UNIVERSITEIT VAN AMSTERDAM & VRIJE UNIVERSITEIT

INPUT ON THE PROPOSED CONSIDERATIONS FOR THE EU'S "INTEGRATED NUTRIENT MANAGEMENT ACTION PLAN" (INMAP)

30 June 2020
Input for the proposals by the European Sustainable Phosphorus Platform for EU's INMAP

By Inge Stammes, Toon Maassen, Fergus Miller Kerins, Giovanni Votano, Daniela Palma Munguia, Zewei Yuan & Mitch Gereadts

HEREBY WE WOULD LIKE TO GIVE INPUT TO THE PROPOSED CONSIDERATIONS FOR THE EU'S "INTEGRATED NUTRIENT MANAGEMENT ACTION PLAN" (INMAP). WE ARE SEVEN MASTER STUDENTS AT THE UNIVERSITY OF AMSTERDAM AND THE VRIJE UNIVERSITEIT WITH BACKGROUND IN CHEMISTRY, PHYSICS, EARTH SCIENCES AND ENVIRONMENTAL SCIENCES. OVER THE PAST MONTH WE HAVE STUDIED THE CHALLENGE OF THE PHOSPHORUS SYSTEM IN THE EUROPEAN UNION AND HOW THESE CAN BEST BE ADDRESSED. OUR RESEARCH HAS BEEN GUIDED BY DR. J.C. (CHRIS) SLOOTWEG AND PHD CANDIDATE STEVEN BEIJER. HAVING READ YOUR PROPOSED CONSIDERATIONS FOR THE EU'S INMAP, WE WOULD SUGGEST TO ADD THE FOLLOWING POLICY PROPOSALS:

The *'Integrate nutrient management and climate change policies'* section in the proposal is focused on sustainable management and efficiency of nutrients to assess long-term benefits of climate change and nutrient conservation. Our recommendation looks at the implementation of a Phosphates Directive which like the Nitrates Directive would limit the use of P in agriculture and the concentration of P in surface waters.

Phosphates Directive

In 1991 the Nitrates Directive was adopted to "protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices" (European Commission, 1991).

There is no equivalent directive for phosphorus (P) at the European Union (EU) level (Garske et al., 2020), yet this is essential for promoting the recovery and recycling of P. Adopting a Phosphates Directive could help limit the overapplication of P to agricultural land and reduce the amount of P lost to the environment and thus help mitigate eutrophication.

The *'Integration and Implementation'* part of your proposal calls for the need of tools that address the problem of nutrient removal and nutrient recycling being 'not economic'. To this end we recommend the use of a P reuse target in fertilisers, an EU import tariff on phosphorus rock and phosphorus fertilisers and a stricter limit on the Cd content in fertilizers.

Mandatory amount of recycled P in fertilizers

To ensure that the recovery and recycling of P happens, we recommend implementation of legislation that makes the use of a certain percentage of recycled phosphate in P-fertilizers mandatory. Moreover, it is recommended that after a transition period of 10 years, phosphorus fertilizers produced and used in the EU have to contain a minimum of 10% of P from recycled sources. The transition period will give fertilizer producers time to adapt their facilities and will give recovery plants the opportunity to recover P in a way that can be recycled. This percentage can then gradually increase over a timespan of 20 years up to 90% recycled P.

Tariff on PR and P fertilizer imports

There is currently no uniform tariff on phosphorus rock imported into the EU, rather any tariffs in place are specified by trade agreements with the country P is imported from. In order to incentivise recycling of P, we propose an increasing tariff on phosphorus rock imported into the EU by 4% in 2025, 8% in 2030, 15% in 2040 and 25% in 2050. These percentages are based on current levels and are not cumulative. This should contribute to secondary phosphorus decreasing in price relative to primary phosphorus. The proceeds from this tariff will be directly granted to EU member states, with payments made on a per capita basis, in order to alleviate food price increases/food poverty that may arise due to potential food price increases from this tariff. Tariffs can vary depending on trade agreements the EU has made with specific countries. Therefore introducing these tariffs will take some time, and some exemptions might occur. However, as we are advising the EU with a 30 year roadmap, it should be possible to revise trade agreements over time and introduce these tariffs.

Lower cadmium limit for fertilizers

Current fertilizer regulations include a limit of 60 mg Cd/kg P2O5 for inorganic mineral fertilizers with a total P content of ≧ 5% P2O5-equivalent, starting after a transition period of 3 years and an option for fertilizers with a Cd content of < 20 mg Cd/kg P2O5 to add the label 'Low Cd content' (Regulation (EU) 2019/1009). Garske et al. (2020) find this regulation to have a 'lack of ambition' and argue that changing this regulation to a more stringent one could significantly increase the competitiveness of recycled-P fertilizers. Following the advice of Garske et al. (2020) and the European Commission (2016) we recommend to include in the Fertilizer Regulation:

- A decrease of the limit value to 40 mg Cd/kg P2O5 and eventually 20 mg Cd/kg P2O5,
- A mandatory declaration of the respected limit value of either 60, 40 or 20 mg Cd/kg P2O5.

Our next recommendations tie into the *'End-of-waste and other regulatory obstacles'* part of your proposal.

We recognize how regulatory obstacles are a large hurdle for bringing products derived from secondary materials to the market. We make the following recommendations on removing legal hurdles for the recovery and recycling of phosphorus:

Removing legal hurdles for recovering and recycling of P

To assist companies in making the P-system more circular, firstly, waste regulations need to align across the EU member states and secondly the approval of the End-of-Waste status of novel recycled-P fertilizers should be more streamlined or reimagined altogether. The following legislative changes are recommended to remove legal hurdles for companies investing in a circular P-system:

- Currently the criteria for the end-of-waste status are set by the member states, which have often delegated the criteria setting to local authorities. This has caused widely varying criteria across Europe, in which only three waste streams have EU-wide criteria; copper scrap, iron scraps and glass cullet. We advise to create EU-wide criteria for the end-of-waste status for all waste streams (Johansson & Forsgren, 2020).

- Secondly, it still is very hard and time intensive to obtain the end-of-waste status. Effort needs to be made to streamline the process and make it easier for companies to get the needed status.
- Wherever possible, it is even better to avert the label of ‘waste’ altogether, rather working with certifications or requirements for certain material streams independent on the status of waste or product, such as Sweden did for anaerobic digestion and the Netherlands did for aggregates (Johansson & Forsgren, 2020). These countries looked at the safety of the materials in the context of the used application, instead of its status.
- Provide legal help for technology start-ups and small P-recycling companies (Hukari et al., 2015)

The Circular Economy Action Plan proposed a *‘Monitoring Framework for the Circular Economy‘* and a ‘market observatory for key secondary materials’. In addition to creating a regulated market for secondary material, we believe that financial support for recovering and recycling technologies is also indispensable towards a high-tech circular economy.

To provide incentives for technical advancement and implementation, we make the following recommendations on investments for recovering and recycling technologies:

Investments for recovering and recycling technologies

In order to enable the recovery and recycling of P from wastewater and other waste streams, a set of EU-wide subsidies and investment possibilities will be needed. We recommend a combination of the following financial incentives:

- Continued subsidies for R&D on phosphorus recovery and recycling technologies
- Public investments and private investments with government guarantees to create the needed financing for large scale applications of recycling and recovering technologies.
- In order to kick-start the recycling process, we suggest an EU-wide subsidy for recovering and recycling P, that can slowly decrease over time as the market for recovered P matures.

These investments can remove the financial hurdles and provide large investment for constructing plants and other infrastructure. Overall, the goal is to create a self-reliant market for recycled P. The minimum percentage of recycled phosphorus in fertilisers will force fertiliser companies to source part of their P from recovered sources. This, together with investments, subsidies and tariffs should enable recycled P to compete with PR.

The first sentence of the *'Farm to Fork'* part of your proposal says that 'Dietary choices are probably the biggest driver of nutrient use and of nutrient losses.'. We agree with this but do not agree with your proposals given in this section. All the proposals mentioned aim at changing dietary choices by giving consumers information on nutrient and nutrition content of food. We believe that a more active approach is needed to reduce consumption of animal-derived foods and therefore reducing the need for phosphorus and other nutrients.

Reduce meat and dairy consumption and production

The majority of phosphorus input directly or indirectly goes to livestock farming (Van Dijk et al., 2016). To become less dependent on phosphate rock, it is therefore important to implement economic measures to decrease overall livestock numbers and support the transition towards a majority plant-based diet. This can be done using the following measures:

- *Divert current subsidies for meat advertisement campaigns, to plant based food campaigns.*
  Currently the EU subsidises advertising campaigns encouraging meat consumption with over 200 million euros (Stichting Wakker Dier, 2020). A first simple step would be to redirect these campaigns to advertise plant-based products in a similar manner.

- *Invest in meat replacement companies.*
  Furthermore, there is a large emerging market for meat substitutes. Europe currently has the largest meat replacements market in the world, with a revenue of USD 1.40 billion in 2014, and an expected growth at 7.5% (Grand Review Research, 2018). However, the price of meat replacements are still often higher than that of animal meat, although the environmental and societal damages are much lower. The EU can support these successful companies, by guaranteeing needed investments.
- *Decrease CAP subsidies for livestock farmers.*
  As animal farming has a very significant impact both on climate change and on the phosphorus cycle, we propose to decrease the Basic Payment under CAP for animal farming by 6%. This will incentivise farmers to switch to crop based farming.
- *Create a fund for animal farmers that wish to convert to crop farming.*
  In order to help those animal farmers that wish to convert to crop-based farming, the money made available by the decrease in basic payment is used for one-time subsidies for farms to convert. This one-time subsidy is the fivefold of their basic payment subsidy, combined with government guarantees for extra loans. This should enable a farmer to make the needed investments to for instance convert a livestock stable to a greenhouse. And it would enable 1% of farmers to convert from animal to plant based farming yearly. This would lead to a decrease in animal farming of 26% by 2050.

In the part of your proposal on '*Integrate nutrients management and climate change policies'*, there is no mention of biofuels. We believe that the use of first generation biofuels is an issue that should be solved and that it should be included in the INMAP. We recommend to:

Reduce the use of first generation biofuels to decrease phosphorus depletion

The European Union has strongly encouraged the use of biofuels, with the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD). RED has a mandatory minimum of 10% for renewable energy transport by 2020 and the FQD has set a target of 6% greenhouse gas reduction. These policies have led to the mixing of gasoline and kerosene with biofuels (Delft, 2015). However, the sustainability of biofuels, especially first generation biofuels is contested. A 2016 study by DeCicco et al. (2016) showed that the use of first generation biofuels (biofuels made from harvested crops rather than biowaste) have a worse net greenhouse impact than fossil fuels.

Further information

For more information on our findings, our research report can be downloaded here:

Towards a circular phosphorus system in the EU, coping with 2030 peak phosphorus

References

European Commission (1991, December 12). Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal of European Community L375: 1–8. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0676&from=EN

European Commission (2016, March 17). Limits for cadmium in phosphate fertilisers, SWD(2016) 64 final. Brussels. Retrieved from https://ec.europa.eu/transparency/regdoc/rep/10102/2016/EN/SWD-2016-64-F1-EN-MAIN-PART-2.PDF.

DeCicco, J. M., Liu, D. Y., Heo, J., Krishnan, R., Kurthen, A., & Wang, L. (2016). Carbon balance effects of US biofuel production and use. Climatic Change, 138(3-4), 667-680.

Delft, C. E. (2015). Assessing progress towards implementation of the ILUC Directive.

Garske, B., Stubenrauch, J., & Ekardt, F. (2020). Sustainable phosphorus management in European agricultural and environmental law. Review of European, Comparative & International Environmental Law, 29(1), 107-117.

Grand Review Research (2018, July). Meat Substitutes Market Size, Share & Trends Analysis Report By Product (Tofu, Seitan, Tempeh, Quorn), By Raw Material (Soy-based, Wheat-based, Mycoprotein), By Region, And Segment Forecasts, 2012 - 2022.

Hukari, S., Nättorp, A. & Kabbe, C. (2015). Phosphorus recycling now! P-REX policy. Retrieved from https://zenodo.org/record/242550#.WowGiOcxmUk

Johansson, N., & Forsgren, C. (2020). Is this the end of end-of-waste? Uncovering the space between waste and products. Resources, Conservation and Recycling, 155, 104656.

Regulation (EU) 2019/1009 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 (2019). Official Journal L170. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2019:170:FULL&from=EN

Stichting Wakker Dier (2020). EU-subsidies voor 'eet meer vlees-campagnes'. Onderzoek naar een onhoudbaar subsidiesysteem. Retrieved from: https://files.wakkerdier.nl/app/uploads/2020/02/12153250/RAPPORT-EU-subsidies-voor-eet-meer-vlees-campag nes.pdf

UNIVERSITEIT VAN AMSTERDAM & VRIJE UNIVERSITEIT

TOWARDS A CIRCULAR PHOSPHORUS SYSTEM IN THE EU, COPING WITH 2030 PEAK PHOSPHORUS

European Commission

PhosCos - June 2020
Advisory report for the European Comission

By Inge Stammes, Toon Maassen, Fergus Miller Kerins, Giovanni Votano, Daniela Palma Munguia, Zewei Yuan & Mitch Gereadts

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This advisory report recommends how to achieve a circular phosphorus (P) system in the EU by 2050 assuming peak phosphorus in 2030. The driving factors for this research are the harmful effects on the environment of P leakage and the phosphorus shortage (both within the EU and globally). Therefore, this report provides the following recommendations: initiating an EU-wide Phosphate Directive, increasing the percentage of recycled P in fertilisers, removing legislative hurdles for P-recycling processes, increasing investments for existing and promising technologies and reducing meat consumption and production. Additionally the report contains a road map which gives guidelines for implementation of report recommendations and outlines the structure of a monitoring and review process should be carried out every five years. The report also contains a detailed technology analysis tool that will be implemented to assess up to date and best technology options. This report advises that these tools are used in collaboration with the main recommendations given in order to move towards a circular phosphorus system.

VISION

Phosphorus is a valuable and finite resource that must be carefully managed. The phosphorus system is vital for our food systems, our health and our environment. Our vision is for a sustainable and achievable circular economy for phosphorus in the EU. We firmly believe that creating such a system will deliver health and prosperity to current and future generations. Such lofty ambitions are readily achievable with proactive policy and leadership.We are PhosCos and together we can build the system the EU, its citizens and the environment deserves.

INTRO-DUCTION

Phosphorus (P) is a natural element necessary for all living things. A majority of P is extracted from phosphate rock (PR) which is a finite raw material of which two-thirds of the world's resources are in China, Morocco, and Western Sahara (Expertanswer, 2010). Today about 90% of the world’s mined phosphate rock is used for agricultural production, predominantly for fertilisers and to a lesser extent for food additives (Neset & Cordell, 2011). Therefore, P scarcity would threaten food security, bioenergy production, and alter ecosystem structure and function (Withers et al., 2015). Moreover, the inefficient use of P in agriculture has led to environmental pollution, such as eutrophication.

Based on its high priority, the European Commission added P and PR in the list of critical raw materials (CRM) for the European Union (EU) of 2017 (European Commission, 2017). This list includes materials essential to Europe’s economy, industry, technology and environment. The European Commission’s goal is to raise awareness of the importance of recycling and efficient use of P and PR due to supply risks. In addition to the CRM list, the European Commission has released the EU Circular Economy Action Plan which focuses on closing the loop to protect EU businesses against scarcity of resources and generate sustainable advantages (European Commission, 2015). This transition is an opportunity for the EU to pave the way for innovative technology and management of resources to support the environment and future food security.

The dependency of P globally and considering there is no substitute for the element makes the projection of peak P in 2030 a critical point for the EU. The concept of peak P is based on the peak resource theory which assumes that a critical period will occur before 100% of the reserve is theoretically depleted (European Sustainable Phosphorus Platform, 2014). Therefore, with an expected timeline of when peak P will occur globally it is crucial that the EU takes proactive steps to recover and recycle P in efforts to build a resilient system which can withstand decreasing reserves. This advisory report provides recommendations in four priority fields, policy, technology, economy, and society. Based upon these recommendations we advise the European Commission to focus on a phosphorus circular economy which can withstand peak P in 2030.

CHAPTER 1

Phosphorus use in Europe & the circular economy

This chapter covers an introduction of the P system flows and balances in the 27 EU countries (EU-27). It also contains an overview of the German and Swiss phosphorus systems as they are the most progressive countries responding to the P challenge. Lastly, a circular economy (CE) of phosphorus is defined and described in terms of its impact on the EU.

1.1 *Phosphorus use in Europe*

An overview of European phosphorus flows and balances can assist decision makers identifying main waste sources that have the potential for recycling. Van Dijk, Lesschen & Oenema (2016) analyzed and quantified the P flows and balances for the EU-27 using data from 2005 (Figure 1.1). Their results showed the imports, exports, losses and internal flows of P in the EU-27. While this data is from 2005, it is largely accurate for the majority of current flows in the EU today.

EU-27 is highly dependent on primary P imports, especially mineral fertilizers for crop production. Due to excessive P input, nearly 40% of imported P accumulates in agricultural soil and is often lost by runoff and leaching. Apart from P accumulation in soils, a significant quantity of imported P is lost as waste (Van Dijk, Lesschen & Oenema, 2012). There are major P losses from the consumption and food processing sectors via wastewater, food waste and slaughter residues (Withers et al., 2015b; Van Dijk et al., 2016). Following this, P is often sequestered in landfills or lost to surface waters.

The EU phosphorus system is characterized by minimal recycling and low use efficiency. Recycling rates are generally low in each sector, except in animal production where the manure is nearly fully recycled (Van Dijk, Lesschen & Oenema, 2016). As a whole the EU food supply system has a low P use efficiency. An input of 4.0 kg P is required for every 1kg P found in final food and additive products produced (Van Dijket al., 2016).

Moreover, manure represents the largest P flow in the system from high P input, but low P use efficiency in livestock farming. In Europe, almost all manure is recycled as organic fertilizer. In countries with intensive livestock farming, for example the Netherlands, nearly 90% of manure is directly applied to the farmland as low emission slurry (Jie, Buisonjé & Melse, 2017). However, this direct application of manure contributes to the excessive input of P into crop production, and therefore leads to long-term accumulation in agricultural soils.

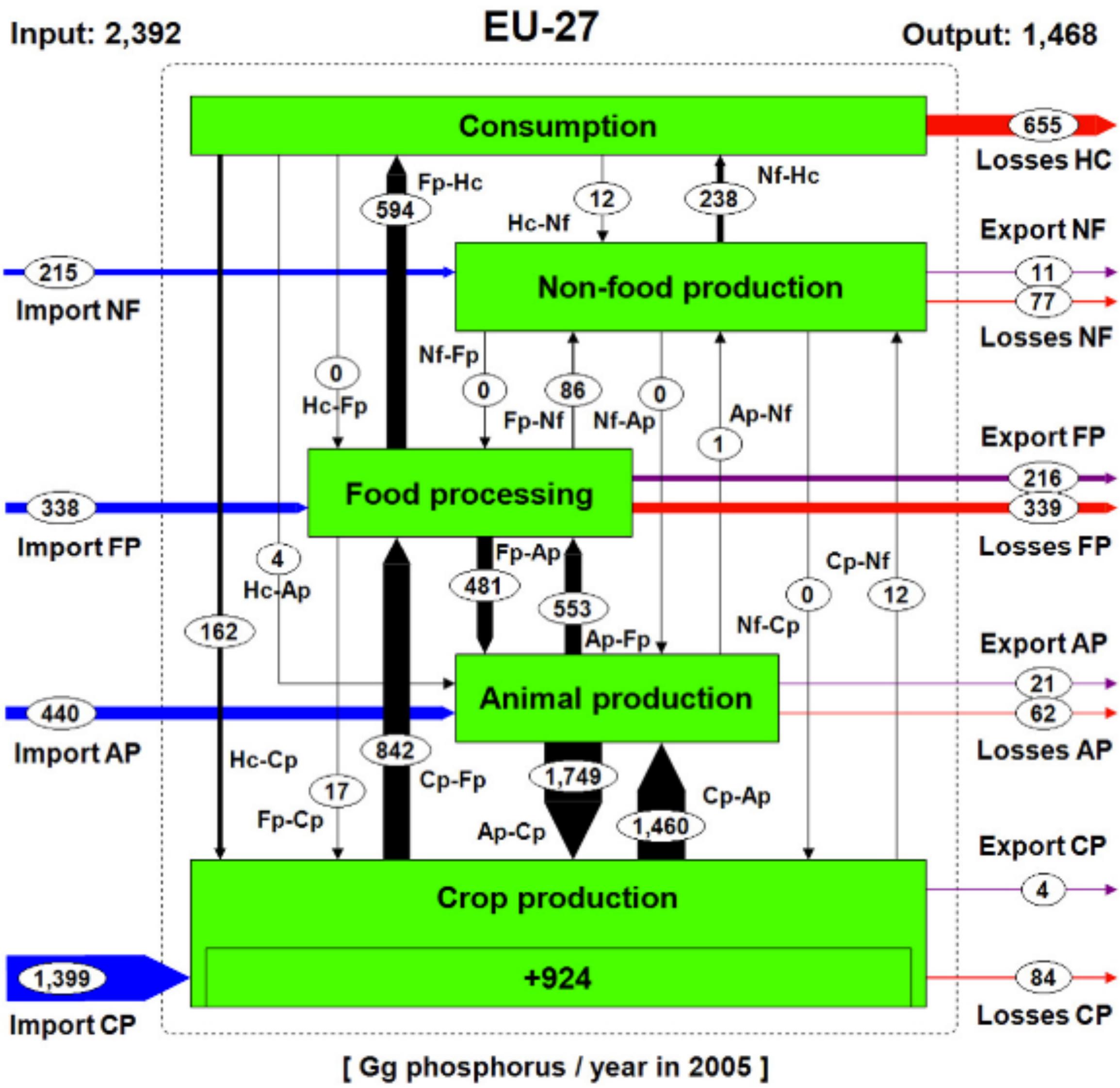


Figure 1.1. Phosphorus use for the EU-27 in 2005 [Gg/year]; Showing the import, export, losses and internal flows for crop production, animal production, food processing, non-food production and consumption. Source: Van Dijk et al. (2016)

To prevent P accumulation in soil, regulation and legislation were introduced in the Netherlands to set the maximum application standards for phosphate and oblige farmers to export surplus manure to other regions or countries (Jie et al., 2017). This transportation of slurry can be costly if no solid/liquid separation is implemented. In addition, although livestock manure contains essential nutrients and trace elements, pig and poultry manure has a relatively low N:P ratio and therefore the nutrient composition is not ideally balanced for agricultural applications (Jie et al., 2017). These limitations justify the need for further local or centralized treatment of manure.

Wastewater from households, agriculture and the food-processing industry is another waste source for P recycling. While the amount of wastewater from other sources is usually limited, municipal wastewater has a high potential for P recovery due to its large quantities and guaranteed accessibility from wastewater treatment plants (WWTPs) (Egle et al., 2015). In the EU-27, less than half of the P is recycled in sewage sludge (SS) and the potential P recycling can be up to 182 Gg P/year (Van Dijk, 2020).

Animal slaughter waste is an additional waste source for potential P recycling. After various steps for P recovery, slaughter waste becomes Meat and Bone Meal (MBM), which is a mixture of calcium phosphate and proteins that can be used as a fertilizer or feed (Withers et al., 2015). Due to the bovine spongiform encephalopathy (BSE) crisis, a BSE-sensitive fraction, MBM Category I, is incinerated instead of being used as feed additive. MBM ash contains a high amount of P and therefore can be a good source for P recovery. However, according to Van Dijk (2020), only 5% of P is recycled from MBM and the potential P recycling can be up to 122 Gg P/year.

Municipal solid and biodegradable waste contains non-negligible P for recycling. Only about 30% of the P is reused and the potential P recycling from solid and biodegradable waste can be as much as 92 Gg P/year (Van Dijk, 2020). Currently, composting is the most common and suitable way to recycle P from municipal solid and biodegradable waste. However, food packaging raises a problem with composting, therefore, further research and development (R&D) on compostable plastic is required to efficiently recycle nutrients from food waste.

1.2 The German and Swiss phosphorus systems

Both Germany and Switzerland are embedding relatively comprehensive P recovery practices within their phosphorus systems and offer interesting lessons to draw upon (Smol, 2019).

The phosphorus system in Germany

Germany is one of the EU member-states with the most comprehensive legislation on P recovery. New regulations active as of 1st January 2018 mandate that P must be recovered from sewage sludge when it contains over 2% phosphorus by 2029 for plants greater than 100,000 person equivalents and by 2032 for plants greater than 50,000 person equivalents (Johansson, 2018; Smol, 2019; Van Dijk, n.d.). Larger (> 50,000 person equivalent) sewage works are prohibited from applying biosolids directly to land (Huygens, Saveyn, Tonini, Eder & Delgado Sancho, 2019; Van Dijk. n.d.).

Germany adopts a top-down, 'command and control' approach to P recovery in WWTPs. A noticeable feature of this approach is that P recovery requirements (and regulations about application of sewage sludge to agricultural land) are purely dependent on the size of WWTPs as opposed to the pollutant content of waste (Johansson, 2018). The regulatory system is motivated by providing value through encouraging phosphorus recovery where it can be done more cheaply. This can be achieved because of the scale of Germany's economy and the viability due to the operator's financial capacity. It is worth noting that through allowing SS to be directly applied to agricultural land for smaller plants there can be harmful effects to the population and the natural environment. Sludge can contain a series of toxic components including pharmaceutical elements (Johansson, 2018). Accordingly Germany has also tightened regulations regarding contaminant content in biosolids applied to agricultural land (Van Dijk, n.d.).

A notable feature of the German phosphorus strategy is the presence of The Deutsche Phosphor Platform (DPP) which consists of stakeholders from industry, science and public bodies (Smol, 2019). The organisation seeks to encourage sustainable phosphorus management including increased recycling and reprocessing ("German Phosphorus Platform", n.d.). The DPP facilitates networking and sharing of best practice amongst stakeholders. Its success highlights the importance of exchanging knowledge amongst relevant parties when enabling transitions to more sustainable P use.

1.3 The circular economy

In a circular economy (CE) goods, products and natural resources are kept in high value use for as long as possible (European Commission, 2014). Raw materials such as phosphorus are used in a sustainable fashion with an emphasis on re-use, recycling and limiting input of raw materials into the system (for example Phosphorus Rock) (Smol, 2019; Withers et al., 2015b). Mehr, Jedelhauser and Binder (2018) note that the implementation of a CE can be a long process with considerable lag between when political decisions are made, and their effects that actually influence the system.

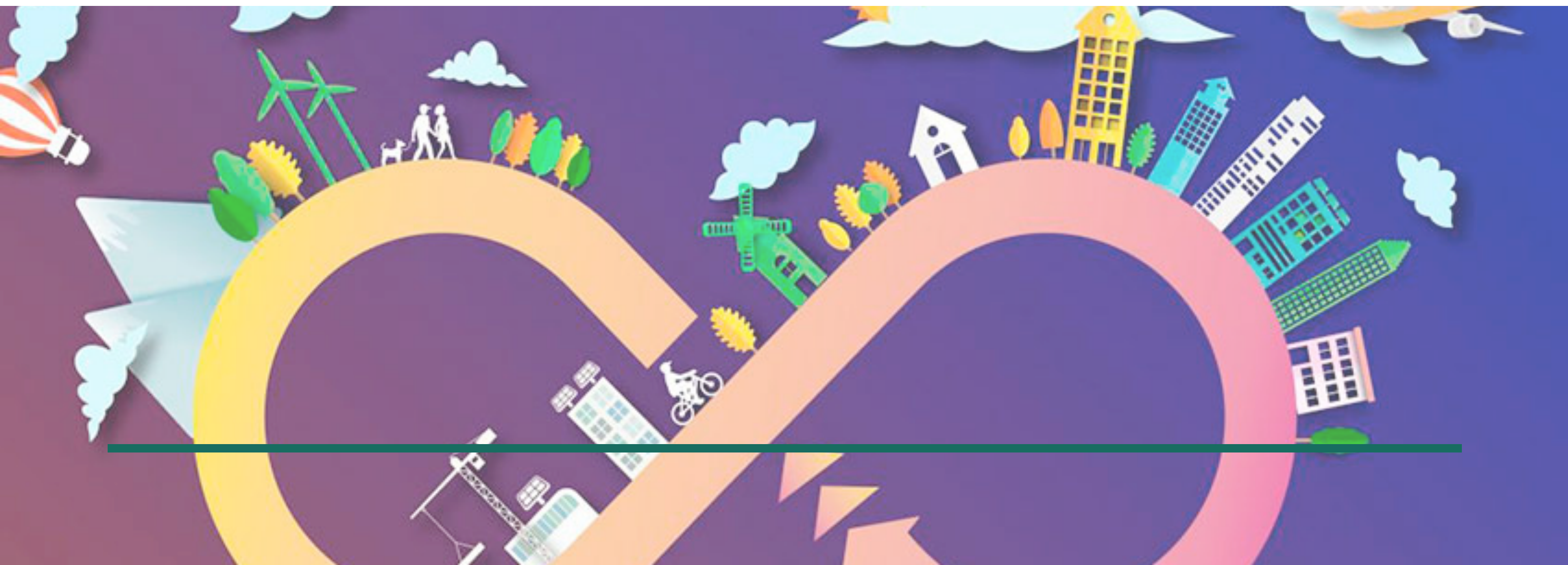
Creating a CE for phosphorus requires a holistic approach which enables systemic change in policy, technology, finance and society (European Commission, 2014). Institutional factors will determine whether promising technologies can have a meaningful impact on the P system (Jedelhauser, Mehr & Binder, 2018).

Strong, coherent policy is required to break down existing barriers where institutions and societies are locked into unsustainable patterns of phosphorus use (Button et al., 2012).

This includes utilising market mechanisms that account for the negative externalities of linear P use and ensure these are reflected in its price (European Commission, 2014).

Legal instruments should be employed to remove legislative barriers to secondary P use, for example to clearly define whether secondary P is a product or waste substance (Garske, Stubenrauch & Ekardt, 2020). Likewise, policy should remove legal barriers to promising recycling and recovery technologies, which in combination with fiscal support will allow waste to be ‘designed out’ of the P system (European Commission, 2014).

Even in a successful CE there will always be some requirement for virgin materials (ibid), as such this report strives towards a 90% circular system (requiring 10% input from external P source). Also, it will seek to negotiate potential conflicts between a circular P system and sustainable P management (such as when use of meat and bone meal can provide both phosphorus but also health and environmental challenges (Mehr et al., 2018)).



The phosphorus system in Switzerland

Switzerland is held as an example of a country making good progress towards a CE of phosphorus and claims to be the first country that obligates P recovery (Smol, 2019). However substantial improvements still need to be made (Binder, De Baan & Wittmer, 2009; Jedelhauser, 2018). The Swiss P system has been impacted by four principle changes, increasing fertiliser efficiency, removing P from laundry detergent, stopping recycling of MBM and banning application of sewage sludge to agricultural land (Mehr et al., 2018).

Firstly, from the 1980's to 2015 the Swiss agriculture sector vastly increased its efficiency and reduced fertiliser requirements, P efficiency in the agricultural system increased by 35%, to 94% (Mehr et al., 2018). This was accompanied by an associated reduction in P imports. The system centres on re-using manure and green waste.

Secondly, as P has previously played a large role in the eutrophication of lakes and water bodies in Switzerland (Binder et al., 2009), the use of phosphate in laundry detergents was banned in 1986. This, in combination with the aforementioned reductions in fertiliser use, limited eutrophication (Mehr et al., 2018).

Thirdly, the spread of BSE disease amongst Swiss livestock in the late 1990's led to an end of recycling animal meat and bone meal (Mehr et al., 2018). This removed one potential stream of P recovery. Fourthly, the ban on direct application of sewage sludge on to agricultural land in 2006, eliminated another method of P re-use at the time.

The most relevant policy going forward is the Swiss Ordinance on Avoidance and Disposal of Waste (VVEA) which entered into force in 2016 and will become active in 2026 (European Sustainable Phosphorus Platform, n.d.). This will require recovery and recycling of P from sewage sludge (or sewage sludge ash) and wastewater (Jedelhauser et al., 2018). It will also require P recovery from MBM in response to Switzerland being deemed to have very-low BSE risk (Mehr et al., 2018).

CHAPTER 2

Scenarios and roadmap

Scenario planning is utilized in this report to provide an in depth analysis of possible future outcomes of decisions made as the EU prepares for and responds to peak phosphorus in 2030. This tool promotes creative thinking for alternative future pathways and the relationship between decisions today and their consequences in the future. By identifying how the environment, technology, society, and economy function together based on important driving factors, a more comprehensive report is provided allowing for a strategic policy implementation to achieve a circular P economy.

2.1 Driving Forces

Figure 2.1 lists the driving forces identified in the scenario planning analysis that affect how a phosphorus CE can develop in time. This list provides the main conditions assessed in this advisory report, however, this system is dynamic and can incorporate alternative driving forces not listed here.

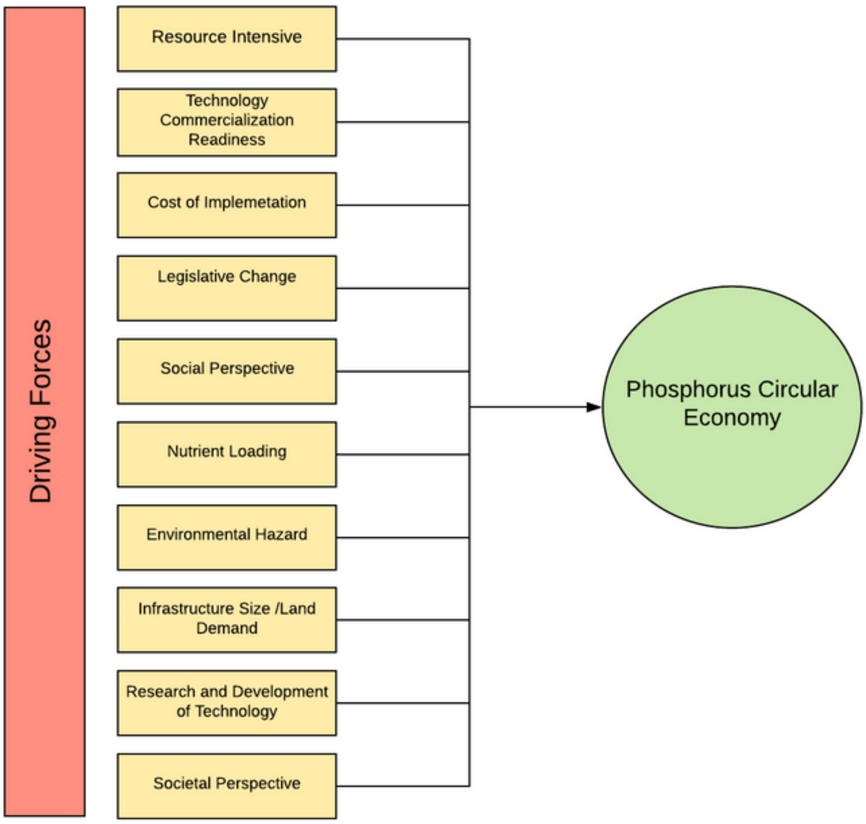


Figure 2.1. Driving forces that affect the phosphorus CE.

2.2 Critical uncertainties and assumptions

The following uncertainties and assumptions were identified in the scenario analysis of the report. These uncertainties represent potential challenges that are unpredictable in the decision making process of each scenario, see figure 2.2.

- Social response to legislation - level of trust in regulations imposed.
- Lack of institutional capacity - this can affect specific member states, as the European Commission applies policies differently than individual member states.
- Environmental effect of reducing P losses to the environment.
- Development of new technologies.

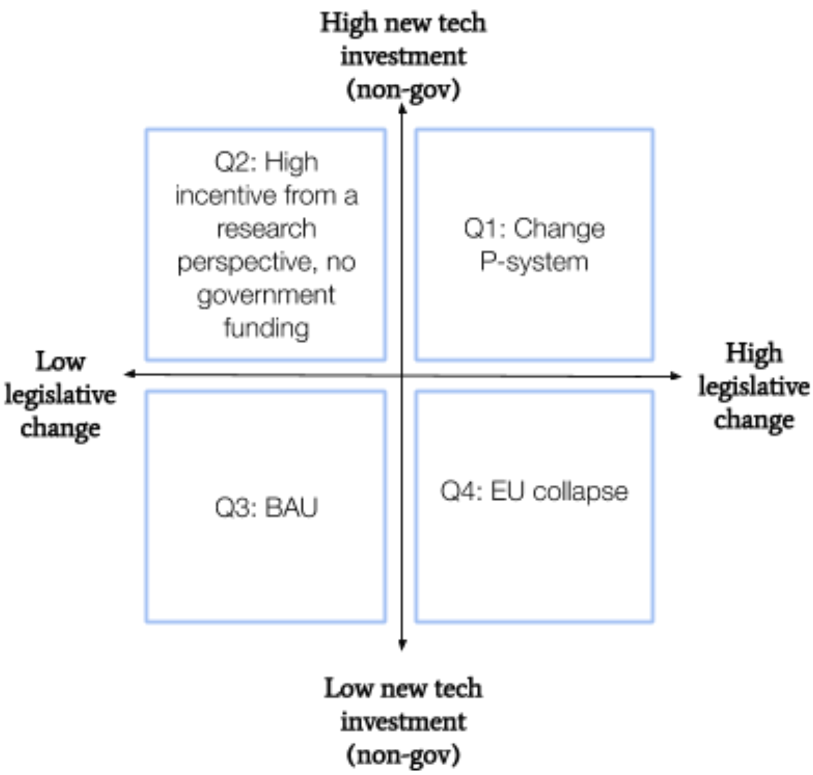


Figure 2.2 Four scenarios based on legislative change and new technology investment drivers

2.3 Scenarios

Scenario 1: Circular Phosphorus Economy from a Systems Approach

In this scenario legislative policy and new technology investment align together to reach maximum capacity in the following years, resulting in a CE breakthrough due to the landscape pressure of peak phosphorus in 2030. Using a systems multi-level perspective analysis we find that the limited supply of phosphorus globally is the driving pressure on the regime and actors involved in the system. In turn this creates space for niche technologies to be adopted into the system.

This scenario looks at an increased demand for legislative policy which will directly impact the rate of niche technology development. EU legislation focused on a CE facilitates the adoption of new technology into the system stimulating the market and increasing funding. The feedback with more phosphorus recycling technology into the system, market share and financial incentive for new technology will take over the current linear system in place.

Additionally, by focusing on policies that are implemented from a top to bottom approach based on limiting phosphorus supply there is more monitoring control to ensure EU member states meet standards put in place. Furthermore, this scenario takes into account a third driver, nutrient loading, which also contributes directly to the landscape level of the system. With increased policy requirements on the recovery of P and new technology available, the market for secondary sources can help reduce the consumption of raw material. In return, nutrient loading will become more efficient and sustainable, reducing pressure from the EU to import PR to meet demand.

Scenario 2: Private Sector Takes the Lead

This scenario explores the possibility of a future where there is minimal legislative change from a central government, but investments for new technology come from non-government entities. It is the private sector that accelerates the CE of phosphorus. Private institutions can offset the risks from their portfolio of linear businesses while capturing part of the upside potential generated by a CE. The financial sector can also provide better access to funding which accelerates the growth of the CE, and improves the economic equation of circular businesses (Oliver Wyman, 2017). This diminishes investment and credit risks and provides more sustainable returns. As a whole this scenario provides an economic incentive for private entities to invest in new technologies even though legislative policy is lagging behind.

Additionally, involvement by banks and institutional investors can stimulate innovation by increasing sustainable investments in the agricultural and industrial sectors of phosphorus. Several stakeholders take part in moving new technologies forward, which helps pave the way to a commercial market setting for secondary P. However, it is important to note that without the legislative support from a centralized government there is a risk of losing raw phosphorus material if the new market prices do not favor secondary material.

This scenario highlights a platform for future growth, as circular businesses become mainstream, and a way of diversifying risks that arise from lending to linear companies (Oliver Wyman, 2017).

Scenario 3: Business As Usual (BAU)

This scenario explores the outcomes of a low technology investment and low legislative change in the EU. This will result in a BAU case as current systemic practices and guiding regulation follow recent trends. In this scenario the current system will continue to produce the same results and challenges and not significantly adapt to a future where phosphorus is maximally circular.

Notably, phosphorus imports will remain high as there is no incentive to use recycled P. The main imports will remain via mineral fertilisers, animal feed and additives, food and non-food materials (Van Dijk et al., 2016). Moreover, there will be low P recycling efficiency, implementation and development of technology. Without policies stimulating P recycling and investment in technology, there will be slow progress in improving the P flows and recycling methods in the current system. The excessive and inefficient use of P will significantly impact the limited resources available. Furthermore, fertilisation of agricultural fields will continue to increase P accumulation in soils. Without proper management, soil erosion will continue to play a key role in eutrophication of water bodies due to high concentrations of phosphorus in soils.

The social component in this scenario is based on little change in dietary uptake of P by society. Phosphorus in food flows will remain high, with no changes to intake of meat and other high P requirement foods (Van Dijk et al., 2016). The price of P will increase when it becomes more scarce and therefore will result in increased food prices. This could lead to crossing a threshold so the system will no longer be able to adapt to a P shortage. Reaching P scarcity is inevitable and will cause major problems with food security. If we continue with this scenario the system will be less resilient and will be unable to deal with a P shortage. The reinforcing aspects of the current system will need to change and adapt to a future with less available P resources. The BAU scenario will result in a system that is unable to adapt and deliver a CE of phosphorus quickly enough.

Scenario 4: EU Falls Behind with Phosphorus Circular Economy

The last scenario provides a forecast of what would occur given a drastic change in legislation within the EU without investments or funding to support new technologies. The outcome of these driving factors looks at how an acceleration of recycled P-products into the international market will make the use of virgin P for products less attractive. These changes also make recycled P-products more cost competitive with common fertilizers, because the Cd limit set increases the cost of common fertilizers.

More products with recycled P from common P-recycling processes are available, such as struvite, fertilizers, compost etc. and the import of rock-P decreases gradually.

The new legislations also make it possible for new technologies to gain quicker access to the (inter)national market, but since funding comes mostly from the government, there is not enough capital to get new technologies in the pilot stage and it takes a long time for a given new technology to move forward with implementation. The many legislative changes that were made to change the entire P-system and stimulate a CE are costly but do not have the intended effect. Instead of having created a market for new P-technologies, boosting P recovery and stimulating economic growth, the EU will fall behind in technological advancements which places distrust from its member countries. This leaves the European Commission with minimal control over the EU's phosphorus system.

2.4 Chosen scenario

Political, Economic, Social, Technological, Legal and Environmental (PESTLE) Model of the EU for scenario 1

The scenario planning analysis revealed scenario 1 as the most effective approach to tackle the phosphorus change in the EU. Several key elements were identified that play a crucial role in the development of a CE that can overcome projections of peak phosphorus by 2030.

This scenario is dependent on three main drivers identified in the first part of the analysis: high legislation changes, increased investment and better nutrient loading management. Further analysis of this scenario is provided in this section using the tool PESTLE to provide a clear understanding of the system transition to a CE based on each factor.

The first factor identified in the assessment of this scenario looks at the government's involvement in establishing regulations for phosphorus in the EU. A centralized government is suggested as the most effective to provide an expert-guided environmental governing hand and produce optimal outcomes (Shearman & Smith, 2007). Centralization of political and economic decision making can provide direction to circular innovations that focus on specific sectors, while also investing in R&D for innovations (Bauwens, Hekkert & Kirchherr, 2020). A central government can remove barriers across the EU that limit the production and distribution of secondary phosphorus material. While a centralized government is seen most effective for general policies across the EU, community-based projects should also be encouraged to support the development of a CE.

In terms of economic factors, this scenario looks at the potential of monetary incentives, tariffs and offsetting costs as the basis of a successful CE of phosphorus. Incentives will play a key role in supporting stakeholders in the agricultural sector to transform current system practices. With the support of legislation, funding will be made available to assist farmers and other key industry members to implement new technology and sustainable practices. Tariffs on PR will become essential with limited supply after peak phosphorus in 2030.

Moreover, offsetting costs will be necessary in order to continue providing food and products.

The social aspect of this scenario represents the customs and values of the EU. This factor is challenging as it places the responsibility on to the individual. This transition requires a change in dietary intake and waste management. On average, meat and dairy products contribute 24% of the environmental impacts from total final consumption in the EU-27 (European Environmental Agency, 2017). Therefore, scenario 1 examines how the transition of the system to a CE must also focus on the local level by pushing for social awareness. For this reason, social awareness and informational campaigns on meat consumption can help move towards a more sustainable phosphorus system. In essence, this scenario relies on the willingness of society to make health and environmental conscious decisions and progress with a changing system.

Technological development in this scenario is expected to have high priority in terms of R&D. The investment in phosphorus recycling technology continues to move forward in this plan as the market has shifted to make the use of recycled material profitable. Both private institutions and government investors are able to stimulate innovation by increasing sustainable investments in the agricultural and industrial sectors of phosphorus. This provides funding for new technologies to emerge at higher rates than in the current system.

Moreover, based on this scenario assessment there are a selection of technologies already known that have promising potential in the following years. These technologies include composting, struvite crystallization, incineration and gasification.

Eutrophication of streams and lakes due to erosion of high phosphorus concentrated soils from fertilizers is directly related to environmental factors (Carpenter, 2005). Therefore, this scenario assumes that the high priority in technology and regulation to manage the finite resource provides additional focus on phosphorus recovery from the environment. Management of nutrient loading is also a main focus in this scenario which helps limit the loss of phosphorus into the environment and water bodies.

The legal organization of this scenario is focused at an EU level and involves policies that can be regulated in all member states. It is important to note that because the EU relies on imports of phosphate rock from other countries all policies and legal frameworks must be implemented with thorough analysis to ensure compliance can be enforced. Moreover, the EC can add a sector similar to the Extractive Industries Transparency Initiative to monitor phosphorus regulation and products. In addition to monitoring, this sector can provide legal help for technology start-ups and smaller recycling companies that do not have a legal team available to get their products status and REACH registration. This can lead to EC-fertilizer approved products which are easily identified in the market as sustainable products.

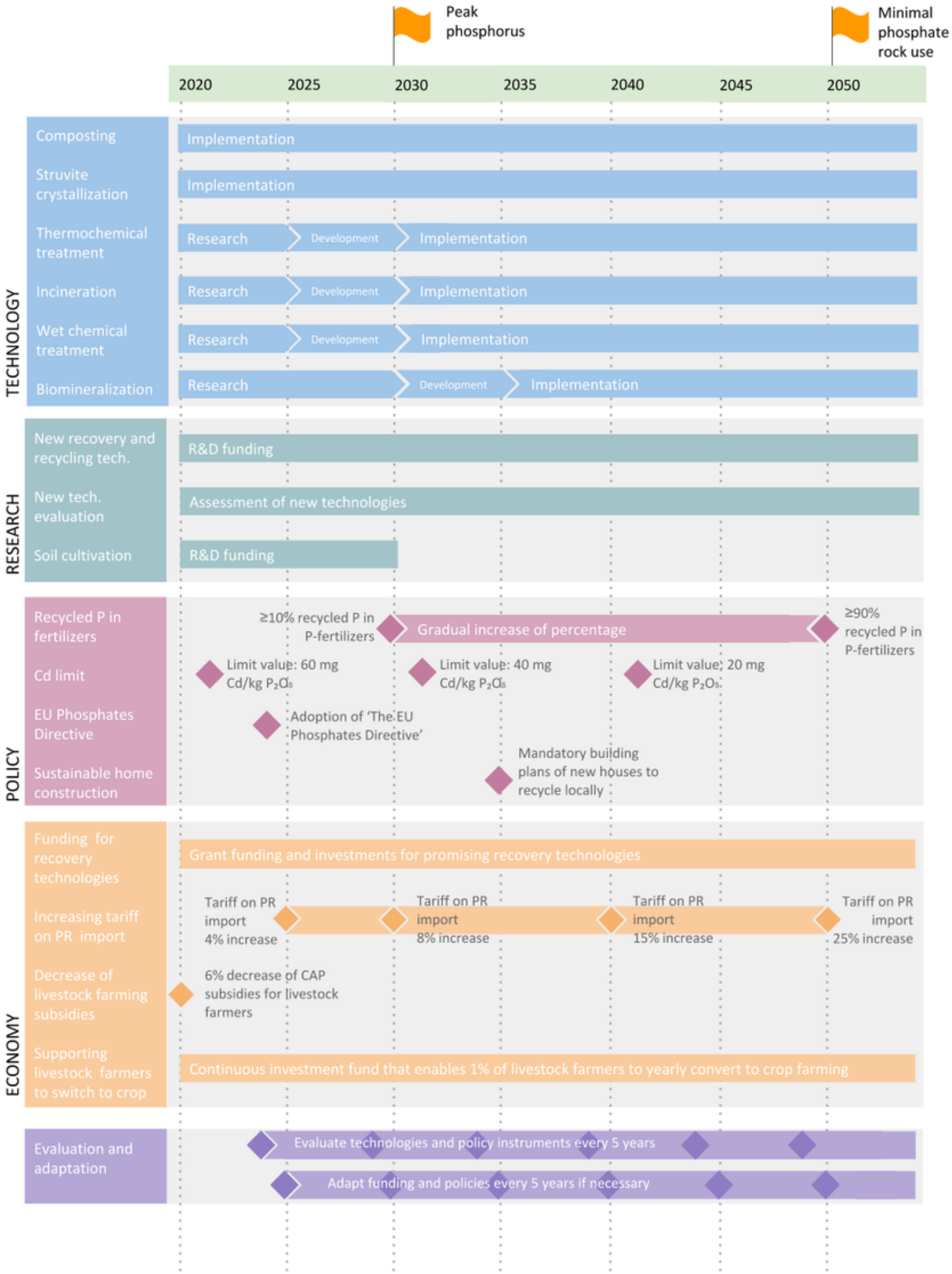


Figure 2.3. Timeline illustrates the main recommendations and implementation strategies in each area.

CHAPTER 3

Recommendations

In our recommendations we aim to take a joined-up holistic approach as we seek to develop a circular phosphorus system for the EU (European Commission, 2014). There must be a high level of interaction between policy, economic, social and technological factors to form an effective approach to such a multi-faceted problem (Mehr et al., 2018).

Figure 3.1 lists key drivers that highlight the importance of sustainable P use, which include limiting supply uncertainties and environmental pollution like eutrophication (Withers et al., 2015b). Based on the scenario analysis in chapter 2, we have assessed recommendations from a combination of both high technology investment and legislative change. If implemented, these recommendations would help the EU cope with peak phosphorus in 2030.

We have outlined five principle policies on which our strategy is centered (Figure 3.1): implementing an EU Phosphorus Directive, increasing the percentage of recycled phosphorus in fertilisers; removing legislative hurdles for the phosphorus recycling process; subsidising R&D for existing and promising technologies and reducing both meat consumption and production. This chapter explains these policies in detail as it deals with the policy, economic, technological and social factors relevant to sustainable P use in individual sections.

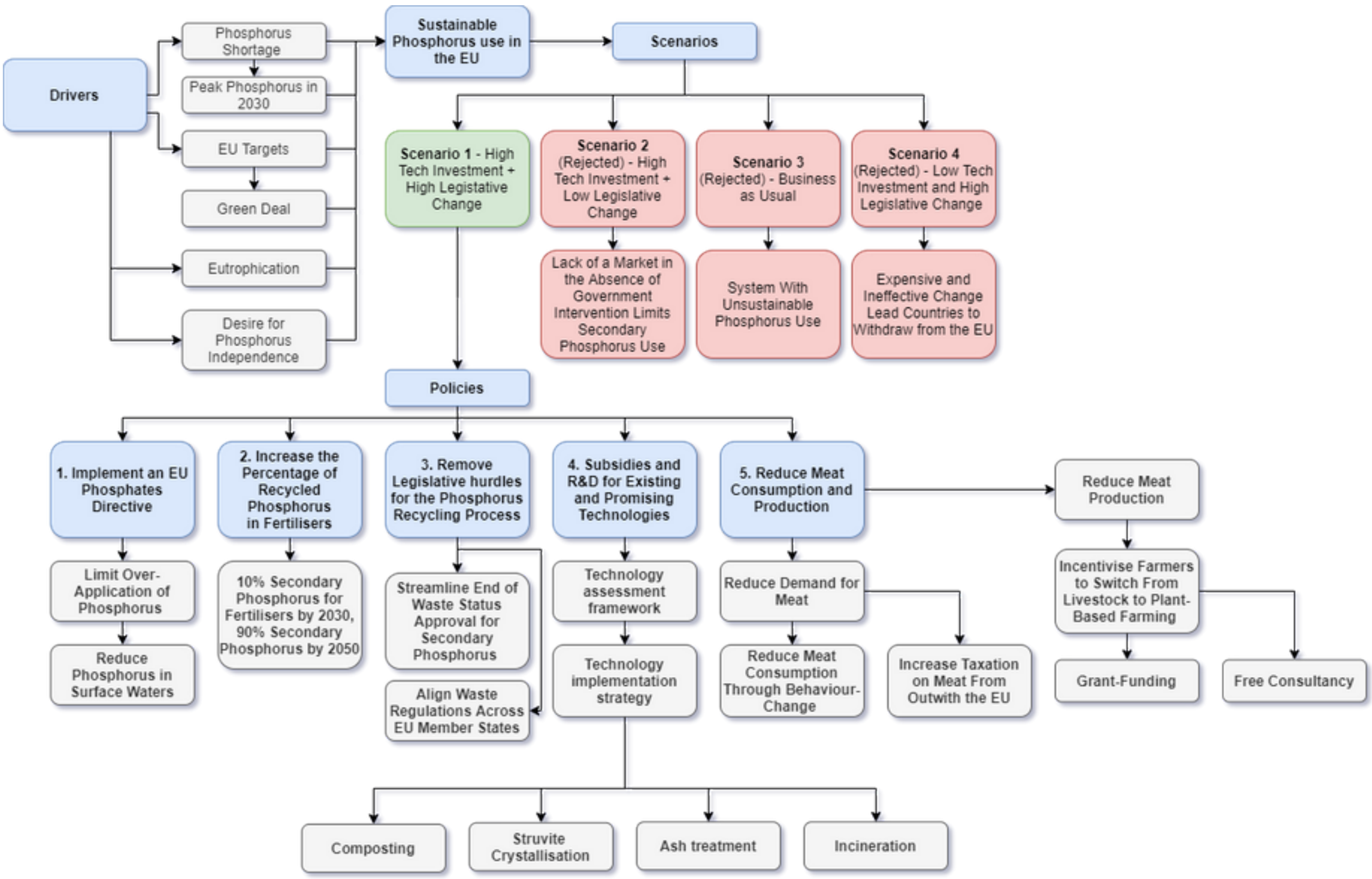


Figure 3.1 A mind map showing our recommendations for a circular P system

3.1 Policies

Main policy recommendations

PHOSPHATES DIRECTIVE

Main recommendation 1

In 1991 the Nitrates Directive was adopted to “protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices” (European Commission, 1991). There is no equivalent directive for P at the EU level (Garske et al., 2020), yet this is essential for promoting the recovery and recycling of P. Adopting a Phosphorus Directive could help limit the overapplication of P to agricultural land and reduce the amount of P lost to the environment and thus help mitigate eutrophication.

A study focused on the performance of the EU Nitrates Directive by Musacchio, Re, Mas-Pla & Sacchi (2020), revealed that the Nitrates Directive’s governance structure does not help spread knowledge nor does it help change farmer’s views. Therefore, it is imperative for the future success of the new Phosphates Directive that farmers and other stakeholders have a high degree of involvement in its transformation.

Besides implementing the Phosphates Directive, it should be mandated that the P in waste streams is recovered in a way that it can be converted in a usable product (Garske et al., 2020). For example, this shoud be implemented by adding this in the Urban Waste Water Treatment Directive. Moreover, landfilling of recovered P should be eliminated from the life cycle of P as in order to help facilitate the transition towards a CE.

MANDATORY MINIMUM RECYCLED P IN FERTILISERS

Main recommendation 2

To ensure that the recovery and recycling of P happens, we recommend implementation of legislation that makes the use of a certain percentage of recycled phosphate in P-fertilizers mandatory. Moreover, it is recommended that after a transition period of 10 years, phosphorus fertilizers produced and used in the EU have to contain a minimum of 10% of P from recycled sources. The transition period will give fertilizer producers time to adapt their facilities and will give recovery plants the opportunity to recover P in a way that can be recycled. This percentage will then gradually increase over a timespan of 20 years up to 90% recycled P.

To achieve this ambitious 90% recycled P in P-fertilizers by 2050, there are a few strategies that should be applied. De Ridder, De Jong, Polchar & Lingemann (2012) report on strategies that promote efficient use of P throughout the value chain and create a basis for recovery and reuse:

- Promote the efficient use of phosphate: advertise P as a valuable resource that has to be used efficiently by everyone.
- Improve efficiency of P in agriculture: mitigate leaching, improve recovery efficiency of P from manure and improve bioavailability of P by discouraging overapplication of fertilizers and promoting precision approaches for fertilizer application and in animal feed.
- Reduce and substitute use of P: substitute P in laundry and kitchen detergents and find alternatives to the use of phosphoric acid as flavor improver in food products.
- Prevent the loss and dilution of P: implement legislation that forbids dilution of P and mitigates P losses to the environment (eg. landfilling) to make recovery of P possible.
- Promote phosphate recovery and facilitate the creation of a sustainable European market of recycled P: the EU should implement legislations that can make products out of secondary sources competitive.
- Facilitate knowledge exchange through networks of excellence: for the recycling of P to be established and to also operate efficiently in the long term, various stakeholders will have to become connected and be able to benefit from each other's expertise.

REMOVE LEGAL HURDLES FOR P RECYCLING

Main recommendation 3

The development of P-recovery technologies has been possible mainly because of EU environmental legislation (European Commission, 2016). By pushing for the recycling of P and recycled P products, a stable market can be implemented in the EU.

To assist companies in making the P-system more circulair, two main objectives are needed. Firstly, waste regulations need to align across the EU member states and secondly the approval of the End-of-Waste status of novel recycled-P fertilizers should be more streamlined. The following legislative changes are recommended to remove legal hurdles for companies investing in a circular P-system:

- Make the End-of-Waste status an EU-wide status: this will streamline the registration process of becoming an electrical conductivity-fertilizer (Hukari, Nättorp & Kabbe, 2015) and incentivize the production and use of recycled-P fertilizers by having EU-wide acknowledgement of these novel products.
- Provide legal help for technology start-ups and small P-recycling companies (Hukari et al., 2015)
- Provide P-recycling companies and start-ups with financial guarantees to make the transport of waste across the borders of Member States possible (Hukari et al., 2015)

Other policy recommendations

Cadmium limit

Cadmium (Cd) is a non-essential mineral and is found in phosphate rock that is used for phosphate fertilizers. By applying P-fertilizers to land containing a high Cd content, Cd can accumulate in soil and be transferred to plants. The consumption of these plants can have adverse effects on human health in the long term. The presence of Cd in soil can also have negatively effect on soil biodiversity and eventually also groundwater quality (European Commission, 2016).

Current fertilizer regulations include a limit of 60 mg Cd/kg P2O5 for inorganic mineral fertilizers with a total P content of ≧ 5% P2O5-equivalent, starting after a transition period of 3 years and an option for fertilizers with a Cd content of < 20 mg Cd/kg P2O5 to add the label 'Low Cd content' (Regulation (EU) 2019/1009). Garske et al. (2020) find this regulation to have a 'lack of ambition' and argue that changing this regulation to a more stringent one could significantly increase the competitiveness of recycled-P fertilizers.

According to the advice of Garske et al. (2020) and the European Commission (2016) we recommend to include in the Fertilizer Regulation:

- A decrease of the limit value to 40 mg Cd/kg P2O5 and eventually 20 mg Cd/kg P2O5,
- A mandatory declaration of the respected limit value of either 60, 40 or 20 mg Cd/kg P2O5.

The limits of 60, 40 and 20 mg Cd/kg P2O5 could lead to a reduction of Cd inputs of 30%, 69% and 81% respectively (European Commission, 2016).

Reducing the use of first generation biofuels to decrease phosphorus depletion

The European Union has strongly encouraged the use of biofuels, with the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD). RED has a mandatory minimum of 10% for renewable energy transport by 2020 and the FQD has set a target of 6% greenhouse gas reduction. These policies have led to the mixing of gasoline and kerosene with biofuels (Delft, 2015). However, the sustainability of biofuels, especially first generation biofuels is contested. A 2016 study by DeCicco et al. (2016) showed that the use of first generation biofuels (biofuels made from harvested crops rather than biowaste) have a worse net greenhouse impact than fossil fuels.

Furthermore, Hein and Leemans (2012) showed that around 2% of global phosphorus production is lost in the production of biofuels. In order to reduce the harmful effects of first generation biofuels on both the climate and phosphorus reserves, we recommend adapting the RED and FQD to incentivise use of advanced biofuels, and reduce use of first generation biofuels.

3.2 Economic policies

In order to create a circular phosphorus system for the European Union, it will be crucial to take certain economic policy measures. For companies that aim to recycle phosphorus it is still hard to compete with the value offered by PR. In order to level the playing field, and bridge the gap between phosphate recovering and recycling, we therefore propose increasing tariffs on PR import into the EU. Also we recommend a set of subsidies and investments for recovery technologies. Combined with increasing the minimum percentage of recovered P in fertilizer, this should enable a growing market for recycled P.

Furthermore, the majority of phosphorus input directly or indirectly goes to livestock farming (Van Dijk et al., 2016). To become less dependent on phosphate rock, it is therefore important to implement economic measures to decrease overall livestock numbers. This should be done both from the consumption as from the production side. On the production side, we propose decreasing basic payment of EU farming subsidies for animal farming.

This money should be used to subsidize those animal farmers that wish to convert their business to crop based farming. On the demand side, we aim to end existing subsidies on meat advertising campaigns, and to increase investments in innovative meat replacement companies.

Main economic recommendations

INVESTMENTS FOR RECOVERING AND RECYCLING TECHNOLOGIES

Main recommendation 4

Every year, over 200,000 tons i.e. 60% of phosphorus in sewage waste is not utilized in the form of crop production (Milieu Ltd, WRc & RPA, 2008; Science Communication Unit, 2013; Van Dijk et al., 2016). Phosphorus from this waste stream is often used for incineration, landscaping or landfilling. However, phosphorus is often lost by being added to concrete.

The potential of different recovery potential techniques can have a valorisation of almost twice that of the current EU mineral P supply see figure 3.2.

An in depth research has been done by the P-REX project, which has analysed and summarized 10 promising phosphorus recovery technologies. Stages of the technologies range from pilot projects to industrial implementations. Some processes can recover almost 100% of phosphorus in sewage waste at the WWTPs. Annual costs of recovery technologies ranges from €0-15 per capita. However, if current undiluted sewage sludge ash is also used, the costs of annual recovery of phosphorus would be less than €5 per capita. In comparison, wastewater treatment costs in europe vary annually between €40-140 per capita.

Process	Maximum recovery rate (%)	Annual cost per capita (€)
Precipitation from SS	15%	0-5
Leaching of SS	50%	5-15
Recovery from SSA	100%	0-5

Table 3.1 Practical and economic values of promising phosphorus recovery technologies as evaluated by the P-REX project

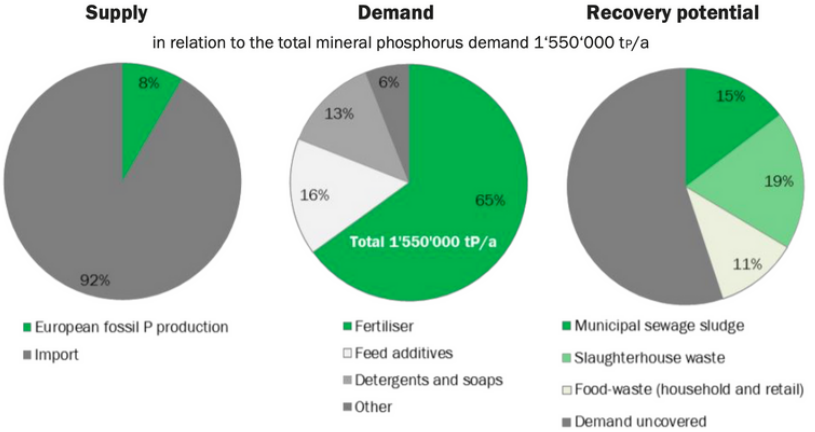


Figure 3.2 European phosphorus production, demand and recovery (Van Dijk, K. C., Lesschen, J. P. & Oenema, O., 2015; Jabinski, B.S.M. 2011)

In order to enable the recovery and recycling of P from wastewater, a set of EU-wide subsidies and investment possibilities will therefore be needed. We recommend a combination of the following financial incentives:

- Continued subsidies for R&D on phosphorus recovery and recycling technologies
- Public investments and private investments with government guarantees to create the needed financing for large scale applications of recycling and recovering technologies.
- In order to kick-start the recycling process, we propose an EU-wide subsidy for recovering and recycling P, that can slowly decrease over time as the market for recovered P matures.

The money to pay for this will come directly from Green Deal Funding, the amount required will be reviewed on a 5-yearly basis to coincide with our regular review programme.

As such it will be responsive to changes in the cost of installing and operating technologies. The money will come both directly from EU budgets as part of the Green Deal and private investment guaranteed by the EU, again utilising the Green Deal framework. Moreover, grant funding will be allocated to alleviate any food cost rises resulting from the use of secondary source fertilisers. This will be directly given to member states who can choose how to do this best in their local context, with clauses inserted to ensure proper allocation of funds.

The goal is to create a self-reliant market for recycled P. The minimum percentage of recycled phosphorus in fertilisers will force fertiliser companies to source part of their P from recovered sources. This, together with investments, subsidies and tariffs should enable recycled P to compete with PR.

REDUCE MEAT CONSUMPTION AND PRODUCTION

Main recommendation 5

Lastly, in order to deliver a more efficient P system in Europe, we advise supporting the transition towards a majority plant-based diet. This should begin with ending the current EU subsidies on meat advertising. Currently the EU subsidises advertising campaigns encouraging meat consumption with over 200 million euros (Stichting Wakker Dier, 2020). A first simple step would be to redirect these campaigns to advertise healthy plant-based products in a similar manner.

Furthermore, there is a large emerging market for meat substitutes. Europe currently has the largest meat replacements market in the world, with a revenue of USD 1.40 billion in 2014, and an expected growth at 7.5% (Grand Review Research, 2018). However, the price of meat replacements are still often higher than that of animal meat, although the environmental and societal damages are much lower. The EU can support these successful companies, by guaranteeing needed investments.

Decrease animal farming subsidies within the Common Agricultural Practice

Currently all farmers within the EU are eligible for subsidies within the Common Agricultural Policy, which has a yearly budget of more than 58 billion euros. Farmers receive €260 per hectare as a basic payment, and when certain sustainable criteria are met, they receive another €115 as a Greening Premium (European Commission, 2019). Lastly, farmers under the age of 41 receive another 50 euros per hectare, to support young farmers.

As animal farming has a very significant impact both on climate change and on the phosphorus cycle, we propose to decrease the Basic Payment for animal farming by 6%. This will incentivise farmers to switch to crop based farming. In order to help those animal farmers that wish to convert to crop-based farming, the money made available by the decrease in basic payment is used for one-time subsidies for farms to convert. This one-time subsidy is the fivefold of their basic payment subsidy, combined with government guarantees for extra loans. This should enable a farmer to make the needed investments to for instance convert a livestock stable to a greenhouse. And it would enable 1% of farmers to convert from animal to plant based farming yearly. This would lead to a decrease in animal farming of 26% by 2050. The proposed policy to help livestock farmers that wish to convert to crop is further worked out in the following section.

Support livestock farmers that wish to convert to crop based farming

As the majority of phosphorus use is related to animal farming, we propose to incentivise livestock farmers to switch to plant based farming. This can be achieved by both giving subsidies to livestock farmers who make the switch to plant based farming and by creating an intermediary organisation that can provide free expert advice and support in doing so.

The underlying reason why decreasing animal farming is important is the fact that crop production (60%) is much more P efficient than livestock farming (12%) (Withers et al., 2015b). Therefore, we propose introducing subsidies and investments to farmers who agree to transition from livestock to plant based farming. Moreover, funding should be allocated to create a team of EU advisors for each EU member state who will operate at a national level providing free expert advice and consultancy to farmers who wish to transition from livestock to plant based farming.

These expert intermediaries will occupy a connecting role both facilitating communication between farmers themselves so they can learn from each other's experiences and linking farmers with relevant governmental and non-governmental organisations who can offer support (Grin, Rotmans & Schot, 2010). They will also provide advice on logistical and technical challenges farmers may face.

Saved phosphorus use:

Animal farming in the EU has a total input (directly and indirectly) of 2381 Mkg annually (Van Dijk et al., 2016). The P efficiency of animal farming in the EU is significantly lower than that of plant-based farming (12% versus 60%). Therefore if 26% of animal farms would have converted to plant-based farming in the EU by 2050, the total agricultural P needed as input would decrease by 297 Mkg, which is 12% of the total P input in the EU.

Saved carbon impact

Furthermore, as animal agriculture contributes significantly to greenhouse gas (GHG) emissions, reducing livestock would contribute to carbon emission goals as well. Currently the total carbon emission of animal farming in the EU is 12% of the GHG emissions of the EU. Plant based farming is 10 to 100 times more carbon efficient than animal farming (Poore & Nemecek, 2018), therefore reducing the EU livestock by 26% would decrease the carbon impact of the EU by about 3%. So, next to reducing the phosphorus input, this policy would also advance the European Commission's goal to reach carbon neutrality in 2050.

26%

DECREASE IN ANIMAL FARMING BY 2050

Supporting 1% of animal farmers to switch to crop farming would lead to 26% reduction in animal farming 2050

12%

REDUCTION IN P USE

Reducing animal farming by 26% would reduce the P use by 12%

3%

REDUCTION IN CARBON EMISSIONS

Reducing animal farming by 26% would reduce the EU's carbon emissions by 3%

Other economic recommendations:

Implement a minimum tariff on P import

Taxes in the EU are managed by the member states, however trade policies are managed by the European Union. The Common Customs Tariff applies to goods imported into the EU (European Commission, 2019). It is dependent on the classification of goods and the country or territory of origin. There is currently no uniform tariff on phosphorus rock imported into the EU, rather any tariffs in place are specified by trade agreements with the country P is imported from. In order to incentivise recycling of P, we propose an increasing tariff on phosphorus rock imported into the EU by 4% in 2025, 8% in 2030, 15% in 2040 and 25% in 2050. These percentages are based on current levels and are not cumulative. This should contribute to secondary phosphorus decreasing in price relative to primary phosphorus.

The proceeds from this tariff will be directly granted to EU member states, with payments made on a per capita basis, in order to alleviate food price increases/food poverty that may arise due to potential food price increases from this tariff.

Tariffs can vary depending on trade agreements the EU has made with specific countries. Therefore introducing these tariffs will take some time, and some exemptions might occur. However, as we are advising the EU with a 30 year roadmap, it should be possible to revise trade agreements over time and introduce these tariffs.

3.3 Technology

An assessment of current phosphorus recovery techniques is an important step towards their full-scale implementation. A methodology has been proposed which incorporates a 7-step program. It is important to look at technologies that show promising returns on investment in the future. A systematic overview of incoming wastewater and P content must be characterised. Additionally, a technical readiness level (TRL) (Rybicka, Tiwari & Leeke, 2016), economic and environmental analysis and a sensitivity analysis must be applied to assess the influence on the market and economic variations of the process profitability. Lastly, a risk analysis of new technologies must be done to assess certain aspects that can interpret different uncertainties. It is important to highlight that many current technologies are still in their infancy, making them either economically or environmentally not feasible. Therefore, ongoing progress must be kept up to assess the development of technologies, this assessment is shown in appendix 1.

Before the most promising technologies for P recovery are provided, an initial framework for the implementation of state-of-the-art technologies is established. Currently, much research is being done on new technologies for P-recovery, these technologies generally have a low TRL (e.g. 'immature'). This framework consists of three different levels, see figure 3.3 .

Technologies that are at level 1 result from start-ups and still need research. By receiving investments from large companies that can employ these technologies, startups can grow. Level 2 is technology that is already proven to work and mostly part of scale-up companies, development and fine tuning is still ongoing. A mandatory subsidy for further development can also give a good incentive for level 1 companies. Level 3 technologies have proven efficiencies and applicabilities and are implemented on an industrial scale. When a technology reaches this level it should be implemented as soon as possible.

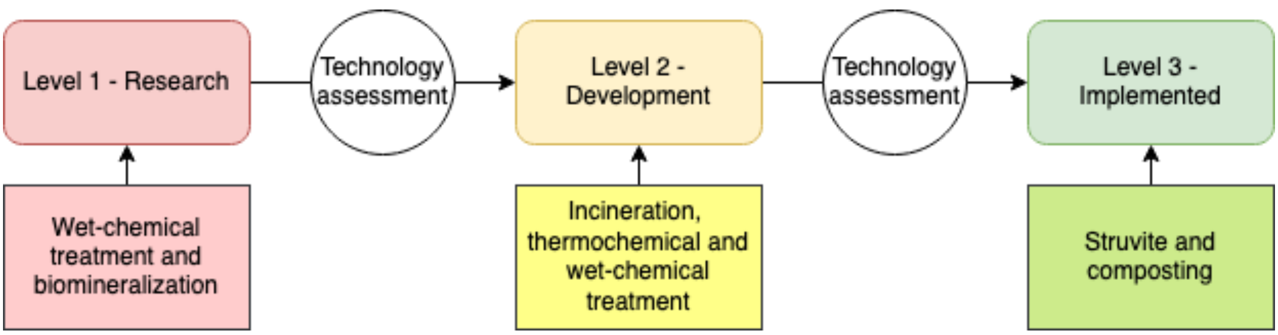


Figure 3.3 Different levels a P-recovery technology can be in

Recommended P-recovery technologies

The assessment of a technology through technical readiness level does not just take into account the technical maturity of phosphorus recovery, but also its stability through the years.

Composting is a traditional process mechanism that manages biomass/waste by using earthworms or microorganisms to break down organic waste into vegetable mould (Cieślik & Konieczka, 2017). However, modern composting processes consist of a multi-step process that is monitored very closely, by using different measured inputs of air, water, and nitrogen- and carbon-rich materials. The result is solid composted waste that contains phosphorus including other nutrients, this could be directly applied to the soil or could undergo further treatment to be made into organic fertilizer. Composting is the most common and suitable way to recycle nutrients from municipal biodegradable waste e.g. food waste. However, research and development on compostable packages is required to improve recycling from municipal food waste by composting.

Chemical precipitation and crystallization is a technology that has been widely employed to recycle P from the liquid phase of wastewater (Kataki, West, Clarke & Baruah, 2016; Schoumans, Bouraoui, Kabbe, Oenema & Van Dijk, 2016; Cieślik & Konieczka, 2017; Egle et al., 2015). Calcium and magnesium ions are commonly used as precipitators to react with phosphate to form calcium phosphate (hydroxyapatite) or struvite.

While calcium phosphate can be recycled in the fertilizer industry, struvite can be directly applied in soil as a low-release fertilizer. In addition, struvite can also be used in the fertilizer industry as a substitution for phosphate rock.

Phosphorus recovery through incineration usually requires mono-incineration plants. Solid waste including SS, MBM or pig manure can be incinerated to produce incinerated ash (Cieślik, Namieśnik & Konieczk, 2014; Egle et al., 2015). The concentration of phosphorus in ash becomes comparable to phosphate rock after incineration. However, SSA and pig manure ash contain a high level of heavy metal, and therefore cannot be directly applied as fertilizer. Further treatment is required to remove the excessive amount of heavy metal especially for Zn, Cu and Pb.

Wet-chemical treatment is a process that can recover P from SS or SSA (Loganathan, Vigneswaran, Kandasamy & Bolan, 2014; Arnout & Nagels, 2016; Egle et al., 2015). Generally, this process uses strong acid (HCl, H2SO4) to release the phosphorus from the SS/SSA at low pH, which is usually followed by precipitation, ion exchange or nano filtration to separate heavy metal and P (Ye, Y., et al, 2017). In addition, phosphoric acid (~ 52% H3PO4) can be used to dissolve phosphate bound in SSA/MBM ash/struvite in a rotary kiln.

Thermochemical treatment that can recover P from SS or SSA (Adam, C., et al, 2009). In this process, chloride additives are mixed with SS/SSA at high temperatures (800–1000 ˚C) to remove heavy metal as volatile heavy metal chlorides in the flue gas. This process can also improve the bioavalability of P in SSA and produce depolluted ash that can be used as fertilizer.

Thermo-electric treatment to incinerated ash is an additional method for phosphorus recovery (Ribarova et al., 2017; Arnout & Nagels, 2016). This process typically fuels incinerated ash or raw phosphate into an electric arc-furnace which is at temperatures higher than the ash’s melting point. The recovered phosphorus undergoes a reduction to white phosphorus (P4) gas in combination with carbon dioxide. Following the flue gas treatment, the recovered phosphorus is condensed and gathered in a water bath and reaches a purity of 99.9% (Tervahauta et al., 2014). In addition, the phosphorus gas can be vaporized and recovered in the form of a pure phosphate element using technologies e.g. InduCarb reactor (Arnout & Nagels, 2016), this reactor reaches temperatures between 1300-1600 C. The products are gaseous phosphorus and CO which can be treated further, e.g. the CO can be used to generate energy.

Biomineralization is a relatively new P-recovery technology that delivers minerals with the use of living organisms, phosphorus is recovered as hydroxyapatite or struvite (Simoes, Vale, Stephenson & Soares, 2018). Such phosphates result in a higher recycle potential and have less chemical supplements, it also allows for more flexible influent composition (P-concentration in influent can be as low as 10 mg/L).

Some technologies such as manure recycling are already being applied by farmers to fertilize their land (Jie et al ., 2017). Additional processes for nutrient recycling exists, this can give a better N:P ratio than directly applying manure to the soil.

However, cattle manure already has a high N:P ratio and can be directly recycled as fertilizer. Pig and poultry manure are often exported after separation or incineration. This practice of manure recycing makes additional treatment obsolete.

Technology readiness level assessment

As aforementioned, technologies are divided into categories of lab, pilot and full-scale implementation based on their readiness level. Although there is a significant amount of technologies at the lab and pilot scale that show promise, serious financial investments need to be made to commercialise these. Linick (2017) has shown that the percentage of R&D costs for each TRL score is the total amount spent on development to the percentage of costs in order to complete a project.

It can be seen in table 3.2 that composting and struvite crystallization are the only technologies that show a TRL score of 9, making them the best currently certified technologies that can be implemented on an industrial scale, R&D costs for future applications of these technologies are negligible.

Secondly, incineration, wet-chemical treatment and gasification are well researched and can be implemented when given enough technological development. However, the process mechanisms and the important factors surrounding biomineralization techniques are currently not well understood. Immaturity in technologies such as biomineralization as well as costs of the transition towards profitable solutions are barriers for commercialization. This TRL assessment can be applied from a government legislation point of view as incentive to grant financial aid towards R&D for industrial and academic collaborative projects which can further new P-recovery technologies for future commercialization.

Technology	Level	TRL Score	Remarks
Composting	Industrial	9	Excellent technological ‘knowhow’ and large number of applications
Struvite Crystallization	Industrial	9	Some technical ‘knowhow’, but with a large number of full scale applications
Biomineralization	Research/pilot	1	A few studies on reaction mechanisms
Incineration	Development	6	A few pilot scale plants in operation, good technical ‘knowhow’
Wet-chemical Treatment	Development	6	Concept proven with pilot operations
Thermo-chemical treatment	Development	5	A proven concept and good technical ‘knowhow’

Table 3.2 Different levels a P-recovery technology can be in

3.4 Social factors

It is important to address the social factors that are connected to the suggested recommendations. The vast majority of phosphorus extracted from PR is wasted in society and most people are not aware of the P challenge and its implications (Withers et al., 2015b). Phosphorus has multiple benefits such as providing food security, improving human health and improving economies (Childers, Corman, Edwards & Elser, 2011). One of the main challenges faced in transitioning the P cycle involves raising awareness on the need for social change.

Dietary changes, particularly reducing meat and dairy consumption, can play a significant role in reducing P losses (Withers et al., 2015b). Meat and dairy consumption is culturally ingrained in diets across most parts of the EU and is generally increasing. Campaigns and marketing should support policies on reducing meat consumption and production.

Every sector of society will need to accept the values of sustainability and use resources efficiently in order to provide future generations with food, energy and a healthy and ecologically diverse environment (Withers et al., 2015). Farmers are another integral part of society that have the highest stake in the P system (Yi Teah & Onuki 2017). Fluctuations in P costs in the market are likely to occur at multiple times during the transition to a more circular system. In 2008 the cost of P climbed to around 800% above the previous year (Yi Teah & Onuki, 2017). The livelihoods of farmers were negatively affected by this and reduced their quality of life. Cumulatively, P cost increases could lead to increases in food prices (Khabarov & Obersteiner, 2017), creating more pressure for citizens (particularly with low income) to feed themselves and their families.

To overcome the global P challenge multiple stakeholders involvement in policies and strategies are necessary to close the loop towards a circular economy. Only with increased awareness on the adverse effects of P loss and overuse can there be a faster transition away from the current system.

CHAPTER 4

Discussions

4.1 Limitations

For our main recommendations, limitations are identified and discussed in order to achieve a comprehensive analysis of the results. This discussion can also guide future research on the CE.The first recommendation of implementing an EU Phosphates Directive aims at reducing overapplication of P to agriculture land. However, this recommended policy does not include suggestions on (1) the design of Phosphate Vulnerable Zone (2) the maximum application standards for phosphate from manure/synthetic fertilizer (kg P2O5/hectare/year) (3) variation of the application standards in different regions/periods. In addition, this recommendation does not suggest solutions to the potential problems that the Nitrates Directive (on which this policy is based) already faces. Further research is required to formulate a concrete implementation plan of the EU Phosphates Directive and look into the governance structure in order to actively involve farmers and other stakeholders in the forming of the directive.

For the recommendation of increasing the percentage of secondary P in fertilizers and feedstock, the 90% goal is not a precise estimate but serves as an incentive for the secondary P market. Due to the limited time of the project, it is unrealistic to perform a precise quantification, which will require intensive investigation. Apart from the 90% goal, this recommendation does not include a concrete implementation plan or monitoring procedure for the transition of fertilizer companies. Nor does it suggest any incentive or support for this transition procedure. Further studies are needed to investigate these aspects.

In terms of removing the legislative hurdle, streamlining the registration process will require innovation and improvement of the EU system. More research is required to design a streamlined registration process and an evaluation of the new system. Additionally, EU-wide End-of-Waste status requires the alignment of waste regulations of different member states. Further research is necessary to look into these waste regulations as well as collaborative legislative change needed to make EU-wide End-of-Waste status possible.

For the subsidy and funding for R&D and implementation of technology, although we have proposed an assessment framework to evaluate technologies, private companies usually offer only general information about technologies, which is not sufficient for comprehensive evaluation. Therefore, more case studies of pilot/demonstration plants are required especially for environmental, economic and sensitivity analysis in order to achieve a better understanding of the practice of certain technology. Furthermore, this recommendation does not include a budget for subsidy and investment. More work is needed to formulate a P-recycling technology investment plan based on the Green Deal.

Overall, the quantitative estimate of P import reduction and P losses recycling is not performed in our report. The team has focused on mostly qualitative advice considering the limited time of the project.

4.2 Risk analysis

Regulatory advice requires an evaluation to identify possible risks and support effective decision making. For this reason a risk analysis is included as part of the advisory report, carried out based upon the PESTLE framework. Informed by the outcomes of the risk analysis decisions can be made to choose the most promising recommendations.

The risk analysis is compiled using the following steps for each recommendation:

1. Identify the possible negative effects of the aspect (Shuttleworth, 2017). Brainstorming is done in this step to identify possible hazards related to the recommendation. As previously mentioned these hazards could be related to one of the PESTLE aspects: political, economic, social, technological, legal or environmental. The points identified here are later assessed and the significant impacts are discussed in more detail.

2 Identify the stakeholders that can be affected. In this step known and potential stakeholders are identified. This can include but not be limited to government institutes, municipalities, fertilizer companies, consumers and regulatory bodies. It is important to identify the actors involved in the recommendation in order to analyse how they will be impacted and how significant the impact may be (Shuttleworth, 2017).

3. Evaluate the risks and assign a value from the 5 x 5 matrix (Shuttleworth, 2017). A literature review can be conducted and used to help assign a risk value to individual recommendations. The assigned value is dependent on the probability and severity of the potential hazards. The 5 x 5 matrix is used to assign risk values in this analysis. With the risk analysis of Phosphorus circularity at the EU scale, the recommendations would be acceptable in the moderate rating range.

This is because the pressure to move to a circular system is high and the necessary steps need to be taken in order to change the current system. The severity of the P challenge will outweigh the possible unfavourable outcome of recommendations. Actions with risks that score a major to severe rating will be given extra scrutiny. These recommendations that score this rating will not be chosen first, or will include preventative measures to reduce associated impacts.

4. Suggest alternative options. Alternative options need to be explored when recommendations score poorly. This step can be used to brainstorm alternative options or solutions to reduce risk.

5. A description of the findings. Each recommendation will be studied in order to assess and holistically describe the benefits and risks involved. It is important to have a comprehensive description of results, to assist understanding of problems faced and potential solutions (Shuttleworth, 2017).

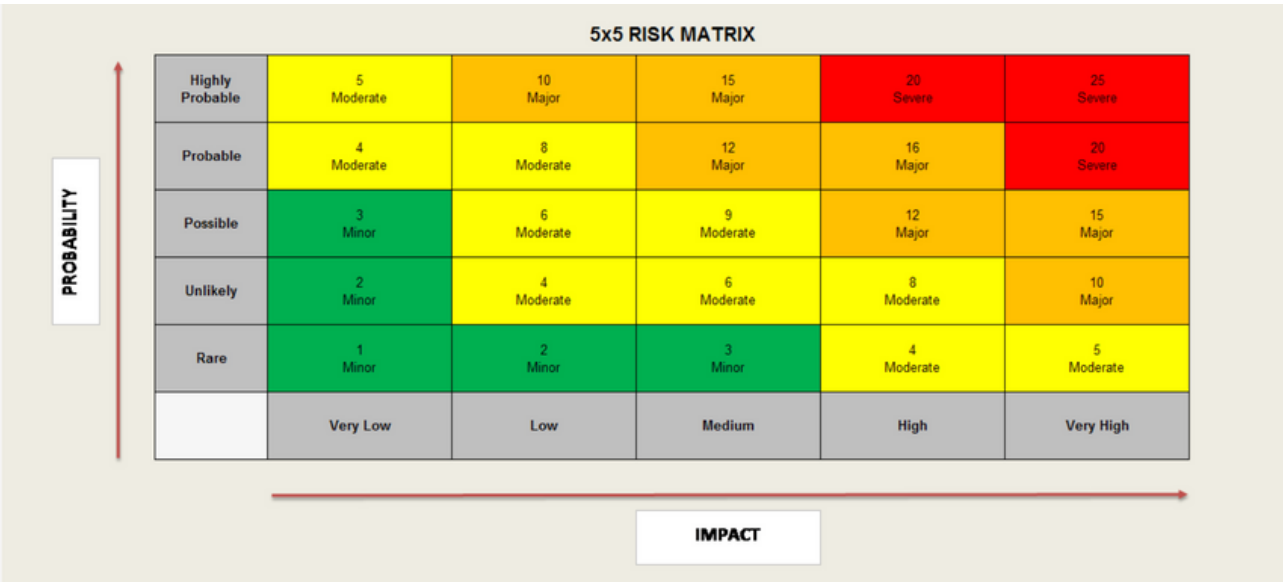


Figure 3.4: Five by five risk matrix (Shuttleworth, 2017)

Risk Assessment

Aspect	Identify possible negative effects	Identify stakeholders involved	Risk value	Findings	Other options
Main Recommendations					
Implement an EU Phosphate directive	Member countries do not take enough initiative and the aims of the directive are not met	EU member countries, The EU, Farmers, Fertiliser companies, WWTPs, and P recycling companies		**NEGATIVE** There may be a need to reduce P loading in different activities (European Commission, 2019). Cost related challenges: ensuring financial investment would be a challenge (many farms cannot afford new investments), challenging to finance the change(European Commission, 2019), market prices driven by market chain Stakeholder challenges: getting all member states to agree or implement the directive, getting fertiliser companies and farmers to make changes **POSITIVE** Gives member states the opportunity to reach goals or aims at their desired pace	Subsidies fo. farms that use P in a sustainable circular manner
Increase percentage of recycled P in fertilizers and feedstocks	Insufficient supply of good quality recycled P in fertilisers, lack of infrastructure to accommodate the required percentage of recycled P, WTO agreements might provide challenges with specific agreements to import P from non EU countries such as Morocco, severing relationships with Morocco	EU member countries, Farmers, Fertiliser companies, WWTPs, and P recycling companies		**NEGATIVE** There could currently be a lack of infrastructure to accommodate the required percentage of recycled P (Van der Kooij et al., 2020), WTO agreements might provide challenges with specific agreements to import P from non EU countries which could damage relationships with countries such as Morocco. **POSITIVE** Clear direction and drive towards circular P and set timeline, stimulates the market for recycled P	Benefits for recycling P, P trading scheme
Remove legislative hurdles	Less control on waste streams, process to get end product can be unmonitored	Fertiliser companies, Waste sources, and Wastewater treatment plants		**NEGATIVE** More contaminants may be present in products (European Sustainable Phosphorus Platform, 2020), pathogens might be present in products **POSITIVE** There are technologies that can be used to remove contaminants and pathogens	Implement monitoring programme for waste processing and waste sources

Subsidize best technologies to use now and funding for research and implementation	Fiscal loses due to underperforming technologies	Research institutes, Technology companies, and EU member states		**NEGATIVE** Investing in technology that does not work the way it was expected to, expected results of implementation is less than projected, could **POSITIVE** Increased rate of technological development, improved efficiency of P recovery and recycling, taking steps towards closing the P cycle	Subsidize technologies that have good preliminary results, offer tax breaks to new and developing technologies
Reduce meat consumption and production (give livestock farmers incentive to switch to plant farming)	Change for farmers could be expensive, cultural heritage of farms could make it challenging to convince farmers to switch to plant based farming, increase in meat prices, meat could be imported from countries that have less regulations and therefore transferring the problem, food security	Farmers, EU member states, Consumers, Fertiliser Companies, and Retail stores		**NEGATIVE** Market could be too stable and therefore switching will be challenging (Sanchez-Sabate, Badilla-Briones & Sabaté, 2019), time consuming to transform farms, new skills and education will be necessary for farmers who are stitching to plant based farming POSITIVE The policy to reduce meat consumption and production is also beneficial to climate change policies (will reduce impacts on climate change) (Sanchez-Sabate et al., 2019)	Increase regulations for dairy and meat farmers instead of change to plant based farming, add a tax on imported meat

4.3 Recommendations for future research

There are a few gaps in our knowledge around the recovery and recycling of P highlighted by our research. We thus recommend further research in the following areas:

- **Making a EU Phosphates Directive.** Since there is no Phosphates Directive yet for all the EU member states, this would have to be newly made. For this the existing Nitrates Directive can be used as a guideline, as long as flaws of this Directive are taken into consideration. Another option would be to combine the new Phosphates Directive and the Nitrates Directive in one EU 'Nutrients' Directive. Stakeholders should be highly involved in the formation of the new directive.

- **Prepare P-recovery and -recycling technologies for widespread implementation.** Some of the technologies we believe are needed for a circulair P-system, like biomineralization, still require some research before they can be developed further. There is also a need for research on the removal of harmful contaminants from recovered P before it can be recycled.

- **Reducing need for P**
  Geeson and Cummins (2020) recently published a paper on making white phosphorus, an P allotrope, obsolete by using Green Chemistry. Green Chemistry is a way of performing chemistry in a most sustainable and safe way. More research in this field is needed to eventually reduce the use of phosphate rock even further. Research is also required for methods of soil cultivation to increase the amount of bioavailable P (Garske et al., 2020).

- **Biodegradable packaging that is suitable for composting on an industrial scale.** Biodegradable plastic currently in use cannot actually be degraded during composting. To be able to fully utilize composting, either biodegradable plastics should not be recycled, which defeats the purpose of using biodegradable packaging, or packaging that can be composted has to be introduced.

- **Using sustainable home construction measures to decentralize recovery and recycling.**
  Aiming for a CE in a few decades time, requires a decentralization of all recovery and recycling practices. Research is needed to move these practices to houses and neighbourhoods. To make this possible in all member states, home construction changes would have to be made price competitive with normal construction.

Most importantly, there is a lack of quantitative data about the impact of our advice. Quantitative analysis is out-with the scope of this report. To be able to fully evaluate the effectiveness of technologies being used and policies being implemented research to quantify our advice is necessary.

A cost-benefit analysis of the suggested policy recommendation should be completed. This should include both the cost of each measure and the money that it can save. Moreover the wider consequence of economic steps such as using import tariffs for meat and reducing PR imports should be quantified. The results from this analysis can be used to provide better quality information to policy makers and if necessary, highlight areas of the report where amendments should be made.

4.4 Conclusion

Phosphorus sits on the EU's list of critical materials because it is both a vital component of world food and production systems and a material suffering from a shortage (European Commission, 2017). This report directly responds to the anticipation of peak phosphorus in 2030. It is imperative that the EU adopts a sustainable P system in response to phosphorus shortages in addition to environmental problems caused by P-runoff (Withers et al., 2015b).

Scenario planning was carried out in order to plot the predicted outcomes of different policy and technological response to the P challenge. The most promising scenario to facilitate a transition from a linear P system was identified as a combination of substantial policy support coupled with a high investment of innovative P recovery and recycling technologies. These two structures mutually reinforced each other, creating a strong market for secondary phosphorus and can eventually deliver a CE for phosphorus. Informed by this transition scenario this report recommends a programme of action in relation to four key areas, policy, technology, economy and society. It provides a holistic response to emphasise the interconnectedness of these areas in order to change the EU's P system.

The report highlights five key policy actions which transcend these key areas and mutually reinforce each other to deliver a CE for phosphorus. Firstly, a phosphates directive would limit overapplication of P to agricultural land helping reduce eutrophication. Secondly, legislation would ensure that a progressively rising percentage of fertilizers and human and animal food products consist of secondary rather than primary P. Thirdly legal barriers to developing P recovery technologies would be removed. Fourthly, R&D and the development of promising P recovery and re-use technologies would be prioritised. Fifthly, support to transition to less production and consumption of livestock would reduce P usage in the most phosphorus intensive sector.

Our recommendations are balanced and grounded in reality with an effort made to demonstrate where funding would come from to fund policies. Moreover, the risks associated with following or deviating from our proposed actions are detailed in chapter 4. Through acting on our recommendations, the EU can see the challenge presented by peak phosphorus in 2030 as an opportunity. An unsustainable P system can be reimagined to the benefit of the EU itself, its member states and its citizens.

REFERENCES

Ahn, J. H., Kim, S., Park, H., Rahm, B., Pagilla, K., & Chandran, K. (2010). N2O emissions from activated sludge processes, 2008– 2009: results of a national monitoring survey in the United States. *Environmental Science & Technology*, *44*(12), 4505-4511.

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., & Egle, L. (2018). Environmental impacts of phosphorus recovery from municipal wastewater. *Resources, Conservation and Recycling*, *130*, 127-139.

Arnout, S., & Nagels, E. (2016). Modelling thermal phosphorus recovery from sewage sludge ash. *Calphad*, *55*, 26-31.

Bauwens, T., Hekkert, M., & Kirchherr, J. (2020). Circular futures: What Will They Look Like?. *Ecological Economics*, *175*, 106703.

Binder, C., De Baan, L., & Wittmer, D. (2009). Phosphorus flows in Switzerland (pp. 1-163, Rep.). Bern: The Federal Office for the Environment FOEN.

Brunner, P. H., & Rechberger, H. (2016). *Handbook of material flow analysis: for environmental, resource, and waste engineers*. CRC press.

Button, J., Potočnik, J., Rehn, O., Tajani, A., Šemeta, A., Hedegaard, C., . . . Lamberts, P. (2012). European Resource Efficiency Platform (EREP) *Manifesto & Policy Recommendations* (pp. 1-16, Rep.). Brussels, Belgium: European Commission.

Carpenter, S. R. (2005). Eutrophication of aquatic ecosystems: bistability and soil phosphorus. *Proceedings of the National Academy of Sciences*, *102*(29), 10002-10005. Retrieved from https://doi.org/10.1073/pnas.0503959102

Childers, D. L., Corman, J., Edwards, M., & Elser, J. J. (2011). Sustainability challenges of phosphorus and food: solutions from closing the human phosphorus cycle. *Bioscience*, *61*(2), 117-124. Retrieved from https://doi.org/10.1525/bio.2011.61.2.6

Cieślik, B., & Konieczka, P. (2017). A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of “no solid waste generation” and analytical methods. *Journal of Cleaner Production*, *142*, 1728-1740.

Cieślik, B. M., Namieśnik, J., & Konieczka, P. (2015). Review of sewage sludge management: standards, regulations and analytical methods. *Journal of Cleaner Production*, *90*, 1-15.

Cordell, D., & White, S. (2011). Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability*, *3*(10), 2027-2049.

DeCicco, J. M., Liu, D. Y., Heo, J., Krishnan, R., Kurthen, A., & Wang, L. (2016). Carbon balance effects of US biofuel production and use. Climatic Change, 138(3-4), 667-680.

Delft, C. E. (2015). Assessing progress towards implementation of the ILUC Directive.

Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of the Total Environment*, *571*, 522-542.

Egle, L., Rechberger, H., & Zessner, M. (2015). Overview and description of technologies for recovering phosphorus from municipal wastewater. *Resources, Conservation and Recycling*, *105*, 325-346.

European Commission (1991, December 12). Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. *Official Journal of European Community L375*: 1–8. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0676&from=EN

European Commission (2014, July 2). Towards a Circular Economy: A Zero Waste Programme for Europe, COM(2014) 398 final. Brussels. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0398&from=EN

European Commission (2015, December 2). Closing the loop - An EU action plan for the circular economy, COM(2015) 614 final. Brussels. Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF

European Commission (2016, March 17). Limits for cadmium in phosphate fertilisers, SWD(2016) 64 final. Brussels. Retrieved from https://ec.europa.eu/transparency/regdoc/rep/10102/2016/EN/SWD-2016-64-F1-EN-MAIN-PART-2.PDF.

European Commission (2017). *Critical raw materials.* Retrieved from https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

European Commission (2019b, December 11). Communication From The Commission; The European Green Deal. Brussels. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

European Environmental Agency (2017). *Food consumption - animal based protein*. EEA. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/13.2-development-in-consumption-of-2/assessment-1.

European Sustainable Phosphorus Platform (n.d.). *Switzerland makes phosphorus recycling obligatory*. Retrieved from https://phosphorusplatform.eu/scope-in-print/news/1061-switzerland-makes-phosphorus-recycling-obligatory#:~:text=Switzerland makes phosphorus recycling obligatory,into force on the 1.1.

European Sustainable Phosphorus Platform (2014). *Phosphate rock in EU Critical Raw Materials list*. Retrieved from https://phosphorusplatform.eu/scope-in-print/news/359-phosphate-rock-in-eu-critical-raw-materials-list

European Sustainable Phosphorus Platform (2020). *Proposed Considerations For The EU'S "Integrated Nutrient Management Action Plan" (INMAP).* Retrieved from https://phosphorusplatform.eu/images/download/Considerations-for-input-INMAP-ESPP-v31_5_20.pdf

Foley, J., De Haas, D., Hartley, K., & Lant, P. (2010). Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water research*, *44*(5), 1654-1666.

Garske, B., Stubenrauch, J., & Ekardt, F. (2020). Sustainable phosphorus management in European agricultural and environmental law. *Review of European, Comparative & International Environmental Law*, *29*(1), 107-117.

Geeson, M. B., & Cummins, C. C. (2020). Let's Make White Phosphorus Obsolete. *ACS Central Science 6* (6), 848-860.

German Phosphorus Platform (n.d.). Retrieved from https://www.phosphorusplatform.eu/espp-members/755-german-phosphorus-platform#:~:text=German Phosphorus Platform,as effective recycling and reprocessing.

Grand Review Research (2018, July). *Meat Substitutes Market Size, Share & Trends Analysis Report By Product (Tofu, Seitan, Tempeh, Quorn), By Raw Material (Soy-based, Wheat-based, Mycoprotein), By Region, And Segment Forecasts,* 2012 - 2022.

Grin, J., Rotmans, J., & Schot, J. (2010). *Transitions to sustainable development: new directions in the study of long term transformative change*. Routledge.

Hein, L., & Leemans, R. (2012). The impact of first-generation biofuels on the depletion of the global phosphorus reserve. Ambio, 41(4), 341-349.

Hukari, S., Nättorp, A. & Kabbe, C. (2015). *Phosphorus recycling now!* P-REX policy. Retrieved from https://zenodo.org/record/242550#.WowGiOcxmUk

Huygens, D., Saveyn, H., Tonini, D., Eder, P., & Delgado Sancho, L. (2019). Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009). *FeHPO CaHPO*, *4*.

Jedelhauser, M., Mehr, J., & Binder, C. R. (2018). Transition of the Swiss Phosphorus system towards a circular economy—Part 2: Socio-technical scenarios. *Sustainability, 10*(6), 1980.

Jie, Y., Buisonjé, F. E., & Melse, R. W. (2017). *Livestock manure treatment technology of the Netherlands and situation of China: white paper* (No. 1048). Wageningen Livestock Research.

Johansson, N. (2018). How can conflicts, complexities and uncertainties in a circular economy be handled? A cross European study of the institutional conditions for sewage sludge and bottom ash utilization (pp. 1-56, Rep.). *KTH Royal Institute of Technology.*

Kataki, S., West, H., Clarke, M., & Baruah, D. C. (2016). Phosphorus recovery as struvite: Recent concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer potential. *Resources, Conservation and Recycling*, *107*, 142-156.

Khabarov, N., & Obersteiner, M. (2017). Global phosphorus fertilizer market and national policies: a case study revisiting the 2008 price peak. *Frontiers in nutrition*, *4*, 22.

Li, B., Udugama, I. A., Mansouri, S. S., Yu, W., Baroutian, S., Gernaey, K. V., & Young, B. R. (2019). An exploration of barriers for commercializing phosphorus recovery technologies. *Journal of Cleaner Production*, *229*, 1342-1354.

Linick, J. (2017, June). Technology Readiness Level (TRL) vs. Percent Development Cost. In *2017 International Cost Estimating and Analysis Association Professional Development and Training Workshop, Portland, United States*.

Loganathan, P., Vigneswaran, S., Kandasamy, J., & Bolan, N. S. (2014). Removal and recovery of phosphate from water using sorption. *Critical Reviews in Environmental Science and Technology*, *44*(8), 847-907.

Lorenzo-Toja, Y., Alfonsín, C., Amores, M. J., Aldea, X., Marin, D., Moreira, M. T., & Feijoo, G. (2016). Beyond the conventional life cycle inventory in wastewater treatment plants. *Science of the Total Environment*, *553*, 71-82.

Mehr, J., Jedelhauser, M., & Binder, C. R. (2018). Transition of the Swiss phosphorus system towards a circular economy—Part 1: Current state and historical developments. *Sustainability*, *10*(5), 1479.

Milieu Ltd, WRc & RPA (2008). Environmental, economic and social impacts of the use of sewage sludge on land, Final report, Part I: Overview report. Retrieved from https://ec.europa.eu/environment/archives/waste/sludge/pdf/part_i_report.pdf

Musacchio, A., Re, V., Mas-Pla, J., & Sacchi, E. (2020). EU Nitrates Directive, from theory to practice: Environmental effectiveness and influence of regional governance on its performance. *Ambio*, *49*(2), 504-516.

Neset, T. S. S., & Cordell, D. (2012). Global phosphorus scarcity: identifying synergies for a sustainable future. *Journal of the Science of Food and Agriculture*, *92*(1), 2-6.

Oliver Wyman (2017). *Supporting the Circular Economy Transition.* Retrieved from https://www.oliverwyman.com/content/dam/oliver-wyman/v2/publications/2017/sep/CircularEconomy_web.pdf

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*(6392), 987-992

Regulation (EU) 2019/1009 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 (2019). *Official Journal L170*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2019:170:FULL&from=EN

Ribarova, I., Dimitrova, S., Lambeva, R., Wintgens, T., Stemann, J., & Remmen, K. (2017). Phosphorus recovery potential in Sofia WWTP in view of the national sludge management strategy. *Resources, Conservation and Recycling*, *116*, 152-159.

De Ridder, M., De Jong, S., Polchar, J., & Lingemann, S. (2012). Risks and opportunities in the global phosphate rock market: Robust strategies in times of uncertainty. *The Hague Centre for Strategic Studies.* Retrieved from http://www.phosphorusplatform.eu/images/download/HCSS_17_12_12_Phosphate.pdf

Rowe, W. D. (1992). Risk analysis: A tool for policy decisions. In *Risk and Society: The Interaction of Science, Technology and Public Policy* (pp. 17-31). Springer, Dordrecht.

Rybicka, J., Tiwari, A., & Leeke, G. A. (2016). Technology readiness level assessment of composites recycling technologies. *Journal of Cleaner Production*, *112*, 1001-1012.

Sanchez-Sabate, R., Badilla-Briones, Y. & Sabaté, J. (2019). Understanding Attitudes towards Reducing Meat Consumption for Environmental Reasons. A Qualitative Synthesis Review. *Sustainability*, 11(22), p.6295.

Schoumans, O. F., Bouraoui, F., Kabbe, C., Oenema, O., & Van Dijk, K. C. (2015). Phosphorus management in Europe in a changing world. *Ambio*, *44*(2), 180-192.

Shearman, D. J., & Smith, J. W. (2007). *Climate change challenge and the failure of democracy*. Praeger Publishers.

Science Communication Unit (2013). Science for Environment Policy In-depth Report: Sustainable Phosphorus Use. Retrieved from https://ec.europa.eu/environment/integration/research/newsalert/pdf/IR7_en.pdf

Shuttleworth, M. (2017, April 2). *Risk Matrix Sizing: Does Size Really Matter?* Retrieved from https://www.project-risk-manager.com/blog/risk-matrix-sizing/

Simoes, F., Vale, P., Stephenson, T., & Soares, A. (2018). Understanding the growth of the bio-struvite production Brevibacterium antiquum in sludge liquors. *Environmental technology*, *39*(17), 2278-2287.

Smol, M. (2019). The importance of sustainable phosphorus management in the circular economy (CE) model: the Polish case study. *Journal of Material Cycles and Waste Management, 21*(2), 227-238.

Stichting Wakker Dier (2020). *EU-subsidies voor 'eet meer vlees-campagnes'. Onderzoek naar een onhoudbaar subsidiesysteem*. Retrieved from: https://files.wakkerdier.nl/app/uploads/2020/02/12153250/RAPPORT-EU-subsidies-voor-eet-meer-vlees-campagnes.pdf

Suh, S. (2005). Theory of materials and energy flow analysis in ecology and economics. *Ecological modelling*, *189*(3-4), 251-269.

Tervahauta, T., Van der Weijden, R.D., Flemming, R.L., Leal, L.H., Zeeman, G. & Buisman, C. (2014). Calcium phosphate granulation in anaerobic treatment of black water: a new approach to phosphorus recovery. Water Res. 48, 632-642.

Van der Kooij, S., Van Vliet, B., Stomph, T., Sutton, N., Anten, N. & Hoffland, E. (2020). Phosphorus recovered from human excreta: A socio-ecological-technical approach to phosphorus recycling. *Resources, Conservation and Recycling*, 157, p.104744.

Van Dijk, K. C. (n.d.). ESPP eNews no. 12 - June 2017. Retrieved from https://phosphorusplatform.eu/scope-in-print/enews/1486-enews12#_Toc485290238

Van Dijk, K. C. (2020, June 3). *Resource Scarcity and Sustainable Phosphorus Use, Part 2: Transition Towards Sustainable Phosphorus Use.* [PowerPoint slides on Canvas].

Van Dijk, K. C., Lesschen, J. P., & Oenema, O. (2016). Phosphorus flows and balances of the European Union Member States. *Science of the Total Environment*, *542*, 1078-1093.

VDI (2012). VDI Guideline 4600:2012-01. Cumulative Energy Demand (KEA) - Terms, definitions, methods of calculation.

Withers, P. J. A., Elser, J. J., Hilton, J., Ohtake, H., Schipper, W. J., & Van Dijk, K. C. (2015a). Greening the global phosphorus cycle: how green chemistry can help achieve planetary P sustainability. *Green Chemistry*, 17(4), 2087-2099.

Withers, P. J. A., Van Dijk, K. C., Neset, T. S. S., Nesme, T., Oenema, O., Rubæk, G. H., ... & Pellerin, S. (2015b). Stewardship to tackle global phosphorus inefficiency: The case of Europe. *Ambio*, *44*(2), 193-206.

Ye, Y., Ngo, H. H., Guo, W., Liu, Y., Li, J., Liu, Y., ... & Jia, H. (2017). Insight into chemical phosphate recovery from municipal wastewater. *Science of the total environment*, *576*, 159-171.

Yi Teah, H. & Onuki, M. (2017). Support Phosphorus Recycling Policy with Social Life Cycle Assessment: A Case of Japan. *Sustainability*, 9(7), p.1223.

APPENDICES

Appendix 1: Technology assessment method

Step 1: Identifying the technology

Phosphorus recovery technologies are defined as processes that can recover bioactive phosphorus with contamination satisfying legal requirements. A new technology is required to satisfy following criteria to be defined as a phosphorus recovery technology:

- Using waste (e.g. wastewater, solid waste) or materials recovered from waste (e.g. struvite, sewage sludge ash) as phosphorus sources.
- Yielding products that contain a substantial amount of bioactive phosphorus or elemental phosphorus.

In addition, technologies or processes with unacceptable negative environmental effects should also be excluded from the beginning of the assessment.

Step 2: Input/Output analysis

For phosphorus recovery technology, an initial analysis in terms of input and output can help decision makers to quickly identify the possible barriers for commercializing the technology. Specifically, for the assessment of a given input waste stream, the following aspects are advised to be taken into consideration:

- Phosphorus quantities (volume/mass flow rate, P concentration, the total P amount available) in the waste;
- Contaminant level (heavy metal, organic compounds, pathogens) in the waste;
- Physical state (solid/liquid, dry/wet) of the waste and
- Distribution (centralized/decentralized) of the waste.

Generally, waste streams with high available phosphorus amount, low contaminant levels are preferred. If the available P amount is deemed too low, or the level of certain contaminant is deemed beyond the processing capability of the technology, more sub-techniques of P enrichment or decontamination are probably required to be developed and incorporated. On the other hand, the physical state and distribution of the waste largely affects the transportation and collection of the waste sources. Therefore, a centralized waste stream is easier to handle and better adapted for recycling.

Similar to the input waste, the following aspects concerning the output product are also advised for consideration:

- Phosphorus quantities (mass/volume ratio) in the product;
- Contaminant level (heavy metal, organic compounds, pathogens) in the product;
- Other impurity in the product;

- Liquid/solid, ash/granular product and
- Bioavailability and water solubility of the product (as a fertilizer).

Apart from the technical aspects, legal and market factors should also be included in a comprehensive assessment:

- Product market (whether the product meets the market standard, with predictable performance and quality) and
- Relevant regulation or legislation (whether the product is approved by current regulation or legislation; whether the product is in 'end-of-waste' status).

Generally, a product in 'end-of-waste' status with known market is the key of a successful technology for commercialization. Nevertheless, technologies with new products may also prove to be promising in the long term, and therefore a dynamic framework of technology assessment and regulation adaptation or formulation is required towards a CE in the future.

In addition to input material and output product, the following factors concerning the process are also recommended to look into:

- P recovery efficiency;
- Input material/ chemical use;
- Output waste/ emission;
- Energy consumption and
- Infrastructure.

These factors will be further discussed in the environmental analysis.

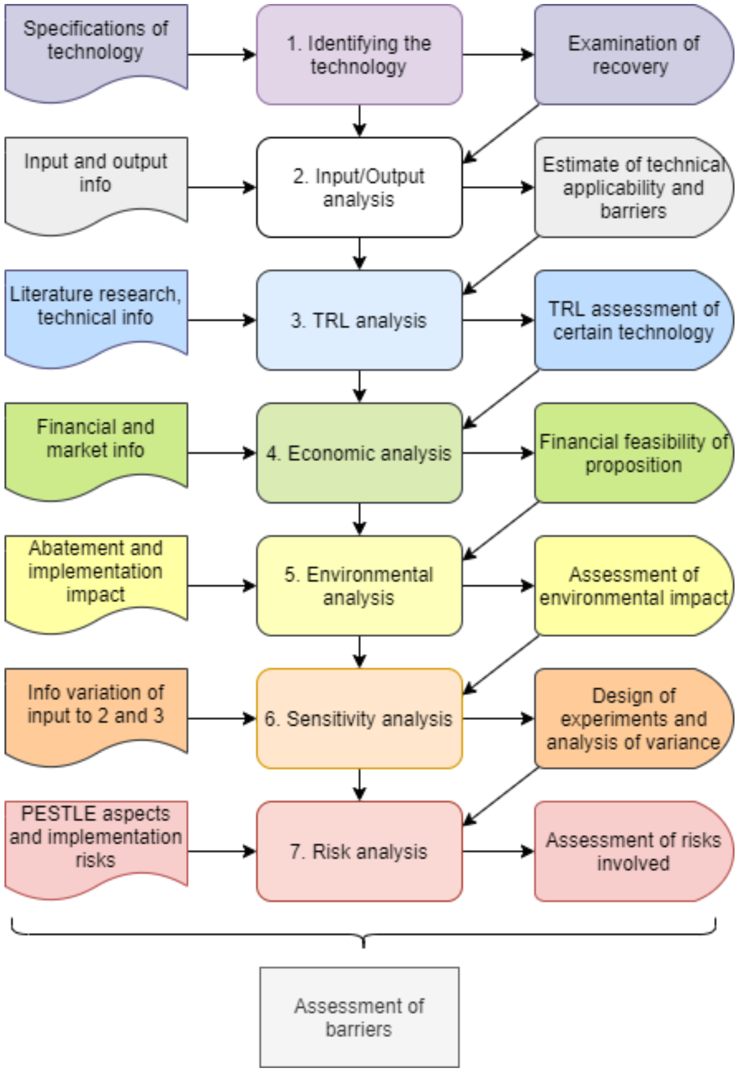


Figure A.1 : Phosphorus recovery assessment of barriers flow chart.

Step 3: Technical Readiness Level (TRL)

The implementation of a certain technology does not only depend on the applicability of a certain waste stream or lab scale efficiency tests, but also depends on the level of maturity of such a technology (Rybicka, Tiwari & Leeke, 2016). To quantify this, a Technical Readiness Level (TRL) is proposed to assess the trustworthiness of a certain technique. This method developed by NASA to evaluate technologies that are applied in space, has since been applied in many other areas of the development of new technologies. By systematically employing a TRL method, the maturity of many different P recovery techniques can be assessed. A TRL score can range from 1-9, where 1 means that a technology is in its beginning and 9 means that the technology is mature.

Categorizing the TRL is based mostly on number of occurrences in literature, a definition of the difference between levels can be explained, Rybicka et al. (2016) have given an first assessment on which these numbers are based on:

- 1-3: lab scale technologies, which is defined as research conducted in a lab environment primarily resulting in a proof of concept.
- 4-6: both lab and pilot scale technologies, which is defined as research conducted resulting in a robust process, the concept is confirmed and the mechanisms are well detailed.
- 7-9: full-scale technologies, which is characterized as the implementation of e.g. a P recovery technology at the industrial level e.g. a wastewater treatment plant.

Step 4: Economic analysis

In order to successfully implement a technology it must not only score a relatively high TRL, but it also needs to be economically feasible. For a technology to be considered economically feasible the maintenance, raw materials, and utilities needs to be lower than the derived revenue (Li et al., 2019). Therefore cost of recovery and revenue generated needs to be calculated.

The cost of recovery includes chemical dosage, energy, maintenance, product refining, staff salaries and infrastructure. Whereas the revenue is affected by the P recovery efficiency, concentrating ratio and the product sale price.

The following equation can be used to calculate the net income (using the variables mentioned above) (Li et al., 2019):

$$Net\ Income\ =\ Revenue_{P.recovery}\ -\ Cost_{P.recovery}$$

The capital costs also need to be included to determine the feasibility of a technology. In order to budget for capital to analyze the profitability of a projected investment the net present value (NPV) can be used. A positive value shows a project that is self-sustainable.

$$PV\ =\ net\ income\ (1 - \frac{1}{(1+r)^{n}})/r$$

This equation can be applied to analyze the present value (PV) for cash flows in the future. The resulting value can be used to help decide if a project is viable and to compare different operating and economic regimes (Li et al., 2019).

Step 5: Environmental analysis

The method for making an assessment of possible environmental impacts (e.g. GHG emissions and energy demand) resulting from different P recovery technologies is done by applying a life cycle assessment (LCA) (ISO 14040, 2006). Setting all the system boundaries, a LCA incorporates all of the related impacts that result from activities not only on-site but also before and after a technology is implemented (e.g. utility manufacturing and waste disposal). Alongside the LCA, functional units and environmental indicators must be taken into account, just as setting up a life cycle inventory (LCI) of relevant material flows.

The technology applied for sewage sludge management is mainly focused on a mono-incineration plant and the disposal of developing wastes is chosen as a reference system. Important sections for this reference system are processes of soil/agriculture, waste management, the hydrosphere and the atmosphere. The WWTP is structured in a way that it can be seen as a modular system, see figure A.1 . It can be seen that there are some steps where a recovery technique can be implemented. In addition, the indirect environmental impacts e.g. from waste disposal or production of utilities are applied in the adapted system.

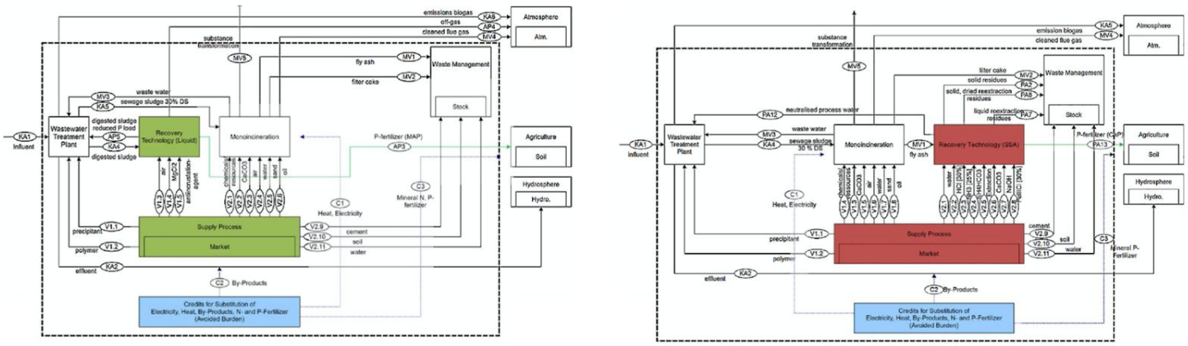


Figure A.2 : Typical system boundaries and process schemes of a WWTP with (left, green) implemented phosphorus recovery from the liquid phase (AirPrex) and (right, red) the sewage sludge ash process (PASCH). Source: Amann et al. (2018)

The boundaries of the system consist of the

- WWTP process,
- implemented P-recovery techniques,
- supply of chemicals and resources,
- mono-incineration of sludge,
- waste disposal management,
- substitution of energy,
- transport of sludge and
- recovered products to agriculture.

Outflows are emissions to the hydrosphere, atmosphere and fertilizer for agricultural purposes. The production of net energy and resources (e.g. heat, electricity, P- and N-fertilizers, by-products) must be accounted for by implementing the avoided burden approach. This approach assigns emission or energy credits to studied systems for substitution of these resources. The most important factor of recovered materials is based on their P content, therefore, technologies need to be compared based on the functional unit of 1 kilogram of recovered P.

Environmental indicators that must be taken into account are the:

- global warming potential (GWP; Lorenzo-Toja et al., 2016; Ahn et al., 2010; Foley et al., 2010)
    - significant CO2 equivalents difference between P recovery technologies
    - calculated by adding direct and indirect gaseous emissions
- cumulative energy demand (CED; VDI, 2012)
    - used to determine energy requirements during a products life cycle
    - calculated by taking the direct energy demand of technologies (e.g. gas, electricity) and indirect energy demand used for production of technology.
- acidification potential (AP; Egle et al., 2016)
    - directly impacts the acidity in the soil which can be linked to P-fertilizer and agriculture
    - calculated by adding direct and indirect gaseous emissions.

By implementing a material flow analysis (MFA) (Brunner & Rechberger, 2016), a systematic structure for the waste stream flow balances can be made, this results in a life cycle inventory, see figure A.3 . From this model, the input of chemicals and raw materials as well as the output of phosphorus rich materials is given. Direct gaseous emission and other waste by-products are looked at in this analysis. Simultaneously, an energy flow analysis (EFA) (Suh, 2005) is applied to quantify the energy output of different external sources and energetic values of raw material. Processes that result in the recovery of energy from raw materials incineration (e.g. biogas, syngas), are positively credited to the energy flow.

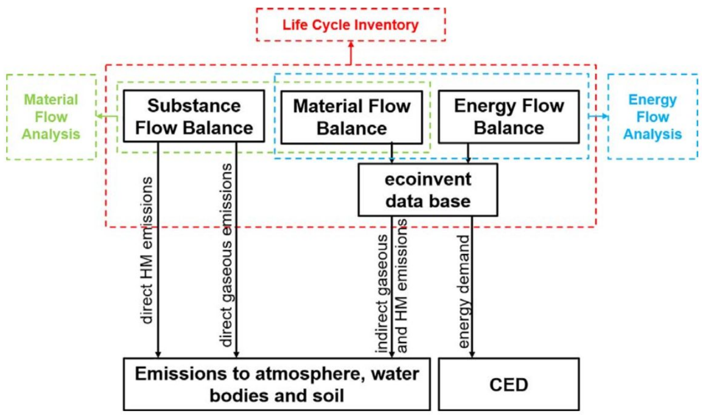


FIgure A.3 : Setup up of a life cycle inventory

Step 6: Sensitivity analysis

Sensitivity analysis is an essential step to identify the barriers for commercializing phosphorus recovery technologies. Based on methods including design of experiments (DoE), analysis of variance (ANOVA) and quantile-quantile plots, key variables in the technical process and market can be identified and their contribution to PV change can be determined. This analysis can be used to direct future research to improve the PV of a recovery technology.
Using these methods, Li et al. (2019) studied the case of struvite crystallization in Oxley Wastewater Treatment Plant (WWTP) in Queensland, Australia. They identified key variables in the technical process and market, and developed scenarios based on the 2nd order function model. The result reveals that most scenarios gave a negative NPV but are close to breakeven, and therefore can be profitable or breakeven if financial assistance is offered. Furthermore, considering the environmental and operational benefits of phosphorus recovery, it’s still recommended to recover struvite from wastewater.

In addition, the result also showed that more than 60% variation in PV is from market variables, while for the technical process, the struvite recovery P efficiency and enrichment efficiency contribute the most to PV change, indicating that future research on improving the efficiency of recovery and enrichment is more valuable than other techniques.

It’s also worth noting that the investment is not taken into account in this analysis, which would make most scenarios unprofitable in a strict economic sense. However, this problem can be ameliorated by preferential borrowing conditions for investors in phosphorus recovery endorsed by the governments or tax credits offered for Wastewater treatment plant operators for investing in P recovery units.

Step 7: Risk analysis

Every regulatory advice and technology needs to be evaluated and the possible risks involved need to be identified in order to make effective decision making. A tool for risk-based decision making is a risk analysis (Rowe, 1992). Such a risk analysis will consider the PESTLE aspects in its evaluation. Each recommendation will undergo analysis and its significant risks will be identified, weighted and briefly discussed. Based on the outcomes of the risk analysis decisions will be made to choose the most promising recommendations. The risk analysis is further discussed in chapter 4.

Appendix 2: P technology chart

Waste Sources	Phase	Technology	Technical Principle	Product	Operation Status
Manure	slurry	low emission application	manure incorporation and injection into farmland	slurry	full-scale
	dried manure	Hitachi Zosen	solid/liquid separation, pyrolysis	biochar	pilot plant
	liquid maure/ digestate	Agro America	solid/liquid separation, clarification by flotation technology, two-stage membrane filtration.	N-K fertilizer solution; P-rich organic fertilizer; clean water	pilot plant
		GENIAAL			full-scale
	manure	BioEcoSim	dissolving of nutrients into liquid, solid/liquid separation; (solid) superheated stream drying, pyrolysis; (liquid) chemical precipitation, membrane distillation, crystallization;	precipitated phosphate salts; ammonium sulphate; K-rich solution; biochar	pilot plant
Wastewater	liquid (digested supernatant/effluent)	Ostara Pearl	crystallization	struvite	full-scale
		NuReSys	precipitation/crystallization	struvite	full-scale
		AirPrex	precipitation/crystallization	struvite	full-scale
		Crystalactor	crystallization	calcium phosphate	full-scale
		PHOSPAQ	precipitation/crystallization	struvite	full-scale
		P-roc	crystallization	calcium phosphate/struvite	pilot plant
		ePhos	electrochemical struvite precipitation	struvite/K-struvite	full-scale
	sewage sludge (SS)	Extraphos	Liquefied CO2 extraction	calcium phosphate	pilot plant
		Pyreg	pyrolysis	biochar	full-scale
		Gifhorn	wet-chemical extraction, sulfidic precipitation of interfering ions, precipitatic	struvite	full-scale
		Stuttgart	wet-chemical extraction, complexation of interfering ions, precipitation	struvite	pilot plant
		Aqua Reci	supercritical water oxidation, acidic/alkaline leaching, precipitation	calcium phosphate	pilot plant
		Phoxnan	wet-oxidation, precipitation	struvite	pilot plant
		RAVITA	post-precipitation, acidic wet-chemical leaching, solvent-solvent extraction	phosphoric acid/ammonium phosp	pilot plant
		TerraNova	hydrothermal hydrolysis carbonization, acid extraction, precipitation	calcium/magnesium phosphate	full-scale
	sewage sludge ash (SSA)	EuPhore	thermo-chemical, heavy metal/organic compound depollution	depolluted ash	pilot plant
		MePhrec	metallurgic smelt-grassing process	P-rich slag	pilot plant
		Kubota			full-scale
		LeachPhos	acidic wet-chemical leaching, precipitation	calcium phosphate/struvite	pilot plant
		EcoPhos	acidic wet-chemical leaching, heavy metal removal through ion-exchange	phosphoric acid/calcium phosphate	full-scale
		Ash2Phos	acidic wet-chemical leaching, extraction and re-extraction	mono-ammonium phosphate	pilot plant
		Phos4Life	acidic wet-chemical leaching, extraction and evaporation	phosphoric acid	pilot plant
		TetraPhos	acidic wet-chemical leaching, precipitation, ion-exchange/membrane filtration	phosphoric acid	pilot plant
		Parforce	acidic wet-chemical leaching, ion exchange/solvent extraction, membrane electrodialysis, precipitation.	phosphoric acid	Batch pilot
		AshDec	thermo-chemical, heavy metal depollution	depolluted ash	pilot plant
		Thermphos	thermo-electric process	P4	pilot plant
		Phos4Green	acidic wet-chemical treatment	P/NPK fertilizer	pilot plant
		Recophos DE		TSP	industrial scale
		ICL fertilizer		SSP	industrial scale
Meat and Bone	MBM ash	ICL fertilizer	acidic wet-chemical treatment	SSP	industrial scale
Struvite	solid	ICL fertilizer	acidic wet-chemical treatment	SSP	industrial scale
		Susphos	acidic wet-chemical treatment	phosphoric acid	pilot
		Parforce	calcination, acidic wet-chemical leaching, membrane electrodialysis, precipitation.	phosphoric acid	Batch pilot
Municipal solid biodegradable waste	solid	Traditional composting	Biodegradation by earthworms or microorganisms	Biomass from compost	full-scale
		Vermicomposting			