (Bogdan et al. 2020) mainly commercial P fertilising products (two struvites (STRLQ, STRSL), one ash (ASH1) and one iron phosphate dry sewage sludge (FeP)), near to one product material from one project demonstrator (ASH2) were used in order to set the optimal methods. In the second batch P fertilising materials mainly produced within the Phos4You project (three P salts (Psalt3_CL, Psalt4_SL, Psalt5_BL), two ashes (ASH2.2RK_PI, ASH3_FB (this one was outsourced), two bio-phosphates (BioP1_MA, BioP2_CCP)) and revalidated the previously selected methods on the new products (Bogdan et al. [in press]).

7.3.1.1 Inorganics

Concentrations of the total and organic carbon (TC and C_{org}), as well as total nitrogen (TN) in the tested fertilising products, were analysed using a carbon CNS analyser (Thermo Electron, CN Flash 2000) by a method adapted from the NF ISO 10694 standard method (ISO 10694:1995). The determination of total mercury (Hg) in the P fertilising products was performed using an automated atomic absorption spectrophotometer, DMA 80 (Milestone), according to EPA Method 7473 (SW-846). As carbon, nitrogen and mercury concentrations obtained by this method were comparable to the ones previously published on the same commercially available P fertilising products these protocols can be suggested as a standard (Huygens et al. 2019).

Sulphur (S) concentration were examined with several methods: CNS analyser (same as for N and C) as well as solvent extractions (microwave digestion with *aqua regia* (AR) (two protocols, discussed below) and with nitric acid plus hydrogen peroxide (HNO_3/H_2O_2), water and 2 % citric acid extraction. The S results obtained with those different methods were compared. No significant differences between the S concentrations obtained via AR1, AR2, Nitric/Peroxide as well as CNS analyser were observed for most of the novel P fertilisers, with slight deviations in the case of sewage sludge ashes. This confirmed that these four methods can be equally used for testing total S concentrations in novel P fertilising products.

All other elements (P, Ca, Mg, Na, K, Al, Fe, Ni, Pb, Zn, Cu, Co, Mn, Cr, As, Cd) on batch 2 samples were assessed using three chemical extraction methods to determine 'total' concentrations of elements in samples: microwave digestion (MW) with *aqua regia* (AR), with two protocols (AR1 and AR2), and microwave digestion with nitric acid (MW NA) plus hydrogen peroxide (HNO_3/H_2O_2). Alongside two additional extractions, water and 2 % citric acid, were utilised to estimate the relative solubility of elements -i.e., to calculate fractions of elements to be likely more extractable or 'phytoavailable' (Kabata-Pendias 2004; Wang et al. 2012).

The highest inorganics concentration for all tested fertilisers was obtained with the microwave *aqua regia* (MW AR) methods. This is in agreement with previous studies that recommended MW AR, a biosolids method by which total metal concentrations can be measured aside the nutrients, as standard P extraction methods for secondary P fertilisers (Huygens et al. 2019). Thus, there should be no doubt in using MW AR for assessing the quality of secondary P fertilisers. However, as AR can be conducted with various modifications, and variations are even offered within a standard such as DIN EN 13346:2000, a more detailed specification should be considered, especially knowing that the hot plate (boiling under reflux) AR method can lead to significant losses of elements. Fast-drying, losses, and variation in results were observed in a pre-study using AR method, and therefore the protocol was immediately switched to AR digestion in closed MW. It is possible that further optimisation of the hot plate AR method in terms of time and temperature could resolve some of the issues. Nevertheless, if the reaction occurs in the microwave oven, especially closed MW, the losses and the discrepancies in results are significantly reduced (Duboc et al. 2017).

In addition, 2 % citric acid and water extraction were used for recovered P fertilising material solubility assessments. They indicated that P, Mg, K, S, and Na are more readily soluble components, while many of the least beneficial/more toxic elements of concern (i.e., Pb, As, Cd) are unavailable. Analysis of samples in batch 1 also indicated that 2 % citric acid may be equivalent MW AR for assessment of all elements in struvites (but not ash and iron phosphate dried sludge).

7.3.1.2 Phosphorus availability

Several pot trials were set to investigate the most adequate and easily reproducible methods to characterise plant P availability from recovered P products. This study aimed to create a proposal for standardising the measurement of available P in secondary P fertilisers based on a comparison of the P in the plant shoots with the P obtained by applying the other quicker methods.

Comparison of quick methods to for estimation of the available P in novel fertilising products

To define an adequate and quick method for measuring the P availability of fertilising P materials, different quick methods were compared with the shoot P concentration and P uptake measured in pot trials.

Based on all the results summarised in Bogdan et al. (2021), it is recommended that:

- the common chemical methods can be used as the quick way to analyse the fertilisers. However, the findings should be further confirmed using larger number of samples and other agronomical settings (other soils, plants, etc.) before considered as a standard.
- the use of substrate pore water sampled by Rhizons can be adequate for measuring P in P salts and BioP1_MA.
- the use of leaf PC/DGDG ratio and the %C16:1t are the best suited as a pertinent biomarker to assess the performance of P fertilising materials.

Recommendations for pot trial standardisation

Several conditions (P dose, test duration, low P substrate) for performing the P availability pot trials were optimised and can be used for repetitive assessment of novel P-recovery fertilising materials.

Choice of pot trial duration: four months are minimum for the tested products and one growing season (7-9 months) the optimum for observing the slow release pattern and concluding high efficiency for the novel P fertilizing materials (Bogdan et al. 2021).

Choice of fertilizing product P dose: equivalent to the typically used P dose for commercial mineral products, which is in the case of ryegrass equal to 60 kg P_2O_5 ha^{-1} (Bogdan et al. 2021).

Choice of nutrient solution: it is crucial to formulate the standardised nutrient solution for each fertilizing product and plant type that will enhance their agronomical P efficiency (Bogdan et al. 2021).

Choice of plant type: ryegrass is a suitable plant for repetitive testing of the P availability of the novel P products, but testing the P availability using other plants should be also explored (Bogdan et al. 2021).

Choice of low P substrate:

- the river sand with the lowest available P, optimal plant pH, and the lowest aluminium and iron concentration proved suitable for assessing the secondary P fertilising product release.
- the artificial mineral substrate with low available P, but higher pH and more complex chemical characteristics, may be valuable for agronomic tests in specific regions with similar soil characteristics as this substrate.
- the three growing mediums developed within the project expressed high potential for use in agronomical tests for P-salts, but further investigation is needed to prove their applicability to a wide range of secondary P fertilisers.

7.3.1.3 Organics

Several POPs are currently listed in the legislation. Moreover, methods used for these POPs are relatively standardised, and no additional investigation was needed in this field. However, as the list of POPs increases continuously we have also analysed the concentrations of PFAS in the recovered fertilisers. While the discovered concentrations were low, their presence is concerning and should be further monitored.

Moreover, fertilising products were also tested on pharmaceuticals and hormones, as well as pesticides using two methods: the most readily 'water' soluble fraction (i.e., compounds readily soluble in soil) and a specific QuEChERS (quick, easy, cheap, effective, rugged, and safe) method. A lower number of compounds were quantified in the fertilising products when using a water based extraction (as expected). The

QuEChERS extraction method confirmed that the highest concentrations were detected in the organic fertilising products. Thus, it is advisable that these organic compounds are regularly monitored in novel fertilising products.

In addition, using an untargeted approach (HRMS) a numerous organic contaminants were detected, but as no limits were available, the amount was estimated against the amount in TSP. Thus, this type of analysis may be a helpful tool for evaluating highly rich organic fertilising materials and fertilising materials produced by mixed wastewater sources or WWTP that use polymers in their treatment line.

7.3.1.4 Ecotoxicity

The two approaches (Thriad approach and Omega-3 Index) adopted within the Phos4You project were used to examine the presence of potentially toxic compounds in fertilising products. The tests were formulated to assess the effect of time and fertiliser dose on exposure of tested organisms. In total, results clearly showed that both approaches yielded similar results and are both suitable as screening options for fertilising materials derived from wastewater or sewage.

7.3.1.5 Pathogens

Analysis of different microbial organisms listed in current regulation showed absence of pathogens in novel fertilisers. However, several microbial colonies other than the one defined in the legislation were detected. Thus, their investigation may be advisable to ensure the safety of the novel P fertilising materials.

7.3.2 LCA methodology for recovering technologies

Authors: Gaspard Chantrain, Sylvie Groslambert, Angélique Léonard (ULiège)

Until now, scientific literature assessing the environmental performance of sludge-sourced products had assumed that no environmental costs were attributed to the production of sewage sludge. This is known as the “zero burden assumption”. However, the emergence of projects such as Phos4You and more generally of sludge-sourced products as well as energy and material recovery technologies from sewage sludge question this hypothesis.

Several methodological approaches are available to assign a part of the environmental impacts of wastewater treatment to sludge production. Firstly, the development of an allocation factor between these two co-products (treated water and sludge) is possible (Pradel et al. 2016). However, the development of such a factor is mathematically complicated and requires the knowledge of parameters internal to the wastewater treatment plant that are often difficult to obtain in practice. It also raises the question of the purpose of the construction of a WWTP, which ultimately remains the treatment of wastewater, and not the production of raw materials for fertilising products.

Another way to take sludge production into account is the system expansion approach. With this approach, the system considered includes both the wastewater treatment and the fertiliser production. This approach requires the adoption of a multi-functional system with a predefined amount of wastewater treatment and fertiliser production as its functional unit. This multi-functional system is often more difficult to interpret despite the fact that it represents a real situation as a whole.

Finally, another way of attributing an environmental charge to sewage sludge production is the “avoided burden” method. In this method the system studied has the function of wastewater treatment, which includes the management of sludge. Sludge management is then done in a conventional way (incineration with energy recovery) in the reference case and through P-recovery technologies in the others. The recovered P-material in these management routes is therefore considered as an avoided product. To do so, the environmental impacts of the conventional mineral phosphorus fertiliser production avoided thanks to P-recovery from sludge is subtracted from the total impacts of the wastewater treatment system. The conventional avoided production discussed here is the production of triple superphosphate from phosphate rock and phosphoric acid. This method has the advantage of involving the use of monofunctional systems (wastewater treatment only) but does not reflect the aim of bio-based materials development projects like Phos4You.

These numerous possibilities for performing the environmental performance of sludge-sourced fertilisers make the comparison of studies aimed at quantifying their impacts very difficult, if not impossible.

Indeed, applying the zero-burden assumption to sludge greatly reduces the environmental impacts of these technologies. Furthermore, even when the zero-burden assumption is not applied, different methodological approaches are possible and the results obtained by applying different approaches vary greatly.

A standardisation of methodological approaches would therefore put all future studies on an equal footing so that their results can be compared. The standardisation of a method for the study of environmental impacts would also increase the acceptance of the results by the developers of sludge-based materials and thus make the LCA work easier for practitioners.

In the case of sludge-sourced fertilisers developed in Phos4you, standardisation already exists through the mineral or chemical fertiliser PCR (Product Category Rules). However, in the PCR, the cut-off approach is required as a strict application of the "polluter-pays principle". This approach does not take the environmental benefits of the production of valuable co-products into account. This impossibility to take these benefits into account strongly biases the results in the case of processes such as EuPhoRe® or PARFORCE which recover large quantities of recoverable co-products.

In order to address the issues related to the environmental analysis of sludge-based materials, a standard document could be produced in the form of a PCR. The major role of this document would be to impose a methodological framework for the environmental assessment of sludge-based materials, including the functional unit, the boundaries, and the approach or methodology. Given the results of the environmental assessment of the Phos4You project, the methodological approach that seems to be the most consistent is the avoided burden approach, taking the wastewater treatment plant into account within the limits of the system. This approach has shown similar results to the system expansion method but with the advantage of being more easily interpreted (monofunctional system). In the case of sludge-sourced fertilisers, this method also has the advantage of simplifying the consideration of the various nutrients possibly present in the sludge-sourced fertiliser as well as the valuable co-products produced. The inclusion of the WWTP in the system boundaries has also the advantage of a general methodology that can be applied regardless of how or where the P-recovery process is integrated into the system, whether upstream (algae), downstream (PARFORCE) or between or instead of conventional treatment steps (Struvia™, Euphore®).

A final bias lies in the characterisation factor for phosphorus. The characterisation factor is used to quantify the environmental impact of the use of the mineral, mainly on the mineral depletion category. This characterisation factor is low for phosphorus, which implies that the use of phosphate rock has little influence on the mineral resource depletion category. This can be explained by two elements, the first being the fact that the characterisation factors are based on the total global reserves of a mineral and that large quantities of phosphorus are still available in some countries like Morocco. This implies that, despite the fact that European reserves of phosphorus are low, the use of this element will have a little impact on the category of mineral resource scarcity studied in LCA.

The last element that biases the results of LCA for sludge-sourced P-fertilisers is the fact that the characterisation factor does not take geopolitical risks into account. Indeed, in the case of phosphorus, the concentration of global reserves makes supply very dependent on geopolitical risks between resource holders and Europe. For the time being, these geopolitical risks are not taken into account. In order to better consider the real situation of phosphorus resources, a European-specific characterisation factor should be developed and integrated into environmental analysis methods promoted by standardisations such as the Product Category Rules (PCR). This characterisation factor should therefore take the exploitable phosphorus reserves in Europe into account as well as the risk of phosphorus supply, in a manner comparable to the factors considered for the establishment of the European critical resources list.

Note: It is important to put this study in its global context when interpreting the environmental assessment. The goal is Europe´s independence on phosphorus supply, requiring complex processes to recover it from waste (sludge or wastewater), which is a complex matrix with a relatively low P-content. These processes, apart from the depletion of mineral resources, will therefore hardly be comparable to the traditional exploitation of P-rich phosphate rocks such as the Moroccan deposits.

7.4 Recommendations towards policy makers at national level

The recommendations for policy makers at the national level follow the same lines as the recommendations expressed for the European level.

The ones concerning specific application at Member States level are reiterated or specified.

7.4.1 All Members States: CAP strategic plans and Eco-schemes

As presented in preceding chapter 7.1.3, it is recommended that EU member states:

a) Integrate as agricultural practice into the eco-schemes developed within their CAP strategic plans, the introduction and use of P-recyclates through farmers in their production chain.

7.4.2 Germany: Sewage sludge ordinance

As presented and justify in preceding chapter 7.1.4, it is similarly recommended that German authorities within the sewage sludge ordinance (AbfKlärV):

a) Authorise co-treatment of sludge with further substrates to optimise efficiency of recovery processes.

7.4.3 Germany: Fertilising products regulation

The German Fertilising Product Regulation (DüMV) allows for sewage sludge ashes to be used as fertilisers when the incinerated sewage sludge is defined according to the Sewage Sludge Ordinance (AbfKlärV).

It is recommended that the Federal Ministry of Food and Agriculture (BMEL):

a) Clearly mentions that sewage sludge from municipal wastewater which is not suitable for land spreading is acceptable as input material for sewage sludge ashes when the purpose of the P-recovery process is to render the sewage sludge ashes compliant as component material for fertilising products.
b) Adopt appropriated solubility requirements in DüMV, annex 2, table 5, line 5.7, column 3 for phosphate fertilisers made from recycling materials.

Justification

P-recovery processes have been developed to specifically reduce the contaminants in the sewage sludge ashes and to make the phosphorus in it available for plants (e.g. the EuPhoRe® process). Such processes provide sewage sludge ashes which comply with contaminants limits required for the component materials of a fertilising product

(DüMV, §3, (1), 3., i.e. Annex 2, Table 1.4). The requirement on the input material for those sewage sludge ashes (DüMV, Table 6.2.3, Table 7.4.3) is that the sewage sludge should be compliant with the definition of the sewage sludge in the Sewage Sludge Ordinance, i.e. sewage sludge produced from domestic and municipal wastewater (AbfKlärV, §2 (2) und (4)). It is understandable that the aim of this rule was to exclude the use of sewage sludge from strongly industrially influenced wastewater. This being said, the addition under Table 7.4.3 that the sewage sludge should be appropriate for land spreading is leading to confusion. If the sewage sludge ashes produced from sewage sludge produced from municipal wastewater present suitable properties as input materials for fertilising products, there is no factual reason to exclude them. Furthermore, the German sewage sludge ordinance foresees the end of land application of sludge independently of its quality by 2029/2032 (AbfKlärV). With this measure and without adaptation of the German regulation on fertilising products, all sewage sludge ashes made from municipal sewage sludge will be automatically excluded from the list of possible fertiliser components in the DüMV . This would be contrary to the fostering of closing the P cylce. Therefore, the recommendation a).

To assess the effectiveness of phosphate fertiliser made from recycling materials, it is appropriate to use further chemical extraction methods than the only one foreseen in the German fertiliser regulation (Wollmann et al. 2018). Therefore, it is questionable why P-recyclates (e.g. struvite, monoammonium phosphate) which can show good fertiliser properties (e.g with plant trials) are excluded from the market only because the regulatory requirements (water extractable phosphate, neutral ammonium citrate and water extractable phosphate, only phosphate soluble in mineral acids) might not be adequate to properly assess their effectiveness. This need for revising the solubility criteria has already been recognised by the Scientific Advisory Board for Fertilisation Issues in Germany (BMEL 2020).

7.4.4 The Netherlands: LAP3-sectorplan 22 and Nutrient Green Deal

If circular industry is aimed for by national government by 2050, a general disposal ban as currently applies to residues from sludge processing after P-recovery currently refrains the implementation of circular economy. Operators of SSIP HVC and SNB need time to develop outlet channels for application of the residue after P-recovery and therefore seek possibilities for temporary disposal options. A level-playing field with German phosphate recovery projects can then be enhanced.

It is recommended to:

a) Adjust the minimum standard as currently stated in the LAP3-sectorplan 22 for treatment of sewage sludge and P-recovery from ashes and remove the condition that residual ashes after P –recovery may not be disposed.
b) Include the challenges on application of by-products, mainly the residual ashes, in a Nutrient Green Deal in which provincial and national governments are involved as well.

Justification:

HVC and SNB want to recover phosphates from SSIP ash. This is a development of strategic importance for all Dutch water authorities and for the Netherlands as such in the field of circular economy. Dutch start-ups, such as Susphos, are also working on upscaling developments especially for valorisation or other outlets of the residue. Dutch parties have entered discussions on a Nutrient Deal (coordination by The Netherlands Water Partnership/ Nutrient Platform) in which commitment between various parties (including HVC/SNB) and the government is recorded. It also mentions phosphate recovery and additional thresholds for realisation. After the recovery of the phosphates, a residue/filter cake remains that differs in composition from the current form of SSIP ashes which are deposited as filler (e.g. asphalt and backfill of salt mines). Without an outlet for the released filter cake/ residue, phosphate recovery from SSIP ash cannot take place in the Netherlands. In Germany there is the option of disposal of the filter cake (from German P-recovery projects). The residue complies with Landfill class DK I. HVC and SNB aspire to a useful application of the filter cake, but recognise that this requires time and volume to explore/ study and realise these routes. HVC and SNB map out sales routes and technical possibilities and establish contacts for application (e.g. cement industry, ceramic industry). The sectoral waste plan (LAP3 - Ministry of Infrastructure and Water Management 2019) offers an opportunity to refine the enforcement of the non-disposal of residues. The SSIP operators want to enter into this conversation, with the aim of temporarily exempting the residue from the disposal ban and seek coordination with national and provincial authorities to facility this.

7.4.5 Scotland: treatment of wastewater in rural areas

Scotland is considered as 97 % rural with around 1,600 WWTP of a capacity lower than 500 PE, most of them concentrated in the northern part of the country (the Highlands and Islands). A large part of eutrophication is caused by the insufficient treatment of wastewater in septic tanks and small wastewater treatment plants (Bunce et al. 2018, pp. 1–15; Scottish Environment Protection Agency (SEPA) 2017).

It is recommended:

a) To further investigate the problem of insufficient treatment of wastewater in rural areas, including any resultant diffuse pollution / nutrient loss.

Justification:

There is a need to identify better and clearer ways of dealing with small sewage systems. Difficulties associated with maintaining and regulating small sewage systems can lead to several issues including pollution of the water environment issues such as eutrophication, ponding and odour. These issues can have significant negative impacts on local communities and are difficult for these communities to address.

7.4.6 Ireland: Bord Bia quality assurance schemes

The Irish Food Board (Bord Bia) operates a number of accreditation or quality assurance schemes that aim to promote Irish food and beverages at a national and international level, by establishing standards for food producers and processors. The beef and lamb quality assurance scheme prohibits the use of sewage or sewage-derived products on Bord Bia approved farms.

It is recommended that:

a) Bord Bia reviews the ban on the use of recovered P fertilisers from sewage-derived products.
b) Bord Bia produces a list of criteria for the use of recovered fertiliser products in Bord Bia schemes, based on the product function categories and contaminant limits outlined in the EU Fertiliser Regulation (EU FPR 2019/1009).

Justification:

The current Bord Bia quality assurance scheme covers some 47,000 producers, in this case, the ban on sewage derived products prevents the effective return of recovered P fertiliser to a large proportion of productive agricultural land.

7.4.7 Ireland: National Wastewater Sludge Management Plan

The National Wastewater Sludge Management Plan (NWSMP) for Ireland, launched in 2016, aims to establish a nationwide and standardised approach to the management, storage and transport of treated wastewater sludge. The NWSMP should develop systems to redistribute treated sludge locally from centralised sludge treatment hubs.

It is recommended that:

a) The potential for smaller distribution points gets reviewed as the stakeholder survey (Egan et al. 2021) indicated that local availability is critical for farmer engagement.
b) The sludge is treated centrally and the product is made available locally.
c) The potential locations for sludge hubs/satellites currently proposed in the NWSMP be reviewed in the context of local availability of the recovered product to determine if the current proposals are still optimal or if a more widespread treatment network is necessary/justified.

Justification:

Increasing local availability of centrally treated sludge can encourage the closing of the national municipal wastewater P–cycle by creating a vital link between sludge production and agriculture. This is important not only to improve access to and availability of these products but also to promote the recovery of P and to close the P-cycle loop.

7.4.8 Ireland: new legislation on nutrient recovery from wastewater

The European Sustainable Phosphorus Platform (ESPP) has highlighted the P-recycling legislation that has been proposed or implemented at a national level in Europe, most specifically in Switzerland, Germany, Austria and Sweden (Thornton 2021). This legislation ensures the recovery of P from sewage sludge and other industrial and agricultural waste sources. The implementation of such recycling legislation is likely to become common across Europe over the coming decades. Through the stakeholders' survey in Ireland (Egan et al. 2021), the respondents highlighted that P-recycling of wastewater effluent would be of benefit and that the development of the associated legislation should be encouraged.

It is recommended that:

a) Mandatory nutrient recovery and new legislation/policy for Ireland should be investigated as the stakeholder survey has indicated this as a preferred solution for urban/ rural P-recovery, as it would improve downstream water quality and also as it is consistent with the trend for management of P-recovery in a European context.
b) The legislation/ policy should be developed consistent with European policy and practice, reflecting the respondents' feedback from the survey of the awareness

of the many benefits of introducing legislation concerning the adequate treatment and the recovery of P from wastewater.

Justification:

Through the stakeholder survey (Egan et al. 2021), the respondents' unprompted responses to the likelihood that P-recovery will change in the rural/ urban context in the medium and long-term was positive, with the respondents suggesting that long-term P-recovery should become mandatory and that recovery of a critical raw material like P should be supported by legislation.

7.4.9 France: French environmental code

As presented and justify in preceding chapter 7.1.4, it is similarly recommended that French authorities within the French environmental code (mainly article R211-29 and D543-226-1):

a) Authorise co-treatment of sludge with other substrates including wastes from vegetal origin, to optimise efficiency of recovery processes.

Justification:

In France most of the sludge is spread on arable lands and the P is partially recovered by this way. An increasing fraction of the sludge is also digested either to reduce the sludge quantity or to produce renewable energy as biogas and/or electricity. The digestate is also, further, generally landspread. In an urban context or in intensive livestock areas, the competition for land is severe and the price for sludge is urging due to the transportation. The results of the Phos4You project have shown that the P can be partly recovered from the sludge as an input for organic or mineral fertilisers entering the circular bioeconomy. Moreover, as the P is usually the limiting factor for sludge spreading, the surface required is decreased (-40%) and the methane production is doubled by the P-recovery process that precipitate phosphate salts precipitation after a bioacidification step (Daumer et al. 2021). The economic efficiency of this process relies to a large extent, on the price of the co-substrate required for bio-acidification. Using sugar rich waste is the best way to decrease the cost. However, due to the French regulation (République française 2021), using waste as co-substrate in WWTP anaerobic digester is nearly impossible, whatever the quality of the waste is. Allowing the use of some wastes complying with strict quality criteria (to define) as co-substrate for bio-acidification could contribute to broke down the economical barrier for increasing P and energy recovery from wastewater.

7.4.10 Belgium: Harmonised regulatory framework for sewage sludge disposal

Belgium currently does not have a national legislation for implementing P-recovery. The recycling of sludge to land is currently regulated at the regional level. In the Flemish Region, the application of sewage sludge to agricultural land is largely prohibited by the Flemish Decree on Waste Prevention and Management (VLAREA) of December 17, 1997, and its amendment of February 9, 2001 (Flemish government 1997). In the Walloon Region, the spreading of sewage sludge is allowed provided that it complies with the legal standards listed in Council Directive 86/278/EEC (The Council of the European Communities 1986), enacted by the Walloon Government Order of January 12, 1995 on the use of sewage sludge on soil (Gouvernement wallon 1995). Currently, almost 50 % of the sewage sludge produced is incinerated (EurEau 2016).

It is proposed:

a) To develop and implement a harmonised regulatory framework for the use and disposal of sewage sludge for all regions and the obligation to recover the phosphorus contained in sewage sludge.

Justification:

Various EU initiatives and action plans aim to promote circular economy and reduce material losses. Phosphorus is included in the EU list of critical raw materials and studies have shown that a significant amount of phosphorus consumed in the EU can be recovered from sewage sludge. Therefore, recycling either by direct application to agricultural land or by recovery processes can reduce P losses.

Depending on the processing of the sewage sludge, the P may or may not be bioavailable, leading to accumulation in the soil (van Dijk et al. 2016). Therefore, harmonised legislation at the national level will encourage stakeholders to conduct studies in the field and mobilise the various technology providers to offer appropriate solutions.

7.5 Recommendations towards EU and national research & education funding bodies

The circularity of the phosphorus management in the EU is subject to challenges in the fields of the implementation on the ground, the use of the recovered P materials and the engagement of stakeholders.

7.5.1 Industrial implementation of P-recovery processes

A high level of challenge associated with the industrial implementation of phosphorus recovery units was identified. As an example, the shift of the ambitions for the future in Switzerland, being the first country making phosphorus recovery mandatory (Bundesamt für Umwelt BAFU 2020b), confirms the challenge of the full-scale implementation.

It is recommended that EU and national funding bodies:

a) Support the full-scale implementation of P-recovery units and the further development of P-recycling solutions, applicable for high and low phosphorus concentration;
b) Support construction of technical capacities to include P-recyclates into the production chains e.g. of fertilising products;
c) Develop economical models and incentive schemes to foster the blending of recovered P into the existing fertiliser production.

Justification:

The sector of P-recovery faces a lack of references of large recovery plants. Furthermore, the diversity of the technologies with a high technical level of readiness are limited. The creation of a pool of references and the further development of existing recovery processes need to be supported to get through.

Investments in the technical capacities at the plant where the recovered P gets recycled are necessary: storage (for recovered materials, additional chemicals, products, by-products or waste), dosing equipment, process adjustments, monitoring tools. To foster the implementation, a pool of exemplary projects is needed.

Due to the diversity of the players in the wastewater sector and in the fertiliser sector, there will not be a one-size-fits-all economic model but rather several ones, with a variable grade of complexity. Therefore, the stakeholders should find support in funding programs in developing efficient economic models for the implementation and financing of phosphorus recycling at their level. On a more global level, detailed incentives mechanisms that could be adopted at a political level should also be developed within research activities.

7.5.2 Investigations on the use of the recovered P materials

The integration of recovered phosphorus materials in existing or new value chains need to fully meet the expectations of the final users. Quality is to be ensured.

It is recommended that EU and national funding bodies enable applicants to:

a) Run pilot tests for the use of recovered P in another sector than the fertiliser one, for example in technical applications or in animal feed products;
b) Further explore qualities and effectiveness of the resultant P products to establish effect on water/ soil/ plant systems;
c) Carry out large scale study on supply and demand of different sources of phosphorus (e.g. ssa, H_3PO_4).

Justification:

Scientific and technical evidence on suitability and innocuity of products using recovered phosphorus materials are essential for a safe introduction to the market and inclusion into positive lists of regulations. Phos4You worked on this, further projects as well (e.g. B-Ferst 2020). As this step is essential, the potential of different products for further application (e.g. in technical application, in phosphate feed, in various fertilising products but also refining their kinetic properties into soils and plants) should be further supported in research programs. As complement, the market study for the new identified value chains should be supported more intensively.

7.5.3 Stakeholders engagement initiatives

The uptake of products including recovered phosphorus materials from wastewater, sewage sludge or sewage sludge ashes is subject to acceptance of the end-users (mainly the farmers, or consumers or concerned industrial products).

It is recommended that EU and national funding bodies enable for projects that:

a) Promote the benefit of P-recyclates by end-users and foster a positive image of P-recycling based on scientific evidence;
b) Foster open mindedness in decision making and encourage a cultural shift by end-users to accept P recovered products from wastewater sources;

c) Support local collaboration between concerned public and private stakeholders and universities, for research and implementation of new technologies and development of effective and safe P products.

Justification:

Consumer trust in agricultural practices needs to be aligned to the introduction of P-recyclates products on farms. Therefore, the promotion of the use of P-recyclates should be accompanied by social sciences. Local collaboration between all involved, including concerned stakeholders, can be a highly transparent way to demonstrate successful implementation and enhance confidence.

8 References

A Circular Economy in the Netherlands by 2050. Government-wide programme for a circular economy (2016).

Agence de l'environnement et de la maîtrise de l'énergie; Direction de l'Agriculture et des Bioénergies.; Institut national de la recherche agronomique (France). Département d'agronomie.; École nationale supérieure d'agronomie et des industries alimentaires (Vandoeuvre-lès-Nancy, Meurthe-et-Moselle).; et al (1996): La valeur phosphatée des boues résiduaires des stations d'épuration urbaines (Valorisation agricole des boues d'épuration.; Connaître pour agir (Paris)).

Alobwede, Emanga; Leake, Jonathan R.; Pandhal, Jagroop (2019): Circular economy fertilization: Testing micro and macro algal species as soil improvers and nutrient sources for crop production in greenhouse and field conditions. In *Geoderma* 334, pp. 113–123. DOI: 10.1016/j.geoderma.2018.07.049.

Antakyali, Demet (n.d.): Die Umsetzung der Anforderungen der Klärschlamm-Verordnung zur Phosphorrückgewinnung in Nordrhein-Westfalen.

Aquafin NV (Ed.) (2020): Aquafin green finance framework. Available online at https://www.aquafin.be/sites/aquafin/files/2020-05/Green%20Finance%20Framework_def_0.pdf.

Bareha, Y.; Saoudi, M.; Santellani, A. C.; Le Bihan, A.; Picard, S.; Mebarki, C. et al. (2020): Use of fermentation processes for improving the dissolution of phosphorus and its recovery from waste activated sludge. In *Environmental Technology*, pp. 1–11. DOI: 10.1080/09593330.2020.1827301.

B-Ferst. Bio-based fertilising products as the best practice for agricultural management sustainability(Horizon 2020 research and Innovation programme and the bio Based Industries Consortium) (2020). Available online at https://bferst.eu/.

Big Mac Index (2021). Available online at https://www.economist.com/big-mac-index, checked on 10/13/2021.

Blöhse, Dennis; Bogaczyk, Dirk (2019): Strategy and concept-approach for the recovery of phosphorus at one of the largest sewage sludge producers in Germany. In Université de Liège (Ed.): Proceedings of ECSM 2019 – 5th European Conference on Sludge

Management Liège. ECSM 2019 – 5th European Conference on Sludge Management Liège. Liège, October 6-8, 2019.

Blöhse, Dennis; Bogaczyk, Dirk; Ploteau, Marie-Edith; Nafo, Issa; Pfeiffer, Ekkehard (2021): Strategical options for recycling phosphorus fromwastewater in the Emscher-Lippe region. Phos4You final conference - Phosphorus recovery from wastewater: approaches developed within Phos4You. Essen, 2021. Available online at https://www.nweurope.eu/media/15015/phos4you_112_bloehse_lv.pdf.

Blöhse, Dennis; Nafo, Issa (2021): Demonstrator I2: Acid extraction of P from ssa (REMONDIS TetraPhos®, PARFORCE, Phos4Life™). In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 42–79.

Blöhse, Dennis; Ruijter, Josien; Sijstermans, Luc; Nättorp, Anders; Ploteau, Marie-Edith (2020): Phosphoric acid (Phos4You Information sheet). Available online at https://www.nweurope.eu/media/12162/phos4you_p-acid_en_nov2020.pdf.

BMEL (2020): Recyclingphosphate in der Düngung – Nutzen und Grenzen. Standpunkt des Wissenschaftlichen Beirats für Düngungsfragen. Edited by Bundesministerium für Ernährung und Landwirtschaft (BMEL). Berlin. Available online at https://www.bmel.de/SharedDocs/Downloads/DE/_Ministerium/Beiraete/duengung/recyclingphosphate.pdf?__blob=publicationFile&v=3.

Boer, Marissa A. de; Romeo-Hall, Anjelika; Rooimans, Tomas; Slootweg, Chris J. (2018): An Assessment of the Drivers and Barriers for the Deployment of Urban Phosphorus Recovery Technologies: A Case Study of The Netherlands. In *Sustainability* 10 (6), p. 1790. DOI: 10.3390/su10061790.

Bogdan, Aleksandra; O' Donnell, Ciaran; Robles Aguilar, Ana Alejandra; Sigurnjak, Ivona; Power, Niamh; Michels, Evi et al. (2021): Impact of time and phosphorus application rate on phosphorus bioavailability and efficiency of secondary fertilizers recovered from municipal wastewater. In *Chemosphere* 282, p. 131017. DOI: 10.1016/j.chemosphere.2021.131017.

Bogdan, Aleksandra; Robles Aguilar, Ana Alejandra; Michels, Evi; Meers, Erik; Taggart, Mark; Pap, Szabolcs et al. (2020): Deliverable 2.2: Deliverable 2.2: Quality assessment of recovered P containing products (unpublished).

Bogdan, Aleksandra; Robles Aguilar, Ana Alejandra; Pap, Szabolcs; Taggart, Mark A.; Coquery, Marina; Le Guédard, Marina et al. (in press): Comparison of methods to assess quality of novel P containing products throughout NWE - Proposed EU standards. UGhent. Ghent.

Bogdan, Aleksandra; Robles Aguilar, Ana Alejandra; Pap, Szabolcs; Taggart, Mark A.; Coquery, Marina; Le Guédard, Marina et al. (in press): Quality assessment of recovered phosphorus materials carried out within the Phos4You project. Edited by Evi Michels, Erik Meers. UGhent. Ghent.

Bunce, Joshua T.; Ndam, Edmond; Ofiteru, Irina D.; Moore, Andrew; Graham, David W. (2018): A Review of Phosphorus Removal Technologies and Their Applicability to Small-Scale Domestic Wastewater Treatment Systems. In *Front. Environ. Sci.* 6, p. 235. DOI: 10.3389/fenvs.2018.00008.

Bundesamt für Umwelt BAFU (Ed.) (2020a): Phosphorreiche Abfälle. Ein Modul der Vollzugshilfe zur Verordnung über die Vermeidung und die Entsorgung von Abfällen (Abfallverordnung, VVEA). Bundesamt für Umwelt,. Bern. Umwelt-Vollzug.

Bundesamt für Umwelt BAFU (2020b): Planung 2.0 «SwissPhosphor». Entscheidungshilfe für die Umsetzung des Phosphorrecyclings in der Schweiz (Referenz/Aktenzeichen: S253-0231).

Bundesamt für Umwelt BAFU Abteilung Abfall und Rohstoffe (2021): Planung 2. 1 « SwissPhosphor ». Entscheidungshilfe für die Umsetzung des Phosphorrecyclings in der Schweiz. Available online at https://pxch.ch/aktuelles.html.

Bundesministerium für Ernährung und Landwirtschaft (2017): Verordnung vom 26. Mai 2017 über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordung - DüV), DüV. In : Bundesgesetzblatt.

Cairoli, Dario; Jutz, Maurice; Nättorp, Anders (2021): Inventar der Schweizer Klärschlammtrocknung als Vorstufe zur thermischen und stofflichen Verwertung. Basel. Available online at https://pxch.ch/aktuelles.html.

Chantrain, Gaspard; Groslambert, Sylvie; Léonard, Angélique; Nättorp, Anders (2021): Life Cycle Assessment – Life Cycle Costs works. In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 98–121.

SWD(2019) 700 final (2019): COMMISSION STAFF WORKING DOCUMENT EVALUATION of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment.

COM(2020) 381 final (2020): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system.

COM(2020) 98 final (2020): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - A new Circular Economy Action Plan For a cleaner and more competitive Europe.

COM(2020) 380 final (2020): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - EU Biodiversity Strategy for 2030 - Bringing nature back into our lives.

COM(2020) 474 final (2020): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability.

COM(2017) 490 final (2017): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on the 2017 list of Critical Raw Materials for the EU.

COM(2014) 297 final (2014): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative.

UWWTD 91/271/EEC (1991): Council directive of 21 May 1991 concerning urban waste water treatment.

Cuoco, Eduardo; Hermann, Ludwig (2020): Joint letter IFOAM - ESPP to DG Agri and DG Grow. Object: inclusion of recovered struvite and calcined phosphate in Organic Farming Regulation annexes. Brussels. Available online at https://phosphorusplatform.eu/images/download/Joint-letter-ESPP-IFOAM-EU-recovered-phosphates-17_6_20.pdf.

Daumer, Marie-Line; Bareha, Younes; Vedrenne, Fabien; Mébarki, Cédric (2021): Demonstrator I6.1: Bio-acidification before P precipitation from sludge (optimised

Struvia™). In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 98–121.

Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2011): Chemisch-physikalische Verfahren zur Elimination von Phosphor aus Abwasser. Mai 2011. Hennef: DWA (DWA-Regelwerk, A 202).

Duboc, O.; Santner, J.; Golestani Fard, A.; Zehetner, F.; Tacconi, J.; Wenzel, W. W. (2017): Predicting phosphorus availability from chemically diverse conventional and recycling fertilizers. In *Science of The Total Environment* 599-600 (Part B), pp. 1160–1170. DOI: 10.1016/j.scitotenv.2017.05.054.

East Lothian Antiquarians and Field Naturalists Society (1998): Arable & mixed farming. The Fourth Statistical Account of East Lothian. Available online at https://el4.org.uk/county/the-land/farming/arable-mixed-farming/.

Egan, Aoife Dr.; Harrington, Joe Dr.; Bremner, Barbara; Barnett, Denise; Power, Niamh Dr. (2021): Stakeholder Engagement of Phosphorous Recovery in a Rural Context for Ireland (unpublished internal report). Munster Technological University. Cork.

ISO 14040:2006, 2006: Environmental management — Life cycle assessment — Principles and framework.

ISO 14044:2006, 2006: Environmental management — Life cycle assessment — Requirements and guidelines.

erzo ZAB Geocycle Holcim ZAR ARA Thunersee (2020): SwissPhosphor: Vernehmlassung Planungsdokument. Swiss forum n°2, 11/6/2020. Available online at https://pxch.ch/aktuelles.html.

Escudero, Ania; Hunter, Colin; Roberts, Joanne; Helwig, Karin; Pahl, Ole (2020a): Pharmaceuticals removal and nutrient recovery from wastewaters by Chlamydomonas acidophila. In *Biochemical Engineering Journal* 156, p. 107517. DOI: 10.1016/j.bej.2020.107517.

Escudero, Ania; Klose, Siegfried; Ploteau, Marie-Edith (2020b): Microalgae biomass (Phos4You Information sheet). Available online at https://www.nweurope.eu/media/12160/phos4you_microalgae_biomass_en_nov2020.pdf.

Escudero, Ania; Reichelt, Lena-Dorothea; Pahl, Ole (2021): Demonstrator I4: Microalgae to recover P from small-scale WWTPs. In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 161–185.

EurEau (2016): Answers to the Sewage Sludge Questionnaire. EurEau document 4.10.2016. With assistance of Erik Salminen, Toivikko, Saijariina. Brussels. Available online at https://www.eureau.org/resources/publications/studies/3249-sewage-sludge-situation-and-trends-2016/file.

EurEau (2021): Position paper - Enabling the circular potential of sewage sludge within the EU legislative framework. A critical analysis of the current urban waste water treatment sludge legislation with respect to the circular economy. Brussels. Available online at https://www.eureau.org/documents/drinking-water/position-papers/5835-position-paper-enabling-the-circular-potential-of-sewage-sludge/file.

European Commission (2020a): Draft of COMMISSION DELEGATED REGULATION (EU) .../... of XXX amending Annexes II, III and IV to Regulation (EU) No 2019/1009 of the European Parliament and of the Council for the purpose of adding thermal oxidation materials and derivates as a component material category in EU fertilising products. Ref. Ares(2021)44204 - 04/01/2021.

European Commission (2020b): Inception impact assessment related with the initiative "Blue bioeconomy - towards a strong and sustainable EU algae sector". Ref. Ares(2020)7837750 - 21/12/2020. Available online at https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12780-Blue-bioeconomy-towards-a-strong-and-sustainable-EU-algae-sector_en.

European Commission (2021a): Draft of COMMISSION DELEGATED REGULATION (EU) .../... of XXX amending Annexes II and IV to Regulation (EU) 2019/1009 of the European Parliament and of the Council for the purpose of adding precipitated phosphate salts and derivates as a component material category in EU fertilising products. Ref. Ares(2021)44195 - 04/01/2021.

European Commission (2021b): Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change. COM(2021) 82 final.

European Commission (2021c): List of potential AGRICULTURAL PRACTICES that ECO-SCHEMES could support. Available online at https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/key_policies/documents/factsheet-agri-practices-under-ecoscheme_en.pdf.

European Commission (2021d): Public consultation (Feedback period 20 Nov. 2020 - 5 March 2021) for the evaluation of sewage sludge use in farming. Available online at https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12328-Evaluation-of-the-Sewage-Sludge-Directive-86-278-EEC-/public-consultation.

European Commission (2021e): Public consultation on EU algae initiative - Blue bioeconomy – towards a strong and sustainable EU algae sector. Available online at https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12780-Blue-bioeconomy-towards-a-strong-and-sustainable-EU-algae-sector_en.

European Commission (2021f): Public consultation on the revision of the Urban Waste Water Treatment Directive. Feedback period: 28 April 2021 - 21 July 2021. Available online at https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12405-Water-pollution-EU-rules-on-urban-wastewater-treatment-update-_en, checked on December 2021.

European Commission (2021g): The new common agricultural policy: 2023-27. The new common agricultural policy will be key to securing the future of agriculture and forestry, as well as achieving the objectives of the European Green Deal. Available online at https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/new-cap-2023-27_en, checked on December 2021.

European Environment Agency (2018): European waters. Assessment of status and pressures 2018. Luxembourg: Publications Office of the European Union (EEA Report, no 2018,7).

Expert Group for Technical Advice on Organic Production (EGTOP) (2016): Final Report on Organic Fertilizers And Soil Conditioners (II). technical advice at the 12th plenary meeting of 14 - 15 December 2015 and submitted the final version on 2 February 2016., pp. 12–17. Available online at https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/final-report-egtop-fertilizers-ii_en.pdf.

Fertilizers Europe ([2019]): Circular Economy & the European fertilizer sector. Available online at https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Circular_Economy_01.pdf.

Fertilizers Europe (5/20/2020): Fertilizers Europe accepts the challenge to reduce nutrient losses for resilient food system. Pasterski, Łukasz; Golombek, Konstantin. Available online at https://www.fertilizerseurope.com/news/fertilizers-europe-accepts-the-challenge-to-reduce-nutrient-losses-for-resilient-food-system/, checked on 11/9/2021.

Flemish government (1997): Decree of the 17 December 1997 towards enactment of the Flemish regulation concerning waste prevention and management, VLAREA, revised 2004. In : Belgisch Staatsblad.

FOEN Federal Office for the Environment (Ed.) (2020): Phosphorreiche Abfälle. Ein Modul der Vollzugshilfe zur Verordnung über die Vermeidung und die Entsorgung von Abfällen (Abfallverordnung, VVEA) (Umwelt-Vollzug, UV-1826-D). Available online at https://www.bafu.admin.ch/bafu/de/home/themen/abfall/publikationen-studien/publikationen/modul-phosphorreiche-abfaelle.html.

Fu, Pengcheng; Secundo, Francesco (2016): Algae and Their Bacterial Consortia for Soil Bioremediation. In *Chemical engineering transactions* volume 49 (2016).

Gaussen-Freidl, B. (2019): Klärschlammentsorgung in der Schweiz in Hinblick auf die Rückgewinnung von Phosphor. Im Auftrag des Bundesamtes für Umwelt BAFU. Available online at https://www.bafu.admin.ch/dam/bafu/de/dokumente/abfall/externe-studien-berichte/klaerschlammentsorgung-in-der-schweiz-in-hinblick-auf-die-rueckgewinnung-von-phosphor.pdf.download.pdf/Datenerhebung_Klärschlamm-Entsorgung.pdf.

German Federal Ministry of Education and Research (2021): Regional Phosphorus Recycling (RePhoR). Available online at https://www.fona.de/medien/pdf/Projektblaetter_RePhoR_EN_2021.pdf.

Gouvernement wallon (1995): Arrêté du 12 janvier 1995 portant réglementation de l'utilisation sur ou dans les sols des boues d'épuration ou de boues issues de centres de traitement de gadoues de fosses septiques. In : Moniteur Belge.

Green Deal Grondstoffen (2014).

Halleux, Hubert (2021): Results of the trials campaigns made with phosphate recovered with the PULSE process. Phos4You final conference - Phosphorus recovery from wastewater: approaches developed within Phos4You. Essen, 2021. Available online at https://www.nweurope.eu/media/15024/phos4you_209_halleux_prayon.pdf.

Heiniger, Rainer (2011): Thermische Herstellung von Düngern aus organischen Abfällen. In : Waste management. Neuruppin: TK Verl. Thomé-Kozmiensky (2).

Helwig, Karin; Teedon; Paul; Escudero, Ania (in press): Phosphorus Recovery: Stakeholder Perceptions on drivers, barriers and opportunities in the Scottish context. ‘In preparation’. In *Water Science & Technology*.

Herzel, Hannes; Krüger, Oliver; Hermann, Ludwig; Adam, Christian (2016): Sewage sludge ash — A promising secondary phosphorus source for fertilizer production. In *Science of The Total Environment* 542 (3), pp. 1136–1143. DOI: 10.1016/j.scitotenv.2015.08.059.

Huijbregts, Mark A. J.; Steinmann, Zoran J. N.; Elshout, Pieter M. F.; Stam, Gea; Verones, Francesca; Vieira, Marisa et al. (2017): ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. In *Int J Life Cycle Assess* 22 (2), pp. 138–147. DOI: 10.1007/s11367-016-1246-y.

Huygens, D.; Delgado Sancho, L.; Saveyn, H. G. M.; Tonini, D.; Eder, P. (2019): Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009). Process and quality criteria, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials. Luxembourg: Publications Office of the European Union (EUR, 29841).

IBU-tec advanced materials AG (2014): Entwicklungsversuche zur batchweisen thermischen Behandlung von Klärschlamm im technischen Maßstab im direkt beheitzen Drehrohrofen BDO. Bericht (unpublished internal report).

International Fertilizer Association (2021): Phosphate products - Processed phosphate - Phosphoric acid. Available online at https://www.ifastat.org/supply/Phosphate%20Products/Processed%20Phosphates, checked on 06.2021.

Irish Water (2016): National Wastewater Sludge Management Plan. 2016 - 2021. Asset strategy (IW/FF/LDB/0115).

Joint letter to the European commission, DG Environment. Object: EU End-of-Waste status for the value chain Food, water & nutrients (2021). Available online at https://www.phosphorusplatform.eu/images/download/Joint%20letter%20DG%20ENVI%20EoW%20v10_5_21.pdf.

Kabata-Pendias, Alina (2004): Soil–plant transfer of trace elements—an environmental issue. In *Geoderma* 122 (2-4), pp. 143–149. DOI: 10.1016/j.geoderma.2004.01.004.

Kennedy, Tamsyn (2021): Stakeholder engagement based on Scottish & Irish experiences. Phos4You final conference - Phosphorus recovery from wastewater: approaches developed within Phos4You. Essen, 2021. Available online at https://www.nweurope.eu/projects/project-search/phos4you-phosphorus-recovery-from-waste-water-for-your-life/#tab-5.

Ketenakkoord Fosfaatkringloop (2011).

Klein, Daniel; Schmelz, Karl-Georg; Pamuk, Levent; Teichgräber, Burkhard; Zepke, Frank (2021): Demonstrator I1: Thermochemical solution to recover P from sewage sludge (EuPhoRe®). In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 80–97.

Klose, Siegfried (2018): Thermo-chemische Klärschlammbehandlung nach dem EuPhoRe®-Verfahren. In Olaf Holm, Elisabeth Thomé-Kozmiensky, Peter Quicker, Stefan Kopp-Assenmacher (Eds.): Verwertung von Klärschlamm. Neuruppin: Thomé-Kozmiensky Verlag GmbH.

Klose, Siegfried; Klein, Daniel; Schmelz, Karl-Georg; Ploteau, Marie-Edith (2020): Sewage sludge ashes (Phos4You Information sheet). Available online at https://www.nweurope.eu/media/12157/phos4you_ssa_en_nov2020.pdf.

Knake, Alexander; Günther, Lars; Reese, Peter; Essing, Christian; Grün, Emanuel; Frehmann, Torsten (2020): Solarthermische Klärschlammtrocknung am Standort der Kläranlage Bottrop. In *Korrespondenz Abwasser, Abfall* 67 (7), pp. 515–519. DOI: 10.3242/kae2020.07.002.

Knickel, Tabaea; Apitz, Simone; Frank, Daniel Dr.; Hagspiel, Burkard; Klose, Siegfried; Spitznagel, Michael et al. (2020): Politikmemorandum der Deutschen Phosphor-Plattform DPP e.V. 2020. Positionen zur Umwelt- und Landwirtschaftspolitik. Edited by Deutsche Phosphor-Plattform DPP e.V. Frankfurt. Available online at https://www.deutsche-phosphor-plattform.de/wp-content/uploads/2020/11/DPP_Politikmemorandum2020.pdf.

Koninkrijk der Nederlanden (1991): Decree of 20.11.91 on the quality and the application on or in soil miscellaneous organic fertilisers, Besluit kwaliteit en gebruik overige organische meststoffen. In : Staatsblad.

Krüger, Oliver; Adam, Christian (2014): Monitoring von Klärschlammmonoverbrennungsaschen hinsichtlich ihrer Zusammensetzung zur Ermittlung ihrer Rohstoffrückgewinnungspotentiale und zur Erstellung von Referenzmaterial für die Überwachungsanalytik. Edited by Umweltbundesamt (Texte, 49/2014). Available online at https://www.umweltbundesamt.de/en/publikationen/monitoring-von-klaerschlammmonoverbrennungsaschen.

Lemming, Camilla; Bruun, Sander; Jensen, Lars Stoumann; Magid, Jakob (2017): Plant availability of phosphorus from dewatered sewage sludge, untreated incineration ashes, and other products recovered from a wastewater treatment system. In *J. Plant Nutr. Soil Sci.* 180 (6), pp. 779–787. DOI: 10.1002/jpln.201700206.

LUFA Nord-West (2020-2021): Prüfberichte von Proben aus der EuPhoRe-Anlage von Dinslaken (unpublished internal report). Edited by Emschergenossenschaft. Hameln.

Luo, Yunlong; Le-Clech, Pierre; Henderson, Rita K. (2017): Simultaneous microalgae cultivation and wastewater treatment in submerged membrane photobioreactors: A review. In *Algal Research* 24 (Part A), pp. 425–437. DOI: 10.1016/j.algal.2016.10.026.

Mébarki, Cédric; Oudouh, Brahim; Ploteau, Marie-Edith (2020): Phosphate salts (Phos4You Information sheet). Available online at https://www.nweurope.eu/media/12169/phos4you_p-salts_en_nov2020.pdf.

Mehr, Jonas; Jedelhauser, Michael; Binder, Claudia (2018): Transition of the Swiss Phosphorus System towards a Circular Economy—Part 1: Current State and Historical Developments. In *Sustainability* 10 (5), p. 1479. DOI: 10.3390/su10051479.

EPA Method 7473 (SW-846), 1998: Method 7473 (SW-846): Mercury in Solids and Solutions by Thermal Decomposition, Amalgamation, and Atomic Absorption Spectrophotometry.

Ministry of Infrastructure and Water Management (2019): Landelijk Afval Plan - National Waste Management Plan. LAP3/NWMP3.

Möller, Kurt; Oberson, Astrid; Bünemann, Else K.; Cooper, Julia; Friedel, Jürgen K.; Glæsner, Nadia et al. (2018): Improved Phosphorus Recycling in Organic Farming: Navigating Between Constraints. In, vol. 147: Elsevier (Advances in Agronomy), pp. 159–237.

Morel, Christian (2017): Qualité et valeur agronomique: disponibilité du P, forme, contaminants. Journée 'Phosphore recyclé en agriculture : Gisements, produits, qualité, réglementation 11. Avril 2017. COMIFER - ESPP. AgroParisTech - Paris, 2017. Available online at https://hal.inrae.fr/hal-02791150/document.

Morel, Christian; Linières, Monique; Guivarch, Armel; Kvarnström, Elisabeth; Parnaudeau, Virginie; Nicolardot, Bernard; Morel, Jean-Louis (2003): Phytodisponibilité et valeur fertilisante du phosphore de déchets urbains. Agriculture et épandage de déchets urbains et agro-industriels. In *Dossier de l'environnement de l'INRA* 25, pp. 35–44.

Muys, Maarten; Phukan, Rishav; Brader, Günter; Samad, Abdul; Moretti, Michele; Haiden, Barbara et al. (2021): A systematic comparison of commercially produced struvite: Quantities, qualities and soil-maize phosphorus availability. In *The Science of the total environment* 756, p. 143726. DOI: 10.1016/j.scitotenv.2020.143726.

Nanzer, Simone; Oberson, Astrid; Berger, Leslie; Berset, Estelle; Hermann, Ludwig; Frossard, Emmanuel (2014): The plant availability of phosphorus from thermo-chemically treated sewage sludge ashes as studied by 33P labeling techniques. In *Plant Soil* 377 (1-2), pp. 439–456. DOI: 10.1007/s11104-013-1968-6.

Nättorp, Anders; Cairoli, Dario; Jutz, Maurice (2021): Phosphorrückgewinnung in der Nordwestschweiz. Available online at https://pxch.ch/aktuelles.html.

Nättorp, Anders; Jutz, Maurice (2021): Mineralisierung und Düngerkonfektion bei ZAB (Bazenheid). Fachhochschule Nordwestschweiz - Hochschule für Life Sciences - Institut für Ecopreneurship. Muttenz. Available online at https://pxch.ch/projekte.html, checked on 11/11/2021.

Nättorp, Anders; Scheidegger, Jan (2019): Inventur der Schweizer Klärschlammverbrennungsanlagen. Basel. Available online at https://pxch.ch/aktuelles.html.

Pap, Szabolcs; Kirk, Caroline; Bremner, Barbara; Turk Sekulic, Maja; Gibb, Stuart W.; Maletic, Snezana; Taggart, Mark A. (2020a): Synthesis optimisation and characterisation of chitosan-calcite adsorbent from fishery-food waste for phosphorus removal. In *Environ Sci Pollut Res* 27 (9), pp. 9790–9802. DOI: 10.1007/s11356-019-07570-0.

Pap, Szabolcs; Kirk, Caroline; Bremner, Barbara; Turk Sekulic, Maja; Shearer, Lisa; Gibb, Stuart W.; Taggart, Mark A. (2020b): Low-cost chitosan-calcite adsorbent development for potential phosphate removal and recovery from wastewater effluent. In *Water Research* 173, p. 115573. DOI: 10.1016/j.watres.2020.115573.

Pap, Szabolcs; Taggart, Mark; Bremner, Barbara (2021): Demonstrator I5: P adsorption for small scale use (FILTRAFLO™-P with CCM adsorbent). In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 186–210.

Pap, Szabolcs; Taggart, Mark A.; Bremner, Barbara; Ploteau, Marie-Edith (2020c): P-rich biomass (Phos4You Information sheet). Available online at https://www.nweurope.eu/media/12161/phos4you_p-rich_biomass_en_nov2020.pdf.

Pistocchi, A.; Dorati, C.; Grizzetti, B.; Udias, A.; Vigiak, O.; Zanni, M. (2019): Water quality in Europe. Effects of the urban wastewater treatment directive : a retrospective and scenario analysis of Dir. 91/271/EEC. Luxembourg: Publications Office of the European Union (EUR, 30003).

Ploteau, Marie-Edith (2016): INTERREG VB NWE application form of Phos4You. Work plan overview. Essen.

Ploteau, Marie-Edith; Althoff, Anke; Nafo, Issa; Teichgräber, Burkhard (Eds.) (2021): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen. Available online at www.nweurope.eu/phos4You.

Ploteau, Marie-Edith; Blöhse, Dennis; Bogaczyk, Dirk; Pamuk, Levent; Klein, Daniel; Schmelz, Karl-Georg; Nafo, Issa (2020): Erkenntnisse aus dem EU-Projekt Phos4You zur Phosphorrückgewinnung. In *Korrespondenz Abwasser, Abfall* 67 (7), pp. 502–510. DOI: 10.3242/kae2020.07.001.

Portal EnBauSa.de (2020): Kohleausstieg sorgt für Knappheit bei Gips. Gips aus Rauchgasentschwefelungsanlagen deckt 55 Prozent des Bedarfs. Available online at https://www.enbausa.de/daemmung/aktuelles/artikel/kohleausstieg-sorgt-fuer-knappheit-bei-gips-6848.html.

Pradel, Marilys; Aissani, Lynda; Villot, Jonathan; Baudez, Jean-Christophe; Laforest, Valérie (2016): From waste to added value product: towards a paradigm shift in life cycle assessment applied to wastewater sludge – a review. In *Journal of Cleaner Production* 131, pp. 60–75. DOI: 10.1016/j.jclepro.2016.05.076.

Prayon (5/6/2020): Prayon acquires parts of Ecophos assets. Engis. Dechamps, Renaud. Available online at https://www.prayon.com/media/cms/PR-200506-Prayon%20acquires%20Ecophos.pdf.

EC 2003: Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers. In : Official Journal of the European Union.

OFR 2018/848 (2018): Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007. In : Official Journal of the European Union.

EU FPR 2019/1009 (2019): Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. In : Official Journal of the European Union.

REMONDIS Aqua Industrie GmbH & Co. KG (2021): Pilot plant test run with SNB/HVC ashes: Demonstration of P-recycling in line with Interreg North-West Europe project "Phos4You" using TetraPhos®-process (unpublished internal company document), 2021.

Renuka, Nirmal; Guldhe, Abhishek; Prasanna, Radha; Singh, Poonam; Bux, Faizal (2018): Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges. In *Biotechnology Advances* 36 (4), pp. 1255–1273. DOI: 10.1016/j.biotechadv.2018.04.004.

République française (2021): Code de l´environnement, article R211-29 and D543-226-1 - Version au 17 novembre 2021. En vigueur depuis le 21 septembre 2000., p. 1126. Available online at https://www.legifrance.gouv.fr/download/pdf/legiOrKali?id=LEGITEXT000006074220.pdf&size=6,3%20Mo&pathToFile=/LEGI/TEXT/00/00/06/07/42/20/LEGITEXT000006074220/LEGITEXT000006074220.pdf&title=Code%20de%20l%27environnement.

Ringeval, B.; Nowak, B.; Nesme, T.; Delmas, M.; Pellerin, S. (2014): Contribution of anthropogenic phosphorus to agricultural soil fertility and food production. In *Global Biogeochem. Cycles* 28 (7), pp. 743–756. DOI: 10.1002/2014GB004842.

Ruijter, Josien; Sijstermans, Luc; Aert, Chris van; Gerritsen, Michael (2021): Sewage sludge ashes for P-recovery purposes in The Netherlands. HVC- SNB.

Schweizerische Bundesrat (2005): Verordnung vom 18. Mai 2005 zur Reduktion von Risiken beim Umgang mit bestimmten besonders gefährlichen Stoffen, Zubereitungen und Gegenständen, Chemikalien-Risikoreduktions-Verordnung, ChemRRV. In : Amtliche Sammlung.

Schweizerische Eidgenossenschaft (2001): Verordnung über das Inverkehrbringen von Düngern vom 10. Januar 2001 (Stand am 1. Januar 2022). Dünger-Verordnung, DüV. Available online at https://www.fedlex.admin.ch/eli/cc/2001/105/de.

Schweizerische Eidgenossenschaft (2019): Verordnung über das Inverkehrbringen von Düngern (Dünger-Verordnung, DüV) - Änderung vom 31. Oktober 2018.

Scottish Environment Protection Agency (SEPA) (2017): Land Use Planning System SEPA Guidance Note 19 (Addendum). Planning advice on waste water drainage.

Shariff, Zaheer; Fraikin, Laurent; Léonard, Angélique; Pfennig, Andreas (2020): Development of solid-liquid-liquid equilibrium speciation and data fitting tool and its application to phosphorus recovery process from sludge. In DECHEMA e.V. (Ed.). Jahrestreffen der ProcessNet-Fachgruppen Fluidverfahrenstechnik, Adsorption und Extraktion. AlpenCongress Berchtesgaden, 26. - 28. Februar. Available online at http://hdl.handle.net/2268/247818.

Shariff, Zaheer; Leleu, David; Pfennig, Andreas; Léonard, Angélique (2021): Demonstrator I3: Acid leaching of P from partially/fully dried sewage sludge (PULSE). In Marie-Edith Ploteau, Anke Althoff, Issa Nafo, Burkhard Teichgräber (Eds.): Technical report of the Phos4You partnership on processes to recover phosphorus from wastewater. Lippeverband. Essen, pp. 122–160.

ISO 10694:1995, 1995-03: Soil Quality - Determination of Organic and Total Carbon after Dry Combustion (Elementary Analysis). Available online at https://www.iso.org/standard/18782.html.

Steffen, Will; Richardson, Katherine; Rockström, Johan; Cornell, Sarah E.; Fetzer, Ingo; Bennett, Elena M. et al. (2015): Sustainability. Planetary boundaries: guiding human development on a changing planet. In *Science (New York, N.Y.)* 347 (6223), p. 1259855. DOI: 10.1126/science.1259855.

Stutter, Marc; Akoumianaki, Ioanna; Coull, Malcolm; Hewitt, Richard; Koseoglu, Nazli (2021): Phosphorus recycling possibilities considering catchment and local agricultural system benefits: a review and regional Scottish case study. Project code: CRW2017_14. Edited by Scotland's Centre of Expertise for Waters (CREW). Available online at crew.ac.uk/publications.

Swiss Federal Council (5/18/2005): Ordinance on the Reduction of Risks relating to the Use of Certain Particularly Dangerous Substances, Preparations and Articles. Chemical Risk Reduction Ordinance, ORRChem, revised June 2021. Available online at https://www.fedlex.admin.ch/eli/cc/2005/478/en.

Swiss Federal Council (12/4/2015): Ordinance on the Avoidance and the Disposal of Waste of 4 December 2015 (Status as of 1 January 2021). Waste Ordinance, ADWO, revised 1/1/2021, Article 15. Available online at https://www.fedlex.admin.ch/eli/cc/2015/891/en.

The British Survey of Fertiliser Practice. FERTILISER USE ON FARM CROPS FOR CROP YEAR 2020 (2021): Department for Environment, Food and Rural Affairs (DEFRA); Scottish Government.

The Council of the European Communities (1986): Directive of 12 June 1986 on the protection of the environement, and in particular of the soil, when sewage sludge is used in agriculture, SSD 86/278/EEC. In : Official Journal of the European Communities.

The European Parliament and the Council of the European Union (2020): Regulation (EU) 2020/2220 of the European Parliament and the Council of 23 December 2020 laying down certain transitional provisions for support from the European Agricultural Fund for Rural Development (EAFRD) and from the European Agricultural Guarantee Fund (EAGF) in the years 2021 and 2022 and amending Regulations (EU) No 1305/2013, (EU) No 1306/2013 and (EU) No 1307/2013 as regards resources and application in the years 2021 and 2022 and Regulation (EU) No 1308/2013 as regards resources and the distribution of such support in respect of the years 2021 and 2022, Regulation (EU) 2020/2220 transitional provision. In : Official Journal of the European Union.

Sludge Regs (1989): The Sludge (Use in Agriculture) Regulations 1989. In : UK Statutory instruments. Available online at https://www.legislation.gov.uk/uksi/1989/1263/made/data.pdf.

WML Regs (2011): The Waste Management Licensing (Scotland) Regulations 2011. In : Scottish Draft Statutory Instruments. Available online at http://www.legislation.gov.uk/sdsi/2011/9780111012147/contents.

Thiriet, Pierre; Bioteau, Thierry (2020): Phos4You Decision Support Tool - Guide. INRAE. Available online at https://dst.p4y.web-maps.fr/, checked on 10/29/2021.

Thornton, Christopher (2021): Opportunities for phosphorus recycling in Europe, today and tomorrow. Phos4You final conference - Phosphorus recovery from wastewater: approaches developed within Phos4You. Essen, 2021. Available online at https://www.nweurope.eu/media/15006/phos4you_103_thornton_espp.pdf.

Tweede Kamer der Staten-Generaal (2011): Grondstoffenvoorzieningszekerheid (32852 nr. 1).

van Dijk, Kimo C.; Lesschen, Jan Peter; Oenema, Oene (2016): Phosphorus flows and balances of the European Union Member States. In *The Science of the total environment* 542 (Pt B), pp. 1078–1093. DOI: 10.1016/j.scitotenv.2015.08.048.

DüMV (2019): Verordnung des Deutschen Bundesministeriums für Ernährung, Landwirtschaft und Verbraucherschutz über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln (Düngemittelverordnung - DüMV). In : Bundesgesetzblatt.

Abfallverordnung, VVEA (2015): Verordnung über die Vermeidung und die Entsorgung von Abfällen (Abfallverordnung, VVEA) vom 4. Dezember 2015 (Stand am 1. Januar 2016). In : Amtliche Sammlung.

AbfKlärV (2017): Verordnung zur Neuordnung der Klärschlammverwertung (Klärschlammverordnung - AbfKlärV). In : Bundesgesetzblatt. Available online at http://www.gesetze-im-internet.de/abfkl_rv_2017/index.html.

Vlaams Reglement betreffende de Milieuvergunning (1995): VLAREM II, Artikel 5.3.1.4 §2.

Walter, Janka (2003): Informationsmaterialien über den ökologischen Landbau (Landwirtschaft einschl. Wein-, Obst- und Gemüsebau) für den Unterricht an landwirtschaftlichen Berufs- und Fachschulen. Edited by Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft. Available online at http://www.biofarmer.de/bsl/b5d_S1_duengemittel.htm.

Wang, Tao; Camps-Arbestain, Marta; Hedley, Mike; Bishop, Peter (2012): Predicting phosphorus bioavailability from high-ash biochars. In *Plant Soil* 357 (1-2), pp. 173–187. DOI: 10.1007/s11104-012-1131-9.

Wernet, Gregor; Bauer, Christian; Steubing, Bernhard; Reinhard, Jürgen; Moreno-Ruiz, Emilia; Weidema, Bo (2016): The ecoinvent database version 3 (part I): overview and methodology. In *Int J Life Cycle Assess* 21 (9), pp. 1218–1230. DOI: 10.1007/s11367-016-1087-8.

Wickham, Richard; Galway, Brendan; Bustamante, Heriberto; Nghiem, Long D. (2016): Biomethane potential evaluation of co-digestion of sewage sludge and organic wastes. In *International Biodeterioration & Biodegradation* 113 (Part A), pp. 3–8. DOI: 10.1016/j.ibiod.2016.03.018.

Wilken, Verena; Zapka, Oliver; Muskolus, Andreas (2015): Product quality: fertilizing efficiency, results of pot and field tests. IaSP, 2015.

Wollmann, Iris; Müller, Torsten; Breuer, Jörn; Möller, Kurt (2018): Standardisiertes Verfahren zur Bewertung des Phosphordüngewerts von Recyclingdüngemitteln. Edited by im Autrag des Ministeriums für Umwelt, Klima und Energiewirtschaft, Referat 25. Available online at https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/3_Umwelt/Abfall-_und_Kreislaufwirtschaft/180201_Standardisiertes_Verfahren_zur_Bewertung_des_Phosphorduengewerts_von_Recyclingduengemitteln.pdf.

Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH (2020): Report of the WOW! project. WP T1-Designing value chains for carbon based elements from sewage; A2-Market potential study. With assistance of Regional Water Authority Vallei en Veluwe (WSVV), Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH (WiW), University of Kaiserlautern (TUK), University of Luxembourg (UL), Natureplast (NTP), REMONDIS Aqua Industrie GmbH & Co. KG et al. Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH. Available online at https://www.nweurope.eu/media/12964/201230_market-potential-study-final_01.pdf.

Appendix A – List of the communication tools generated by Phos4You

Webpage of the project (www.nweurope.eu/phos4you) including the following tabs:

- **Overview**, giving the project summary and the list of involved partners
- **News**, with the project related news
- **Documents**, to download project reports, posters and information sheets
- **Videos**, as precised below
- **Conferences**, referring to the dissemination events carried out by the project
- **Publications**, including the main articles published by the partners based on the works achieved within the Phos4You project

For the following media please follow the link: www.nweurope.eu/phos4you

Videos on phosphorus recovery processes demonstrated in Phos4You (en)

- "**Trailer Phos4You**": The phosphorus problem and the project's solution approach are presented; experts from science and practice have their word
- "**Phos4You in 60 seconds**": The project's problem and solution approach in short
- "**Phos4You: Overview - approaches and technologies for P-recycling**": Phos4You demonstrates innovative technologies to recover P from waste water, showcases the use of recycled P (e.g. fertiliser) and fosters P-recycling in the partner regions and beyond. The video shows different technologies and solutions for urban and rural areas.
- "**Phos4You: P-recovery from sewage sludge ashes**": This video shows P-recovery options from sewage sludge ashes after incineration.
- "**Phos4You: P-recovery from sewage sludge during incineration**": This video shows a demonstrator at a WWTP of the Emschergenossenschaft to recover P from sewage sludge with the EuPhoRe®-process.
- "**Phos4You: Recovery of phosphorus from sewage sludge** (Struvia™)": This video shows a demonstrator at a WWTP in Tergnier, France, to recover P from sewage sludge with the STRUVIA™ – process, optimised by a biological acidification step to enhance the P-recovery rate.
- "**Phos4You: Increasing the phosphorus recovery rate**": This video shows a demonstrator at the Oupeye WWTP near Liège, Belgium, to recover P from sewage sludge with the PULSE process, resulting in P-salts adapted to the users' demands.

- "**Phos4You: Recovery of phosphorus at small-scale wastewater treatment plant** (microalgae – Filtraflo™ P with CCM)": This video shows P-recovery with the use of microalgae and innovative adsorbents.

<u>Factsheet about the general description of the project in 4 languages (en, de, fr, nl):</u>

- Information sheet 0 "**Phos4You - Phosphorus recovery from wastewater for your life**"

<u>Factsheets on 7 phosphorus recovery processes in 4 languages (en, de, fr, nl)</u>

- Information sheet 1 "**Thermochemical solution to recover phosphorus from sewage sludge: EuPhoRe®**"
- Information sheet 2: "**Acid extraction of phosphorus from sewage sludge incineration ash: REMONDIS TetraPhos®**"
- Information sheet 3: "**Acid leaching of phosphorus from partially/ fully dried sewage sludge: PULSE process**"
- Information sheet 4: "**Microalgae to recover phosphorus from small-scale waste water treatment plants**"
- Information sheet 5: "**Phosphorus adsorption for small scale use: Filtraflo™**"
- Information sheet 6: "**Biological phosphorus dissolution before P precipitation from sludge liquor (Struvia™)**"
- Information sheet 7: "**Phosphorus precipitation at small-scale sewage plants: Struvia™**"

<u>Factsheets on 5 phosphorus recovered materials in 4 languages (en, de, fr, nl)</u>

- Product information sheet "**Sewage sludge ashes**"
- Product information sheet "**Phosphate salts**"
- Product information sheet "**Microalgae biomass**"
- Product information sheet "**P-rich biomass**"
- Product information sheet "**Phosphoric acid**"

<u>Product to visualise fertiliser from recovered phosphorus:</u>

Appendix B – Sequence of partner meetings and dissemination events of the Phos4You project

Meeting	Place	Date	Title	Site visit/Highlight
1st partner meeting	Paris (FR)	2017 Apr	1st meeting of the Project Steering Group (PSG) and Working Groups (WG)	
Phos4You launch event	**Basel (CH)**	**2017 Oct**	**European Nutrient Event - Nutrient recycling R&D projects and technologies meeting including technology fair**	**Event co-organised by ESPP, DPP; FHNW, BaselArea.Swiss and Phos4You (INTERREG VB NWE)**
2nd partner meeting	Basel (CH)	2017 Oct	2nd PSG and WG meeting	Visit of the FHNW labs in Basel
Phos4You at Environ2018	**Cork (IE)**	**2018 Mar**	**28th Irish Environmental Researchers Colloquium - Arriving at a Sustainable Future**	**Inclusion of numerous presentations and posters from Phos4You (INTERREG VB NWE)**
3rd partner meeting	Cork (IE)	2018 Mar	3rd PSG and WG meeting	Visit of the CIT facilities to carry out trials within Phos4You (Cork)

4th partner meeting	Rotterdam (NL)	2018 Oct	4th PSG and WG meeting	Visit of the sewage sludge mono-incineration plant of HVC in Dordrecht Workshop with fertiliser stakeholders to define the user requirements to showcase at least one recycling pathway for each Phos4You recovered material.
5th partner meeting	Glasgow (UK)	2019 Mai	5th PSG and WG meeting	Visit of the wastewater development centre at the Scottish Water wastewater treatment works in Bo'ness near Falkirk, where the micro-algae reactor operates in Bo´Ness
Phos4You at ECSM2019	**Liège (BE)**	**2019 Oct**	**5th European Conference on Sludge Management**	**Event organised by ULiège with support of Phos4You (INTERREG VB NWE)**
6th partner meeting	Liège (BE)	2019 Oct	6th PSG and WG meeting	Visit of the manufacturing plant of phosphoric acid of Prayon S.A. in Engis
7th partner meeting	Essen (DE)	2020 Jan	7th PSG and WG meeting	Visit of the EuPhoRe demonstration plant at the Technikum of the Emschergenossenschaft at the wwtp of the estuary of the Emscher in Dinslaken Visit of the REMONDIS TetraPhos® demonstration plant at the sewage sludge incineration plant of WFA Elverlingsen GmbH in Werdhol
8th partner meeting	Rennes (FR) (online due to COVID)	2020 Mai	8th PSG meeting	WG was cancelled due to first COVID lockdown

9th partner meeting	Ghent (BE) (online due to COVID)	2020 Oct	9th PSG and WG meeting	Presentation of the LafargeHolcim activities in the field of phosphorus recovery from sewage sludge
10th partner meeting	Rennes (FR) (online due to COVID)	2021 Apr	10th PSG and WG meeting	Virtual visit of a fertiliser plant making use of recycled phosphorus materials at Groupe Roullier in Saint Malo Workshop with fertiliser stakeholders on logistic aspects linked with phosphorus recovery out of sewage sludge ashes
11th partner meeting	Essen (DE) and online	2021 Sept	11th PSG meeting	
Phos4You final conference	**Essen (DE) and online**	**2021 Sept**	**Phosphorus recovery from wastewater: approaches developed within Phos4You**	**Excursion to the EuPhoRe demonstrator at the Emschergenossenschaft-Technikum in Dinslaken**

DOI: 10.17185/duepublico/75173
URN: urn:nbn:de:hbz:464-20211216-101853-7

The project Phos4You was co-funded from the European Regional Development Fund within the INTERREG North-West Europe VB Programme (2014-2020)

www.nweurope.eu/phos4you

EGLV Lippeverband

Interreg North-West Europe Phos4You