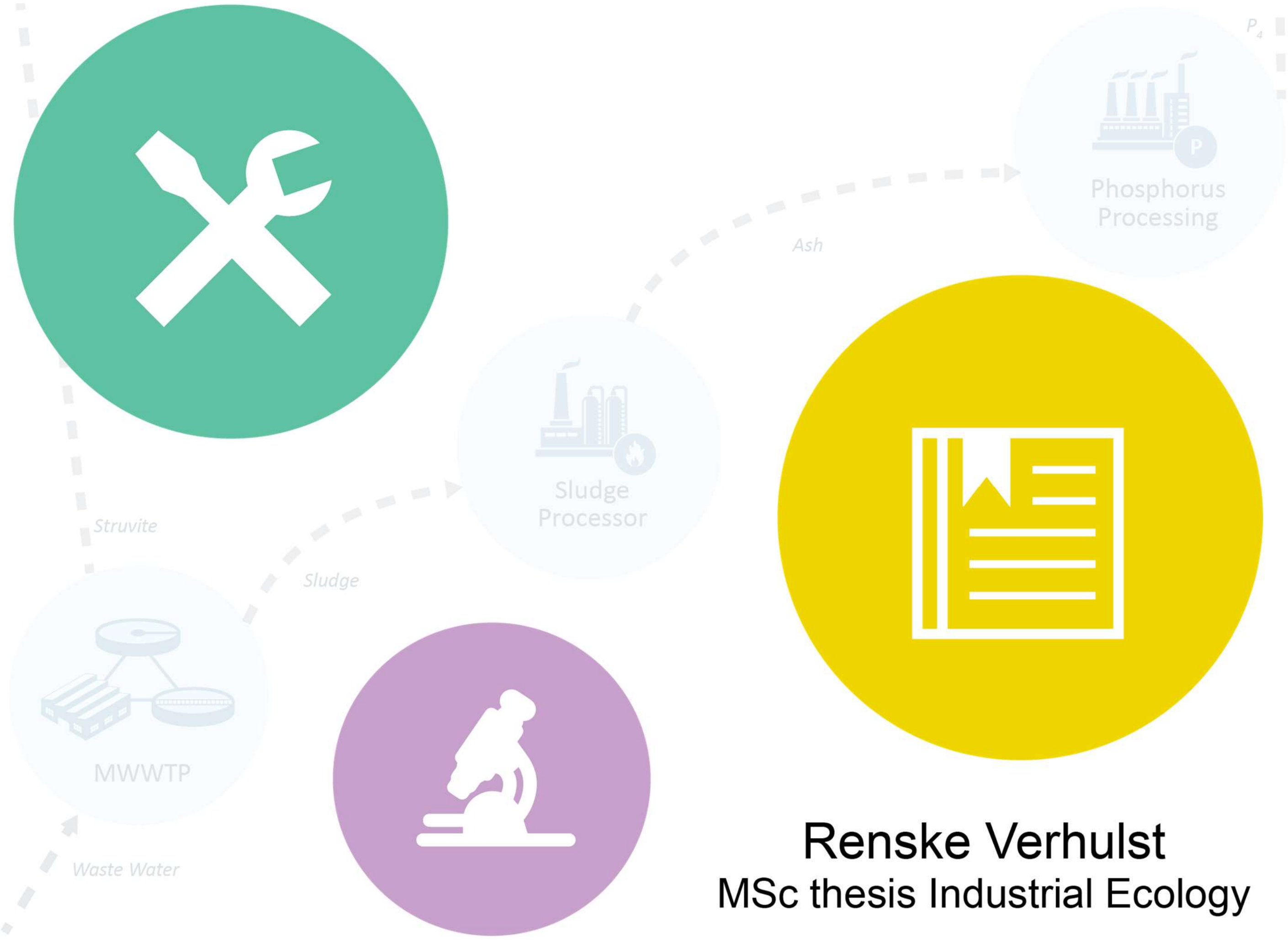
Phosphorus recycling in the Dutch communal wastewater chain

Barriers to growth



Renske Verhulst

MSc thesis Industrial Ecology

Author: Renske Verhulst
Student ID Delft 1522175
Student ID Leiden s0871885
Email: renske_verhulst@hotmail.com

Delft University of Technology | Leiden University
Programme Master Industrial Ecology
Course 4413TRP30Y Thesis Research Project

Delft University of Technology
First supervisor Dr. Linda Kamp, TPM- Engineering Systems and Services
Second supervisor Dr. Ir. Steven Flipse, TNW- Science Education and Communication

Schuttelaar & Partners
External Supervisor Dr. Alexander Duyndam

Graduation report

Phosphorus recycling in the Dutch communal wastewater chain

Barriers to growth

Renske Verhulst

For the degree of Master of Science in Industrial Ecology
At Delft University of Technology & Leiden University
Submitted on 29 June 2017

Preface

This is the final report for the fulfilment of the master Industrial Ecology. The thesis started with a question from the company Schuttelaar & Partners to look at the field of resource recovery from wastewater. Before this research, I had never heard of a phosphorus problem, but I was interested in the possibilities of making more from waste. The enthusiasm, persistence and drive of the actors involved with phosphorus recycling were inspiring. The case study was rich and there was always more to discover, learn and read, but I learned that at some point it is enough. The most valuable part of research is not gathering the data, but presenting it in a clear way. This was a real challenge for me as I find everything interesting and did not want to leave anything out.

The report has become quite long and therefore I would like to make a reading suggestion. To be able to get a clear understanding of this research, read the Summary and the Conclusion. Read the the Reflection of the author for a critical reflection. For an Industrial Ecology student the Theoretical Contribution, Relevance for IE in the chapter Reflection and the Recommendations for Future Research are interesting. For the actors from the field, the Recommendations and Discussion could provide additional interesting information. If you have time and want to get an overview of the whole system, the chapters on Struvite and Ash are the ones to read.

The completion of my thesis would not have been possible without the support of many. Therefore I would like to thank the following people:

- First of all, thanks to my supervisors for their support throughout the whole project. Without your help this thesis would be still in progress... Linda and Steven, thank you for your patience, encouraging me to write and by being strict sometimes. Without that, most of the information would be still in my head. I learned good feedback and support is only possible when you have something on paper. Alexander, thank you for having me at S&P. You saw the richness of the subject and tried to help me with staying focused, which was a challenge, I know.
- I would like to thank my colleagues at Schuttelaar & Partners, I enjoyed my time there and it was really nice to see the dedication of you all to work on a more sustainable world.
- Thanks to all the interviewees. I appreciate you took time to answer my questions, to give me information on the case and to introduce me into the world of phosphorus, water treatment and legislative issues.
- I would like to thank my parents, brothers and sister for their patience, support and trust during my whole study and my final project that took a bit longer than expected. I love you.
- Thanks to my study mates in the graduation room for the many cups of tea, constructive discussions, Illustrator lessons and getting me through the last months. I wish you all the best.
- Thanks to my housemate, who knows about all the ups and downs during my study and although I was often busy, I loved coming home.
- Thanks to my friends of PK&A. The Friday meetings served as a moment to reflect on our projects, struggles, to stimulate each other and helped to learn much more about myself. I will not forget the cookies, egg battles and creative drawings.
- All my friends during my study time, from Slopend, Jacht, MST, SEC, IE, Yeti, scouting and others, in the Netherlands and abroad. Thanks for all the wonderful moments.

To all, let's make it a more sustainable world!
Renske Verhulst

Summary

Phosphorus (P) is an element that is essential for growth of plants. It is used in fertilizers and the current food production is depending on the use of fertilizers. P is extracted from phosphate rocks and is considered a non-renewable resource. The mining of phosphorus has negative environmental effects and next to that, the EU is depending on other countries for their phosphorus supply. In addition the Netherlands has problems with water quality and try to reduces the phosphorus concentration in surface waters. The recovery of phosphorus from the Dutch communal wastewater chain could contribute in reducing the phosphorus problems by providing an alternative source of phosphorus and thereby contributes to closing the phosphorus loop.

The goal of this research is to identify barriers that hinder the development of phosphorus (P) recycling by the communal water chain. Insights into these barriers can lead to a better understanding of the situation and can lead to possible solutions to overcome the obstacles. The research shows that P recycling is a complex field with numerous actors involved and with multiple options to recover phosphate. To identify the barriers, a list of potential barriers was created based on the Innovation System theory, the theory of Functions of Innovation Systems and barriers from Circular Economy literature. Based on six perspectives, the institutional, technological, financial, infrastructural, knowledge and social perspective, the value chain was analysed to create an overview of the current situation of P recycling in the Dutch communal wastewater chain. A desktop study in combination with interviews were used to explore whether the barriers from the literature study were actually experienced in this case study and which barriers were deemed most relevant.

The analysis shows several positive developments that stimulate phosphorus recycling. Over the last couple of years, awareness of the phosphorus challenge has increased in Europe, because of concerns about food security and dependence on external resources. The Ketenakkoord Fosfaatkringloop, the attention for Circular Economy and the set-up of Green Deals have been a stimulant for phosphorus recycling. A diverse but small group of actors is working on phosphorus recycling, connected by the Nutrientplatform. These actors include water boards, sludge processors, research institutes, the government and fertilizer producers. The field mostly knows the barriers and some of the barriers are addressed together. The actors are driven by sustainability motives, financial advantages and the wish to act as a role model.

The research focused on two value chains that are interlinked. In municipal wastewater treatment plants (MWWTPs) struvite, a material containing phosphate, can be recovered. Struvite can be used directly as fertilizer or as input for fertilizer production. With the current technologies about 10-40% of the phosphorus from the wastewater can be recovered. A second option is to recover the rest of the phosphorus that ends up in the sludge by burning the sludge and recover P from the sewage sludge ash. It is expected that 90-95% of the P in the ash can be recovered as pure phosphorus or phosphoric acid. These can be used in fertilizer production and in the chemical industry.

In the last couple of years six struvite reactors were installed at Dutch MWWTPS, which can recover 3.6 kt ofr struvite on a yearly basis. Research shows that it would be possible to recover 2.7 kt P if struvite recovery takes place at all MWWTPs. Recovering phosphorus from burned sludge can lead to an additional 8.2 kt P. In 2008, the amount of P in imported fertilizer was estimated at 12 kt P per year. The two Dutch sludge processors HVC and SNB work together with EcoPhos to recover P from ash. In the Netherlands the fertilizer producer ICL is also involved in P recovery from ash.

The barrier analysis provides the following insights:

- The demand-side of recycled phosphorus is less developed and recycling is supply driven.

- There is still no real urgency for phosphorus recycling. The phosphorus problem does not play a role for the demand-side, but the acceptance of recycled phosphorus from the communal water chain by consumers is experienced as a potential barrier.
- The network of actors, who are involved in phosphorus recycling, has increased since 2010, but there are still some big players missing. These include representatives of the agriculture and the chemical industries as consumers.
- Struvite can be produced on a small scale and has a limited application potential because of its chemical composition. Next to that, there are risks associated with the product, partly due to the uncertainty about standards for drug residues and pathogens in the product. This can influence social acceptance.
- The struvite technologies do not all produce the same quality of struvite. Some technologies produce an EG-certified fertilizer, but most of the technologies produce struvite with a waste status. This makes it difficult to put the struvite as one product on the market.
- The market for recycled struvite is small, because of the Dutch phosphate surplus. Pure phosphorus could be used in the Netherlands in industrial applications.
- Legislation is one of the main obstacles for phosphorus valorisation, especially for struvite. The legislation is a complex process in which an end-of-waste status and REACH declaration are needed to be able to sell struvite. The revision of the EU Fertilizer Directive is expected to create opportunities if struvite is taken up in the revision as an approved fertilizer.
- The recovery of struvite on the MWWTP influences the economic feasibility of phosphorus recovery from sludge ash.
- Phosphorus from ash can be recovered on a larger scale and has a wider application potential. Additionally, it has no problems with pathogens in the product. However, for the production of phosphorus, the concentrations of heavy metals in the product are a point of attention.
- The price of mineral phosphorus is low, partly because externalities are not expressed in the price of materials.
- There is no clear vision on how phosphorus recycling should take place in the Netherlands. This can hinder the development as it brings uncertainty for long-term investments.

The lack of demand is regarded as the most important barrier. Therefore, the lack of a sense of urgency by consumers and the price gap between primary and recycled materials should be addressed. In addition the risk perception related to struvite should be addressed.

Practical solutions to stimulate phosphorus recycling are the use of regulatory pressures, the revision of legislation in order to facilitate valorisation, create more awareness of the phosphorus challenge and use economic measures to decrease the price gap. Next to that, certification and research on the risks of recycled phosphorus are important as these can influence the social acceptance.

To be able to contribute to closing the phosphorus cycle with phosphorus recycling from the communal water chain, it is important to increase cooperation between actors of the two identified pathways. If not, investments in one part of the value chain will be frustrated by developments in another part of the value chain. The creation of a shared vision or roadmap can prevent such situations. Other developments within the communal water chain such as decentral sanitation or other types of sludge valorisation should be taken into account as well. Choices for strategies will

have to be looked at from a bigger perspective to see which choices contribute the most to objectives such as sustainable phosphorus recovery or reducing phosphorus scarcity.

The theoretical framework gave starting points to identify barriers in the case study, but the framework was found to be insufficient. The theories on Innovation Systems are mostly focused on the integration of (sustainable) technologies, but in this case study the barriers were mostly related to the valorisation and reuse of the product instead of the technology. In the theoretical literature on Circular Economy more attention on social acceptance could be found, but this was more related to the acceptance of new business models. The case study showed that for nutrient recycling other type of barriers play a larger role. For example, social acceptance related to the use of waste, product quality, risk perception and conflicting sustainability goals. To be able to analyse other nutrient recycling cases, this research provides the first step to an adjusted theoretical framework that takes the above findings into account.

Samenvatting

Fosfor (P) is een element wat nodig is voor plantengroei. Het wordt gebruikt in kunstmest en ondertussen is de huidige voedselproductie hiervan afhankelijk. Fosfor wordt gewonnen uit fosfaatrotsen en wordt gezien als een eindige grondstof. Het mijnen van fosfaat heeft nadelige milieu effecten en daarnaast heeft de EU nauwelijks eigen bronnen waardoor zij afhankelijk is van andere landen. Daarbij heeft Nederland problemen met waterkwaliteit en wordt geprobeerd de fosfaatconcentratie in oppervlaktewater te beperken. Het herwinnen van fosfor uit communale afvalwaterketen in Nederland zou kunnen bijdragen aan het reduceren van deze fosfaatproblematiek door een alternatieve bron van fosfor te verzorgen en draagt hierdoor bij aan het sluiten van de fosfaatkringloop.

Het doel van dit onderzoek is het in kaart brengen van de barrières die worden ondervonden door partijen welke zich bezig houden met fosforherwinning via de communale afvalwater keten. Inzicht in de barrières kan leiden tot een beter begrip van de situatie en tot mogelijke oplossingen om de obstakels te overkomen. Dit onderzoek toont aan dat fosforrecycling een complex veld is, met verschillende actoren en meerdere manieren om fosfor (P) te recyclen. Om de barrières in de casestudie te analyseren, is er een lijst van potentiele barrières samengesteld op basis van Innovatie Systeem theorie, Functies van Innovatie systemen theorie en op basis van Circulaire Economie literatuur. Vervolgens is er een desktop studie gedaan aan de hand van zes perspectieven, te weten het institutionele, technologische, financiële, infrastructurele, kennis en sociale perspectief. Hierbij is de waarde keten doorlopen om een beeld te krijgen van de huidige situatie. De desktop studie, in combinatie met interviews van betrokkenen uit het veld, werd gebruikt om te kijken in hoeverre de barrières uit de literatuur ook daadwerkelijk spelen in de casestudie en welke als het meest belemmerend worden ervaren.

De analyse liet een aantal positieve ontwikkelingen zien die de fosforrecycling stimuleren. The laatste jaren is de bewustwording over het fosfaatprobleem groter geworden, onder andere door zorgen over voedselzekerheid en afhankelijkheid van fosfaatbronnen buiten Europa. Het Ketenakkoord Fosfaatkringloop, de aandacht voor Circulaire Economy en de Green Deals die zijn opgezet stimuleren fosforherwinning. Een diverse en kleine groep van actieve actoren werkt aan fosforherwinning, waarbij het Nutrientplatform een verbindende rol vervult. Waterschappen, slibverwerkers, kunstmestproducenten, onderzoeksinstituten en de overheid zijn onderdeel van deze groep. De barrières die zijn gevonden, lijken bekend te zijn in het veld en sommigen worden ook tezamen aangepakt. De actoren worden gedreven door duurzaamheidsmotieven, financiële voordelen, maar zijn ook betrokken om een rolmodel te vervullen.

Het onderzoek richtte zich op twee waardeketens die elkaar gedeeltelijk overlappen. In rioolwaterzuiveringsinstallaties (RWZI) kan struviet, een fosfaathoudende stof, uit rioolwater worden gewonnen. Het struviet kan gebruikt worden als directe meststof of als input voor kunstmestproductie. Met de huidige technologieën kan ongeveer 10-40% van het fosfor uit het afvalwater gehaald worden. De tweede mogelijkheid is om het fosfor, wat in het slib achterblijft, na verbranding van het slib uit as te herwinnen. Naar verwachting kan 90-95% van het fosfor uit het as gehaald worden in de vorm van pure fosfor of als fosforzuur. Deze producten kunnen gebruikt worden als input voor kunstmestproductie en kunnen toepassing vinden in de chemische industrie.

In de afgelopen jaren zijn er 6 struvietreactoren geplaatst bij RWZI's in Nederland, die tezamen jaarlijks 3,6 kton struviet kunnen herwinnen. Onderzoek toont aan dat het mogelijk is om in totaal 2,7 kton fosfor te herwinnen via struvietreactoren indien struvietherwinning plaatsvindt bij alle RWZIs. Via slibverbranding is er nog eens 8,2 kton fosfor herwinning mogelijk. In 2008 was de

hoeveelheid fosfor in geïmporteerde kunstmest geschat op rond de 12kton fosfor per jaar. De twee Nederlandse slibverwerkers HVC en SNB werken samen met EcoPhos om fosfor te herwinnen uit hun slibas. Daarnaast houdt kunstmest producent ICL zich bezig met fosfor herwinning uit as.

Uit de barrière analyse zijn de volgende inzichten verkregen:

- De vraag voor gerecycled fosfor is onderontwikkeld en de fosfaatherwinning is vooral aanbod gedreven.
- Er is nog steeds geen echte urgentie voor fosfaatrecycling en de fosfaatproblematiek speelt geen rol bij de vraagkant. Daarnaast wordt de acceptatie door consumenten van herwonnen fosfaat vanuit de communale afvalwater keten als barrière ervaren door de betrokken partijen.
- Het netwerk wat zich bezig houdt met fosfaatrecycling is licht gegroeid sinds 2010, maar nog steeds ontbreken een aantal grote spelers in het actieve netwerk. De ontbrekende spelers zijn de landbouw en potentiele afnemers vanuit de chemische industrie.
- Struviet kan maar op kleine schaal geproduceerd worden en is beperkt toepasbaar gezien zijn chemische samenstelling. Daarnaast is er onduidelijkheid over de toegestane hoeveelheden medicijnresten en ziektekiemen in het product. Hierdoor wordt het gebruik van struviet als mogelijk risicovol gezien, wat de sociale acceptatie beïnvloedt.
- De struviet technologieën produceren niet allemaal eenzelfde kwaliteit product. Dit betekent dat een deel van het struviet direct verhandeld kan worden, maar een ander deel een afvalstatus heeft. Dit maakt het lastig om een eenduidig product op de markt te zetten.
- De markt voor gerecyclede fosfaten ligt in het buitenland, vooral door het Nederlandse mestoverschot. Fosfor zou wel een binnenlandse markt kunnen hebben voor industriële toepassingen.
- De wetgeving blijkt een groot struikelblok voor de verwaarding, vooral voor struviet. De wetgeving is een ingewikkelde zaak waarbij een einde-afvalstatus en REACH registratie aangevraagd moet worden voor verdere verkoop. De herziening van de EU Fertilizer Directive kan voor verlichting zorgen indien struviet in de herziening wordt opgenomen als toegestane meststof.
- Het herwinnen van struviet op de RWZI invloed heeft op de economische haalbaarheid van fosfor herwinnen uit slibas.
- Fosfor uit as kan op grotere schaal worden gewonnen en is breder toepasbaar. Daarnaast heeft het product heeft geen last van hygiëne eisen met betrekking tot pathogenen. Voor de productie van fosfor is de hoeveelheid zware metalen in het product wel een aandachtspunt.
- De prijs van minerale fosfor is laag, onder andere doordat externaliteiten niet in de prijs worden meegenomen. Dit maakt herwonnen fosfor minder aantrekkelijk.
- Er is geen eenduidige visie over hoe fosfaatrecycling plaats zou moeten vinden of wat belangrijk is. Dat hindert de ontwikkeling aangezien het onzekerheid brengt voor lange termijn investeringen.

De onderontwikkelde vraag wordt als grootste barrière gezien. Om dit te verbeteren zal de urgentie van de fosfaatproblematiek duidelijker moeten worden voor de vraagkant en het prijsverschil tussen minerale en herwonnen fosfaten aangepakt worden. Daarnaast is voor struviet de risico perceptie een belangrijk punt.

Praktische oplossingen om fosfaatrecycling te stimuleren zijn: het inzetten van wetgevende drukmiddelen, het aanpassen van wetgeving om de handel te vergemakkelijken, meer bewustwording over fosfaatproblematiek bij consumenten te creëren waarmee de urgentie van het fosfaatprobleem onder de aandacht gebracht kan worden en economische instrumenten inzetten om gerecycled fosfor te promoten. Daarnaast is certificering van gerecycled fosfor en onderzoek naar risico's van het gebruik belangrijk voor fosfaatrecycling via de communale water keten, dit zal ook sociale acceptatie beïnvloeden.

Om fosfaatherwinning uit de communale waterketen te laten bijdragen aan het sluiten van de fosfaatkringloop, is het belangrijk om de verschillende partijen van de twee routes te laten samenwerken. Zo niet, dan kunnen investeringen teniet gedaan worden door ontwikkelingen binnen een ander deel van de keten. Het creëren van een gedeeld beleid kan dit voorkomen. Ook andere ontwikkelingen binnen de communale water keten die fosforrecycling beïnvloeden, waaronder decentrale sanitatie of andere manieren van slibverwaarding zoals biogas productie, zullen hierin meegenomen moeten worden. De keuzes voor bepaalde strategieën zullen ook vanuit een groter perspectief bekeken moeten worden om te toetsen welke keuzes het beste bijdragen aan de hogere doelstellingen, zoals duurzame fosforherwinning en het tegengaan van fosfaat schaarste

Het gebruikte theoretisch raamwerk gaf aanknopingspunten voor het identificeren van barrières maar was niet toereikend. De theorieën over Innovatie Systemen richtten zich voornamelijk op de ontwikkeling van (duurzame) technologieën, maar in dit onderzoek bleken de barrières vooral bij de valorisatie en hergebruik van het product zelf te liggen dan bij de technologie. In de theorie van Circulaire Economie was er aandacht voor sociale acceptatie, maar deze keek meer naar acceptatie van service modellen. De casestudie liet zien dat bij het gebruik van gerecyclede producten andere type barrières belangrijker worden. Bijvoorbeeld de sociale acceptatie, product kwaliteit, risico's bij hergebruik en conflicterende visies op duurzaamheid. Dit onderzoek geeft ook een aantal richtlijnen voor het analyseren van andere nutriënten recycling cases, waarin het bovenstaande is meegenomen.

Table of content

List of Abbreviations

CE	Circular Economy
EFGF	Energy and Nutrient Factory
EoW	End-of-Waste status
ESPP	European Sustainable Phosphorus Platform
ETS	Emission Trade System of the European Union
FIS	Function of Innovation Systems
IE	Industrial Ecology
IS	Innovation System
Kt/kton	kilotonne
LCA	Life Cycle Assessment
Ministry of EA	Ministry of Economic Affairs
Ministry of I&E	Ministry of Infrastructure and Environment
MWWTP	Municipal Wastewater Treatment Plant
P	Phosphorus
SLLRA	Struvite Recovery & Learning Alliance
TIS	Technological Innovation System
UvW	Unie van Waterschappen (Union of Water boards)

List of Figures

List of Tables

1 Introduction

The first part of this thesis will describe the context and explain why this research looks at phosphorus recycling in the communal wastewater chain. The introduction leads to the formulation of the problem statement and the research aim and to guide the research, main- and sub- questions are formulated. At the end of this chapter a reading guide can be found.

1.1. Why phosphorus recycling?

The context describes the background of this research and why phosphorus recycling is an interesting and relevant subject for this thesis.

1.1.1. The phosphorus cycle

Phosphorus is the element P, an essential element for plants, animals and growth. P is part of energy carriers (ATP), cell membranes, bones and teeth and needed for plant photosynthesis (Buckwell & Nadeu, 2016; Schipper, 2014). In natural ecosystems the phosphorus is taken up by plants in the form of phosphate (PO_4^{3-}) and becomes part of the organic matter. Animals or humans eat these plants and the phosphorus is excreted through urine and faeces. Bacteria and fungi are able to convert the phosphorus in the excreta, or dead material, back to a form that is usable by plants again. Looking at a longer time scale, phosphorus leaks into the ground in deeper soil layers and is partly washed to water bodies where it is not available for plants anymore. The phosphorus cycle is kept in balance by the weathering of rocks, which brings phosphate back into the soils. Organic decomposition in the sea leads to marine sedimentation which will eventually create phosphate rock, but this regeneration flow takes millions of years, see Figure 1 (Schipper, 2014; Buckwell & Nadeu, 2016; Cordell et al, 2009).

The natural phosphorus cycle is interrupted by several actions of humans. The removal of crops from the land means phosphorus is taken from the land without being replaced by natural processes. To bring phosphate and other nutrients back into the soil, animal manure and sewage sludge, which both contain phosphate, can be used. Another way to prevent a phosphorus shortage in the soil, is adding the phosphorus by means of fertilizers. The ingredient of fertilizers, phosphoric acid (H_3PO_4), is produced from rocks containing phosphate oxide (P_2O_5). As these phosphate rocks take 10-15 million years to form, they are considered a non-renewable resource, which runs the risk of being depleted.

After phosphorus is applied to the land part of it leaks away in water and soil. The estimations of losses through run-off and of phosphorus build-up in the soil are varying. For the European Union (EU) member states, it is estimated that 30% of the applied phosphorus remains in the soil and less than 5% is lost through run-off (Buckwell & Nadeu, 2016). Phosphorus is also lost from the phosphorus cycle through discharge of wastewater to surface waters. As soon as phosphorus leaks into the ocean, it is almost impossible to recover it (Schipper, 2014). Figure 1 shows the phosphorus cycle of phosphate rock to phosphate loss under the influence on human impact.

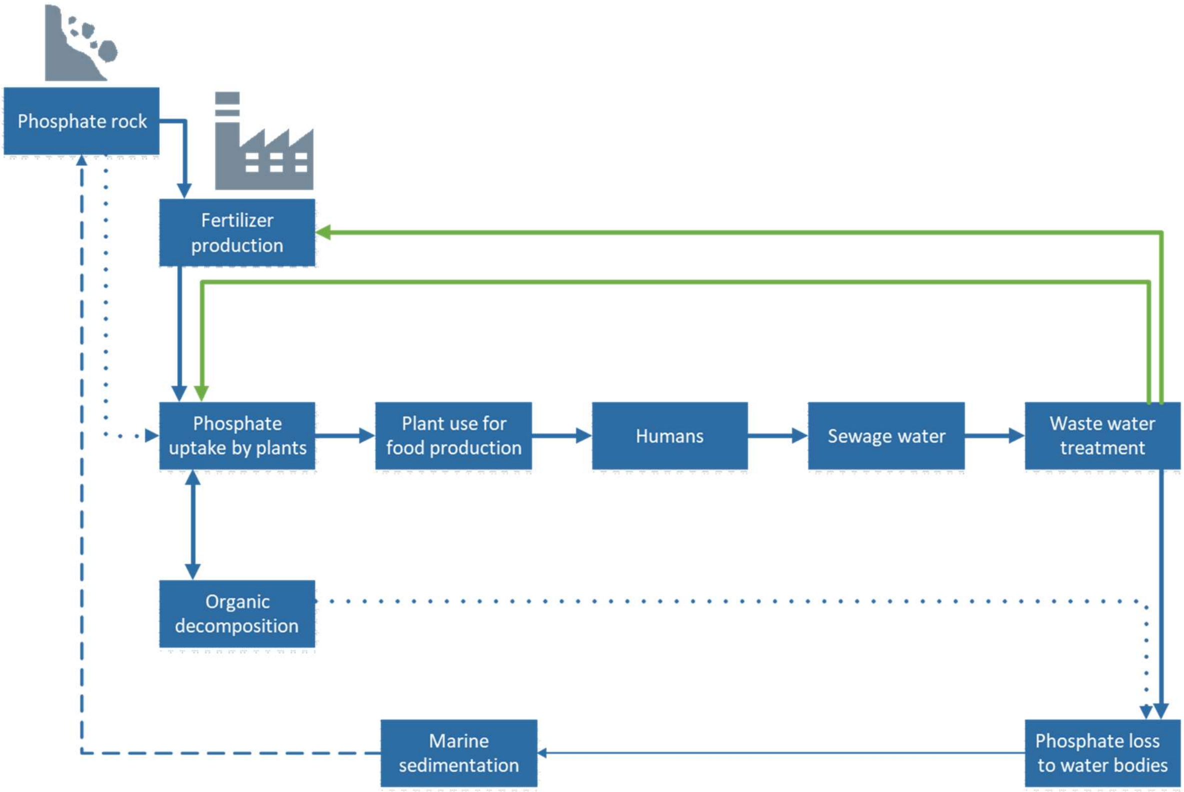


Figure 1. Phosphorus cycle with human impact

1.1.2. Environmental impacts

Phosphate production is very resource intensive. A large amount of energy, water and land is needed and the mining is done in open mines. The production of one kilogram of phosphorus is estimated to cost 20 MJ for mining, fertilizer production and trade (Cordell et al, 2015). In the whole process 21 tonnes of waste are produced and of this waste 25% is phosphogypsum, which is radioactive due to the presence of uranium and thorium (Buckwell & Nadeu, 2016). The presence of heavy metals in the phosphate rock such as cadmium leads to the risk of the cadmium ending up in the agricultural soils and through crops in the human food chain, thereby creating a risk for public health (Cordell et al, 2015).

Another environmental impact related to phosphate consumption is eutrophication due to the leakage of phosphate to surface waters and oceans. Eutrophication is an overload of nutrients, specifically phosphorus and nitrogen. Eutrophication can lead to the blooming of toxic algae which leads to an oxygen deficient and thereby polluting drinking water, killing other plants and fish (Cordell et al, 2015). The Netherlands is experiencing problems with phosphate surplus in surface waters as in 2015 only 45% of the water bodies met the nutrient norms (Gaalen et al, 2015).

1.1.3. Phosphorus depletion

As described in Subsection 1.1.1., phosphate rock is a non-renewable resource and therefore there are concerns about phosphorus depletion. The literature provides various estimates of phosphorus rock reserves, ranging from 50 up to 400 years, but in any case it can be stated that the quality and the accessibility of the reserves will decrease and the costs of mining will increase (Cordell & White, 2011). Appendix A provides more information on phosphorus reserves, resources and depletion.

One of the factors influencing the accessibility of phosphate is the location of the reserves. Phosphate rock reserves are located in Northern Africa, China, the Middle East and the United States (Jasinski, 2016) and production takes mostly place in Morocco, the US and China which makes the EU dependent on these countries. The political situations in these countries can impact the supply. For example, the Arab spring impacted the global phosphate rock production (De Ridder et al, 2012). Some phosphate rock producing countries, such as China, are implementing trade barriers and other forms of resource protectionism (Schipper, 2014). Unstable political situations, for example in the Middle East, raise concerns about potential disruptions to the phosphate rock supply (Cordell et al, 2015). There is no substitute for phosphorus and at the moment the world is dependent on mined phosphate to keep the food production at the current level (Buckwell & Nadeu, 2016). Reduced accessibility can therefore impact food security.

1.1.4. Future expectations

The demand for phosphorus is expected to increase due to the following reasons: (a) a growing world population, (b) a growing demand for meat and dairy, which requires a higher use of phosphorus, (c) the shift towards biofuels and (d) the need to improve the soil in phosphorus-deficient regions (Cordell & White, 2011). A higher demand for phosphate is expected to lead to higher prices and competition to secure phosphate supplies (De Ridder et al, 2012). Higher prices lead to a reduced access to fertilizers, which is expected to impact mostly poor farmers in less developed countries and in turn impact food production.

Another less often mentioned consequence is the social consequence of phosphate rock mining, such as the exploitation and displacement of local people due to mining activities (Cordell et al, 2015). Furthermore, as the phosphate resources with high quality phosphate decrease, the increased level of impurities in phosphate rock and the decrease of the P_2O_5 content lead to increased processing costs, energy use and waste (Buckwell & Nadeu, 2016; Cordell & White, 2011).

To conclude, Cordell and White (2011) foresee severe consequences if no action is taken to improve phosphorus security, see Figure 2.

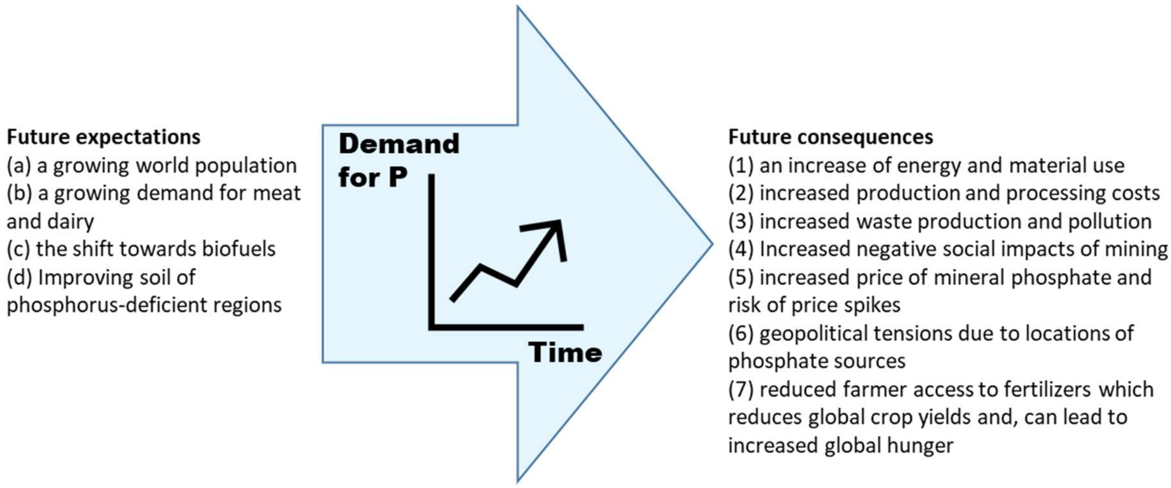


Figure 2. Consequences of rising demand for phosphorus

The severity of the consequences asks for action. To secure phosphate rock supply, Ridder et al. (2012) call for improving the efficiency of phosphate fertilizer, preventing loss of phosphorus and promoting phosphorus recovering. Cordell and White (2011) propose measures, such as increased efficiency in agriculture and food chain, but also reusing phosphate from food waste, human excreta and animal manure, see Figure 3.

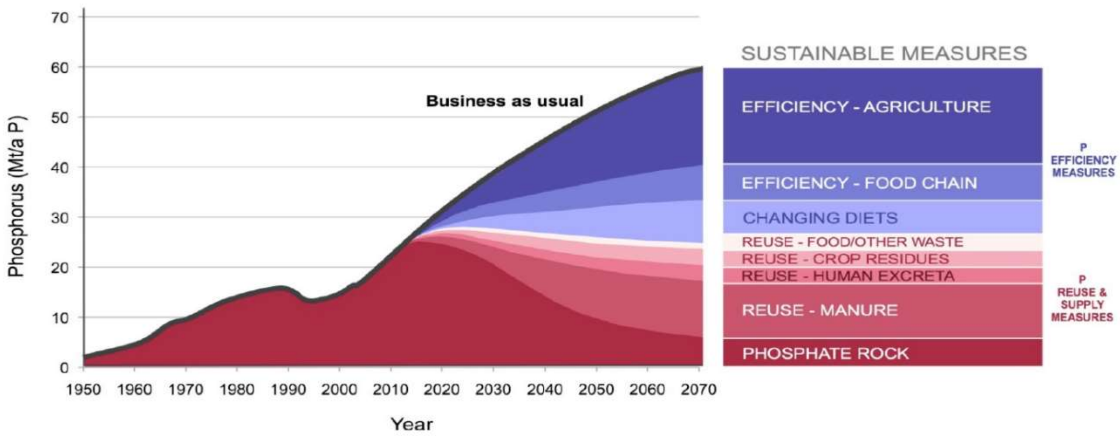


Figure 3. Integrated demand management (efficiency) measures (blue) and supply-side (reuse) measures (red). Taken from Cordell & White, 2011.

1.1.5. Current developments in the EU

The price of phosphorus spiked in 2008 with a short-term increase of 800%, partly caused by unforeseen demand, capacity constraints and unfavourable exchange rates. The price spike triggered the consciousness on the need for phosphorus security (Cordell et al, 2015; Cordell & White, 2011). Since 2013 phosphate rock is recognized as a critical resource of the EU (EU, 2014). The list of critical raw materials contains materials that are crucial to Europe's economy and have a high risk associated with their supply. Especially because of the dependency of Europe on other countries for their phosphate supply, phosphate rock was put on the list. Another development that stimulates recycling of phosphorus is the attention for Circular Economy. The EU action plan for the Circular Economy is focused on actions for closing the loop. Although most of the actions seem to concern 'traditional' closing the loop systems such as recycling waste and mining from solid waste, some of the actions support nutrient and phosphorus recovery. For example, a proposal for a revised fertilizer regulation is expected and the development of quality standards for secondary raw materials are part of the action plan (European Commission, 2015a).

Phosphorus can be recovered from animal manure, industrial wastewater, waste from the food chain, waste from agriculture and from municipal wastewater. Buckwell and Nadeu (2016) looked at the recycling of N and P in Europe, see Figure 4. In Europe animal manure is already reused a lot through application of manure on land. Recycling of phosphate from food chain waste and from sludge gives room for improvement. Egle et al. (2015) state that theoretically up to 50% of the mineral P fertilizer used in agriculture could be substituted in Europe if the sewage sludge is efficiently used.

	TOTAL N in stream	Recycled N	TOTAL P in stream	Recycled P
Raw manure	7-9	7.1	1.8?	1.75
Food chain waste				
Household waste	0.5-0.7	0.16	0.11	0.03
Slaughterhouse waste	?	?	0.28	0.02
Sewage	2.3-3.1	0.5	0.32	0.10
Totals of these streams	> 10-13	>7.8	2.5	1.9
Current recycling (%)	**60-80%**			**76%**
Not recycled (Mt)	**2-5**			**0.6**
For comparison, mineral fertiliser use in crop production (Mt)	**10.9**			**1.4**
Not recycled nutrient as percent of mineral fertiliser	**18-46%**			**43%**

Figure 4. EU estimation of recycled (recovered/collected + reused) amounts of N and P (Mt) for three waste streams (Buckwell & Nadeu, 2016)

1.1.6. Developments in the Netherlands

De Ruijter et al. (2016) looked at P recycling from the waste sector in the Netherlands and identified that the communal water treatment leads to the largest flow of lost P in the waste sector, but the highest perspectives for phosphorus recovery can also be found here due to the size of the flow and recoverability of phosphorus.

In the last couple of years the Netherlands strived for Circular Economy as part of their sustainability strategy and Circular Economy was promoted through the 'The Netherlands Circular Hotspot' campaign during the Dutch presidency of the EU (NLCH, 2016). The Ellen MacArthur foundation defined a circular economy as 'an industrial system that is restorative or regenerative by intention and design'. It aims to keep products, components and materials at their highest utility and value at all times. The goal is to decouple economic growth from finite resource use. Principles of a circular economy are no waste, diversity as resilient strategy, using renewable energy sources, thinking from a system perspective and cascading materials to use their full potential (EMF, 2013).

Part of the circular economy strategy is resource recovery. Therefore, resource recovery from wastewater, including nutrients such as phosphate, is receiving increased interest. For example, the theme recovery of nutrients is part of the TKI Water technology. TKI's are consortia for knowledge and innovation, which are set up to stimulate innovation and to increase the economic value of the sector (TKI, 2016). Initiatives to work on phosphorus security and recycled phosphate started in 2011, when the Ketenakkoord Fosfaatkringloop (Phosphate Value Chain Agreement) was signed by more than 20 organisations and companies to commit themselves to create a sustainable market for recycled phosphate (Ketenakkoord Fosfaatkringloop, 2011). In the same year the Nutrientplatform was established to support organisations through the whole value chain in closing the phosphorus cycle (Nutrientplatform, 2017). Members of the platform include fertilizer producers, water boards, knowledge institutes, sludge processors, companies and ministries of the government. The water boards expressed their aim to play an important role in closing the loops in their roadmap for 2030, in which nutrient recovery, including phosphate, is part of a new strategy (STOWA, 2010; UvW, 2013).

1.1.7. Summary

In conclusion, phosphorus is essential for human life, but the current production and use of phosphorus is unsustainable as it leads to an interrupted phosphorus cycle, environmental problems and potential depletion of phosphorus sources. Food security and environmental impacts are drivers to stimulate sustainable use of phosphorus. By recovering phosphorus from waste sources, phosphorus can be reused and thereby improving the phosphorus cycle. On a European scale phosphorus recycling from slaughter waste and sewage sludge offers the biggest potential for improving the recycling. In the Netherlands several parties, including actors from the communal wastewater chain, are actively stimulating the recycling of phosphorus as part of a circular economy strategy.

1.2. Problem definition & research aim

Phosphorus is needed for our society, but is currently being used in an unsustainable way. Recovering phosphorus from waste sources, such as wastewater, will increase phosphorus security and stimulate the sustainable use of phosphorus. The Netherlands still has waste streams from which phosphate is not yet recovered and the reuse of recovered phosphate could be improved. In line with the Circular Economy strategy, the Netherlands want to stimulate the recycling of phosphorus. The water boards are active in recovering phosphate in their sewage treatment plants and sewage sludge processors are involved in phosphorus recovery from burned sludge.

So far, a variety of sources report on subsets of barriers in the P-cycle, but none has provided an in-depth and complete overview for the situation in the Netherlands. This represents a knowledge gap. So, the aim of this research is to provide the reader with an understanding of the current state of phosphorus recovery in the communal wastewater chain and to identify the barriers that are preventing the growth of phosphorus recycling.

1.3. Research questions

From the research aim and the problem definition the following research question can be formulated.

Main research question

Which barriers need to be addressed in the current situation to increase phosphorus recycling in the Dutch communal wastewater chain?

This research question will be answered by means of the following three sub-questions:

Sub-questions

1. *What is the current state of phosphorus recycling in the Dutch communal wastewater chain?*
2. *What types of barriers towards phosphorus recycling are described in literature?*
3. *Which barriers are experienced in the recycling of phosphorus in the Dutch communal wastewater chain?*

Sub-question 1 will results in a description of the current state of phosphorus recovery and a short explanation of the two possible pathways for phosphorus recovery that are currently used in the Netherlands.

Sub-question 2 will result in a list of potential barriers from literature through which the case can be analysed.

Sub-question 3 will use the theoretical list of barriers to analyse the case and give an overview of the encountered barriers for phosphorus recycling.

1.4. Research approach

This Section describes the scope of this research, the methodology and approach to data gathering.

1.4.1. Scope and boundaries

This research is solely focused on the Dutch communal wastewater chain. This means the focus area is household and industry water entering the sewage treatment plants of water boards. Other phosphorus sources such as separately treated industry water, animal manure, slaughter waste, food waste and agricultural residues are out of the scope of this research.

This scope has some practical benefits, namely the data on municipal wastewater is easier accessible than separately treated industrial wastewater. In the starting phase of this research it was experienced that industrial companies with wastewater flows are less open about their waste flows due to commercially sensitive information. The water boards on the other hand are public bodies and research on phosphorus recycling in the communal wastewater chain was easier to find. Because the study Industrial Ecology is a multidisciplinary study, which looks at complex systems and thereby taking social, environmental and economic aspects into account, this research has a broad scope. Considering the interplay between multiple aspects, rather than exploring a single aspect, means that some parts of the research are elaborated more in-depth than others.

In Chapter Reflection a reflection on the scope and boundaries can be found, see Subsection 9.2.1.

1.4.2. Phases of research

This research consists of five phases as illustrated in Figure 5, which is going to be further elaborated in the following paragraphs.

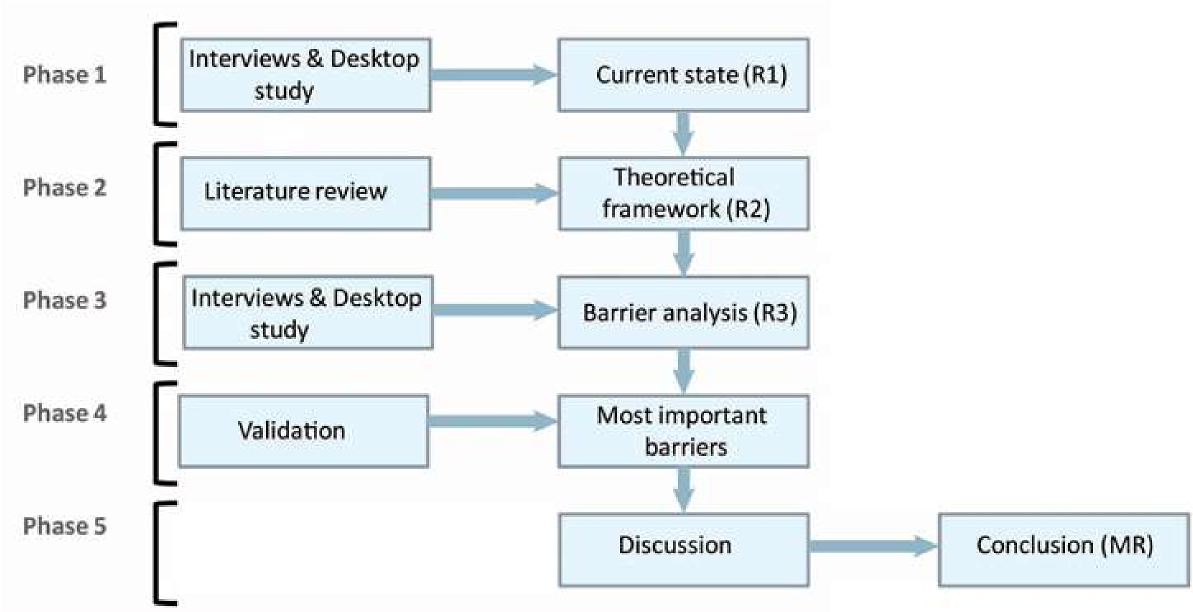


Figure 5. Schematic overview of research approach

Phase 1 Data gathering and setting research scope

To determine the boundaries for the case study, first the current state of phosphorus recycling in the Dutch communal wastewater chain was identified. This provided also the answer to the first sub-question. The identification of the current state included the determination of actors, current projects and technologies in phosphorus recovery from municipal wastewater. This phase also led to an understanding of how the communal wastewater treatment system works in the Netherlands.

The first step was the identification of the most important actors in the playing field. This was done by looking at organisations or companies publishing reports and news articles and by using the snowballing effect during the interviews. This means that the interviewees were asked to name other important players in the field. The research started with six open interviews with people from the field to orientate the direction of the research.

The interviewees were asked about barriers they were experiencing, but also asked to reflect on potential barriers found in the data gathered so far. The open interviews gave the opportunity to react on the information that was given during the interview, which means not all questions were the same. The interviewees were contacted by email and the interviews were held by telephone or at location. The information from these interviews did not only give direction to the research, but proved to be valuable data for the research itself and have been used as data resources. The current state was analysed following a value chain perspective, which means a line was followed from installation of the technologies to the buying of the recycled products by consumers.

Phase 2 Theoretical framework
The interviews in the first phase indicated that different types of barriers were experienced. A theoretical framework, based on literature review, was constructed for the barrier analysis. This phase answered sub-question two.

To construct the theoretical framework, a list of requirements was made to see whether the framework would meet the goal of the research. Several theories, which seemed to be the most appropriate at that time, were chosen to be able to construct a list of barriers for the case analysis. In order to grasp the whole system the case study was viewed from six different perspectives: institutional, technological, financial, infrastructural, social and a knowledge perspective.

The collected information was assigned to one of the six perspectives.

- The institutional perspective includes formal institutions, which are all policies, guidelines and formal written institutions (Suurs, 2009).
- The technological perspective entails all the technologies, factors that influence the installation of the technology and the technology characteristics that influence the product.
- The financial perspective beholds financial aspects of the installation of the technologies and the aspects influencing the demand side, such as prices or market outlook.
- In the infrastructural perspective the embedding of the technology in a broader perspective is described. This includes the scale of supply and the integration in the incumbent industry. Incumbent refers to the current system in place. It can also be used for actors who are embedded in the system. This can provide advantages over newcomers.
- The knowledge perspective relates to all the information on research, development of technology or product and knowledge dissemination.
- The sixth perspective is the social perspective and encompasses drivers, opinions, social acceptance and informal institutions. Informal institutions are social norms or paradigms (Suurs, 2009).

Phase 3 Data gathering
The first round of interviews was followed by a large desktop study to collect more information on the current situation. At the same time several events were visited to get an idea of what the main issues are. The desktop study was combined with a second round of six open interviews to get input from a broader range of actors. The information from the desktop study and previous interviews

served as input for the interviews of the second round. The questions in the interviews were not standardized but adjusted to the interviewees. Data collection and data analysis were done simultaneously, which means the interviews and data collection were iterative processes and information of both sources was used to guide the research.

The interviews consisted of introduction questions on the function of the interviewee within their organisation and how their organisation was involved with phosphorus recycling. If the organisation owned a phosphorus recovery technology, the interviewee was asked why the installation was build and why a certain technology was used. The interviewees were asked how sustainability played a role in the phosphorus recycling. They were asked to name barriers and asked about issues mentioned in other interviews. The interviewees were also asked to name which actor or sector they would like to become involved and whether they had ideas on incentives to stimulate phosphorus recycling.

Phase 4 Barrier analysis and validation
The potential barriers found in literature were compared with the gathered information in phase 1 and 3. This barrier analysis gave insights in which barriers were recognized by actors and insights on whether these barriers were addressed.

A method was set-up to analyse to what extent the barriers were relevant for this case study. The barrier analysis led to the identification of the most important barriers for phosphorus recycling at the MWTTP and from sludge ash. The barrier analysis was complemented with a short validation step in which the interviewees were asked by email to fill in the barrier list on a scale of 0 to 2.

Phase 5 Discussion of results and conclusion
During the gathering of the data and the analysis of the barriers, a vision on how the phosphorus recycling in the communal wastewater chain could develop was created. In the Discussion this vision and which extra barriers will need to be overcome in order to reach this future state are described. The results, in combination with the discussion, lead to the answering the research questions.

1.4.3. Data gathering

In this research a combination of data gathering methods was used. By using literature review of scientific articles and media articles, visiting network workshops and doing interviews a comprehensive analysis of the field was made.

Data
Data was retrieved from newspapers, company websites, articles in magazines, reports and scientific literature. In addition several symposia were visited. These include the Watervisie 2016 symposium on 18 February 2016, the ARREAU and LIFE event on 16 June 2016 and the STOWA phosphate symposium and Opening Omzetpunt Amersfoort on 17 June 2016.

Interviews
Twelve open-interviews were done, at location or by telephone. These interviews took place in two rounds in April- May and August- September 2016 and were recorded to be able to analyse the interviews. An example of the interview protocol can be found in Appendix B. The interviewees represent actors from the two main phosphorus recycling value chains routes and other involved parties:

> *The association of water boards, a fertilizer producer, a network organisation focussed on resource recovery, a research institute, a consultant, the government, the branch organisation of the chemical industry, a company that works on waste valorisation and actors with different roles at water boards.*

1.5. Relevance of Research

Research has been conducted on how to recover phosphorus and on how recovered phosphates such as struvite can be used in agriculture, for example by STOWA. The P-REX project of the EU focused on the sustainability of phosphorus recovery technologies by LCA studies (P-REX, 2015a) and student groups of the master Industrial Ecology have tried to define what sustainable phosphate recovery beholds and did an attempt to do a LCA on the EcoPhos technology (Feijen et al, 2014; Thalen et al, 2015). A network analysis (Bosma, 2014) and a socio-technical analysis (Lommen, 2010) have been performed in the last years to understand the phosphorus playing field and actors are brought together in conferences with actors from the water and bio refinery sector to share knowledge (DBC, 2016). Some barriers to closing the loop of phosphorus have been identified (DBC, 2016) and the field is actively changing as legislation is altered on national and European level, which influences the business case and developments on phosphorus recycling.

However, the information is scattered and there is no clear overview on what the different barriers are and what factors influence the development of certain types of phosphorus recycling in the Netherlands. The government has the aim to reduce the use of primary materials with 50% in 2030. From this perspective it means the use of phosphate rock should be reduced by 50%. The Dutch water boards are increasingly active in recovering phosphate in their wastewater treatment plants but also the Dutch sludge processors are working on phosphorus recovery from sludge ash. This provides an interesting study case for many reasons: it is a complex field with actors from multiple sectors such as agriculture, water sector and the chemical industry including fertilizer producers, in which two routes for phosphorus recycling can be followed. This research will contribute to a better understanding of the barriers and hence will give insights in how to improve recycling of phosphorus through the Dutch communal wastewater chain and increase the use of recycled phosphorus.

1.6. Reading guide

2 CURRENT STATE. A short introduction on wastewater treatment and phosphorus recovery in the communal water chain. Two main routes were found in the Dutch communal water chain: Struvite precipitation and phosphorus recovery from ash. The important actors are introduced and a short history of both routes is given.

3 THEORETICAL FRAMEWORK. The theoretical background and the framework used in this research. This chapter explains different theories used to describe barriers and how the list of barriers was constructed.

4 5 STRUVITE & ASH. The empirical part of the study, based on the desktop study and interviews. The two main routes for phosphorus recycling are discussed and each route is described from six perspectives; an institutional, technical, financial, infrastructural, knowledge and social perspective.

6 ANALYSIS. A short summary of the two routes, the identification of drivers and the barrier analysis. The barrier analysis uses the theoretical framework to identify which barriers exist for both routes.

7 DISCUSSION. Discussion on the results and the interlinkage of the two routes. In addition, the discussion provides a vision the future development of phosphorus recycling in the communal wastewater chain.

8 CONCLUSION. The answers to the research questions.

9 REFLECTION. The reflection on the theoretical framework and the methodology. This chapter is completed by looking at the case from a system perspective and the reflection of the author.

10 RECOMMENDATIONS. Recommendations for practice and future research.

2 The current state of phosphorus recycling

This chapter describes the current state of phosphorus recovery from the communal wastewater chain in the Netherlands. First the communal wastewater treatment system is explained, followed by the identification of two routes for phosphorus recycling. The relevant actors are described in Section 2.3 and in the last two Sections a short history of both routes is given.

2.1. Municipal wastewater treatment

In the Netherlands human faeces is treated in municipal wastewater treatment plants (MWWTP's). Industrial wastewater can be treated by separate installations or also by the MWWTPs. The wastewater contains phosphate and to bring this phosphate back in the phosphorus cycle it is possible to use the sewage sludge on land, recover the phosphate from the aqueous sludge or recover the phosphorus from burned sludge and use it as an input for fertilizer production. Since 1 January 1995 it is not allowed in the Netherlands to apply sewage sludge on soil. As a consequence sewage sludge must be treated and is mostly burned (CLO, 2016).

In the Netherlands there are 22 water boards. They manage the municipal wastewater treatment plants (MWWTPs), take care of water quality, manage the water levels and work on nature protection (UvW, 2017; Mostert, 2015). In 2014 there were 337 MWWTPs in the Netherlands. There are two main types of wastewater treatment installations: biological treatment and chemical treatment. Because of environmental problems , there are strict regulations on the amount of phosphate that is allowed in the effluent of MWWTPs, see Subsection 4.1.2. Figure 6 shows the type of phosphorus removal installations that are present in the MWWTPs.

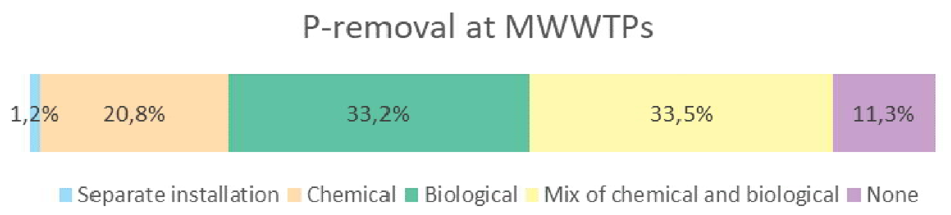


Figure 6. Phosphorus removal installations at 337 MWWTPs in the Netherlands (source data: CBS, 2016a)

There are five routes for sludge disposal in the Netherlands, see Figure 7. In 2007 50% of the sludge was treated by sludge processors, 25% was dried and co-incinerated in power plants or in cement kilns, 15% was composted, 6% was co-incinerated in a waste incinerator and 4% went to other destinations (Ellenbroek, 2008). In 2015 79% (weight) of the wet sludge was burned, 9% burned in power plants, 10% was used in cement kilns, 0,7% disposed of and 0,3% to others including composting (CBS, 2016b).

There are two sludge processors that threat the municipal sewage sludge, these are SNB and HVC. Sludge from both biological and chemical treatment plants can go to these two sludge processors. The sludge can be burned by mono-incineration or co-incineration. If mono-incineration is used, the dewatered sludge is burned in special incineration plants whereby steam and fly ash is produced. Another option is co-incineration with municipal solid waste or industrial waste in incineration plants, which is often done with the aim to produce energy (Buckwell & Nadeu, 2016).

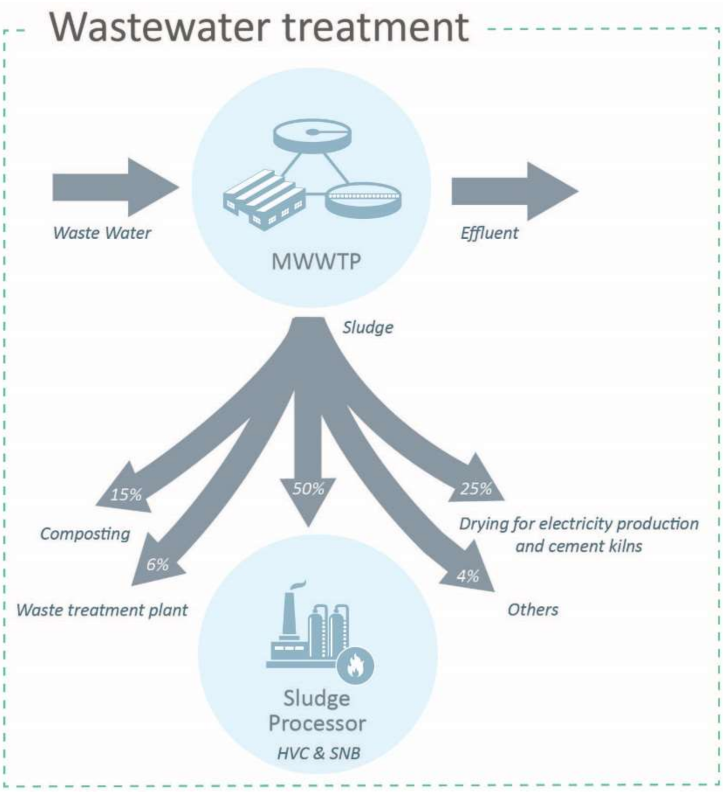


Figure 7. Sewage sludge disposal possibilities in the Netherlands

2.2. Possibilities of phosphorus recovery in the communal wastewater chain

In the Netherlands two routes are used in the communal water chain to recover phosphorus: through struvite precipitation in the MWWTPs or through phosphorus recovery from sludge ash. Currently there are 6 full-scale struvite reactors installed at municipal MWWTPs, which can recover 10-40% of the phosphate inlet. The struvite can be used in agriculture or as input for fertilizer production. The rest of the phosphate ends up in the sludge. If the sludge is incinerated, phosphorus can be recovered from the sewage sludge ash. The Dutch sludge processors HVC and SNB have a contract with the Belgian company EcoPhos to deliver their phosphate-rich ash to EcoPhos. In the Netherlands the fertilizer company ICL is also able to process sludge ash and recover phosphorus from it. The pure phosphorus can be used in the chemical industry or for fertilizer production. For the possible flows, see Figure 8.

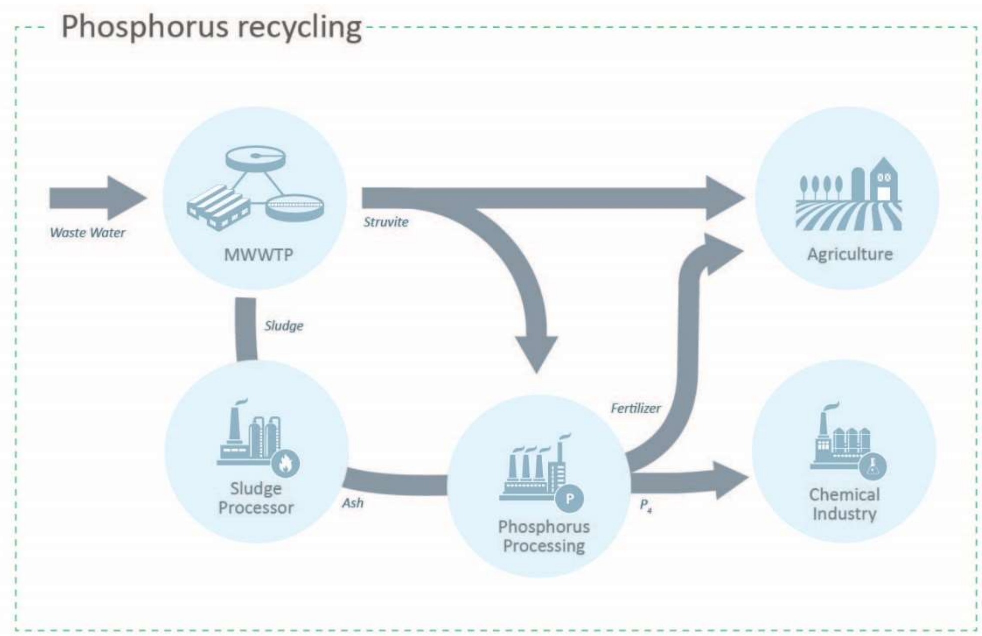


Figure 8. Possible phosphorus recovery routes

Current struvite projects

At the moment the following six full-scale struvite installations at MWWTPs can be found in the Netherlands:

- Since 2013 there is a struvite reactor installed at the MWWTP of the water board Reest en Wieden in Echten. The installation delivers 180-200 ton struvite per year (ESPP, 2015c).
- Since 2013 Waternet has installed a struvite reactor at their MWWTP in Amsterdam with a capacity of 950 ton struvite per year (STOWA, 2015).
- Since 2015 water board Vallei en Veluwe has a struvite reactor at their MWWTP in Apeldoorn, which is able to produce 900 ton struvite per year (Dutchwatersector, 2015).
- In 2015 the MWWTP in Land van Cuijk, under the management of water board Aa en Maas, installed a struvite reactor with a capacity of 200 ton struvite per year (STOWA, 2015).
- In 2016 water board Vallei en Veluwe installed a struvite reactor with a capacity of 900 ton struvite per year at the MWWTP in Amersfoort (Dutchwatersector, 2016).
- In Tilburg a struvite reactor is operational since 2016 and managed by water board De Dommel. The struvite production is approximately 430 ton (I1, 2016; Kabbe, 2017).

Current ash projects
The company ICL in Amsterdam has acquired the RecoPhos technology in 2016 and is working on the further development of this technology. The sludge processors SNB and HVC are working together with the Belgium company EcoPhos to recover phosphorus from Dutch sewage sludge and will start delivering the sludge ash in 2018 to EcoPhos (SNB, 2016d).

2.3. Relevant actors

To be able to understand the different players in the field of struvite recycling, a short introduction on the main actors is given.

Water boards

The water boards are regional water authorities. This is a public authority that is in charge of water management in a given area. That includes the treatment of wastewater, managing water levels, taking care of the dikes, active water quality management and work on nature protection (Mostert, 2015). There are 22 water boards in the Netherlands and they collect a treatment levy from citizens and as a public body they should not pursue profit. The working area of a water board is not determined by municipal or provincial boundaries, but by watersheds or catchments in the region. Water boards are interested in phosphate recovery for several reasons, of which maintenance cost reduction and sustainability are important reasons (I1, 2016). Currently there are five water boards involved with phosphate recovery from municipal wastewater: Vallei & Veluwe, Aa en Maas, Reest en Wieden, De Dommel and Waternet.

Unie van Waterschappen (UvW)

The UvW is the union of water boards in which 21 of the 22 water boards in the Netherlands are united. The UvW represents the water boards on national and international level, defends the interests of the water boards and stimulates knowledge development and exchange (UvW, 2017). The UvW is part of a Green Deal with STOWA, Ministry of Economic Affairs and the Ministry of Infrastructure and Environment in which the parties committed themselves to take away barriers for resource recovery, including phosphate. The aim of UvW in the Ketenakkoord Fosfaatkringloop was to realise 3-5 large scale phosphate recovery locations in 2015. Based on a report of STOWA the UvW created a vision brochure on the wastewater chain in 2030 (UvW, 2013).

STOWA

STOWA is the Foundation for Applied Water Research. It is the knowledge centre of the regional water managers, which are mostly water boards. Their aim is to develop, share and implement knowledge (STOWA, 2015). STOWA is actively contributing to research on phosphate recovery and struvite. STOWA identifies the knowledge need and directs the questions to the right knowledge providers, thereby working together with independent knowledge institutes such as Wetsus, Wageningen University, TU Delft but also companies such as Sweco (former Grontmij) and Tauw[1]. The research can be focused on technology, science, legislation or in the field of social sciences (STOWA, 2014). STOWA researched the factors influencing the further development of the MWWTPs. The results showed nutrient recovery came in fourth, after effluent quality, costs and energy neutrality which means nutrient recovery is seen as an important point in the further development of MWWTPs.

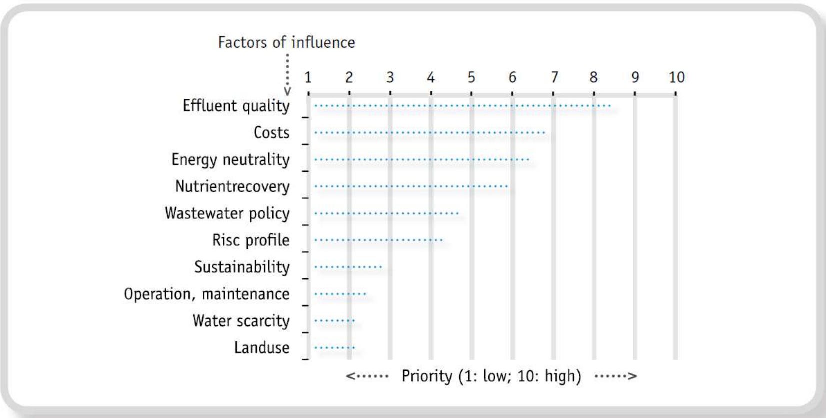


Figure 9. Priority of influence factors (STOWA, 2010)

[1] Sweco is a European engineering, advice and architect company, see company website http://www.sweco.nl/over-ons/. Tauw is a European advice and engineering company with a focus on environmental advice and sustainable development, see company website http://www.tauw.nl/over-tauw/

Nutrientplatform

The Nutrientplatform is established in 2011 by Aqua for all, GMB, Sweco (former Grontmij), Thermphos, WASTE, SNB and Wageningen UR (SNB, 2011). The main goal of the platform is to connect and support parties from the whole phosphorus value chain to close the phosphorus loop. The Nutrientplatform is a cross-sectoral network and members of the platform include actors with phosphate sources such as water boards and farmers, phosphorus processors like ICL and end-users like animal feed producers. The first members of the Nutrientplatform were waste stream owners, but now other members have joined, driven by their sustainability vision or because they see business opportunities (I3, 2016). Currently the Nutrientplatform has more than 34 members including companies, knowledge institutes and the government, who is involved to help organisations overcoming regulatory barriers. The wish of the Nutrientplatform is to have more end-users involved in the platform in order to create a phosphorus market (Van Kasteren, 2014). In the Ketenakkoord Fosfaatkringloop (2011) the platform formulated the goal to create a common agenda for making the nutrient management more sustainable and to contribute to at least 5 joint business cases from parties in the value chain.

European Sustainable Phosphorus Platform (ESPP)

The European Sustainable Phosphorus Platform (ESPP) was formed through a declaration which was signed by more than 150 organisations after the first European Sustainable Phosphorus conference in 2013 (ESPP, 2013). Members from the whole phosphorus value chain are represented in the ESPP. The ESPP has the aim to address the phosphorus challenge by raising awareness and trigger actions. It wants to stimulate knowledge sharing, create network opportunities, facilitate discussion between market, stakeholders and regulators and to contribute to a long-term vision on phosphorus sustainability in Europe (ESPP, 2013). The Nutrientplatform and the Netherlands Water Partnership played an important role in the foundation of the ESPP as they mapped the actors who were involved in phosphorus recycling and organised of the first conference and the foundation of the platform. Arnoud Passenier, from the ministry of Infrastructure and Environment, has been the president of the ESPP for a couple of years (I8, 2016).

Energy and Nutrient Factory (EFGF)

EFGF is the Energie en Grondstoffen Fabriek. It is a network organisation of the water boards and was founded to share knowledge, create clearness and make rules on how to transform the MWWTPs into factories producing energy and recovered nutrients. Their main objective is to contribute to a circular economy by recovering, processing and marketing of energy and nutrients from wastewater (EFGF, 2015b). The EFGF has nine working groups.

Aquaminerals BV (former ReststoffenUnie)

Aquaminerals is a cooperation of drinking water companies to commercialize by-products of the production of drinking water. Their objective is to reduce the ecological and climate footprint of producing drinking water, find high value circular applications for residuals and focus on efficient and sustainable transport (Aquaminerals, 2016). Aquaminerals has experience in valorisation of waste streams and is therefore working together with water boards and EFGF to commercialize the struvite produced by the water boards. Interviewee 2 explains the cooperation of EFGF and Aquaminerals: A water board alone is often too small to commercialize their idea, so cooperation and a bigger volume are needed. The EFGF wants to stimulate the recovery of nutrients from wastewater and Aquaminerals sees itself as an ideal partner to bring the materials to the market (I2, 2016).

Rijksoverheid (government)

There are two ministries active with phosphorus recycling: the Ministry of Economic Affairs (EA) and the Ministry of Infrastructure & Environment (I&E). Both ministries are member of the Nutrientplatform. In the Ketenakkoord Fosfaatkringloop the Rijksoverheid stated they see the ecological, economic and political value of closing the phosphate loop and creating a market for secondary phosphate. The Rijksoverheid wants to take away unnecessary legislative hurdles and to prohibit the use of phosphate-containing products for low-grade application as soon as possible. The following divisions of the government are also mentioned in this report: Rijkswaterstaat is the executive organisation of the ministry of Infrastructure and Environment. RIVM is the government institute for Public Health and Environment and is part of the Ministry of Public Health, Welfare and Sports. They give advice on public health, healthcare, food and nature & environment (RIVM, 2017).

ICL Amsterdam

ICL Fertilizers Europe is a producer and consumer of phosphorus products. ICL is a multinational with its own phosphorus mines. ICL has one production facility in Amsterdam and this facility is a frontrunner in the fertilizer industry with respect to using secondary phosphorus as input. Their aim is to replace 15% of phosphate rock with secondary phosphates by 2015 and 100% by 2025 (I7, 2016; Ketenakkoord Fosfaatkringloop, 2011). To reach this goal they are actively involved in platforms like Nutrientplatform and ESPP.

ICL Amsterdam is focused on recovered phosphorus in general and not specifically on phosphorus from the communal wastewater chain. Over the last seven years they have looked at different options of recycled phosphorus, including struvite, sludge ash, slaughter waste and wood ashes (I7, 2016). Interviewee 7 thinks that using recycled phosphorus is the life insurance for the company ICL. 'If the market goes bad, the government will support ICL because recycling is a Dutch idea' (I7, 2016). One of the reasons to invest in phosphorus recovery is the fact that ICL uses 30-36,000 tons of elemental phosphorus (P_4), but does not have P_4 production itself. This means ICL is depending on a couple of suppliers from 'not the most ideal countries' (I7, 2016). Therefore ICL has bought the RecoPhos[2] technology to manufacture elemental phosphorus and phosphoric acid from ashes (ICL Europe, 2016; I7, 2016).

Slibverwerking Noord-Brabant (SNB)

SNB is a Dutch sludge processor and six water boards are shareholders of SNB. SNB is one of the founders of the Nutrientplatform and is actively communicating their ambitions on phosphorus recovery through news item and blogs and are calling themselves frontrunners in phosphate recovery (SNB, 2011; SNB, 2016a). SNB stated in the Ketenakkoord Fosfaatkringloop they want to use 100% of their ash in 2015 for phosphate recovery (Ketenakkoord Fosfaatkringloop, 2011). SNB, together with HVC, signed a contract with EcoPhos to deliver their ash for phosphorus recovery.

HVC

HVC is the one of the two Dutch sludge processors. HVC has 46 municipalities and six water boards as shareholders (HVC, 2015). In the Ketenakkoord Fosfaatkringloop HVC stated their ambition to recover 85% of the phosphate from their ash (Ketenakkoord Fosfaatkringloop, 2011). Together with SNB they have signed an agreement with EcoPhos to recover phosphorus from their fly ash.

---

[2] T*here are currently two RecoPhos technologies on the market (Kabbe, 2015). ICLs (Inducarb) RecoPhos is a thermic process, while the other RecoPhos technology is a chemical process involving phosphoric acid.*

EcoPhos

EcoPhos is a Belgium technology developer and has developed a technology to recover phosphorus from ash. The process was originally designed to extract phosphoric acid from low quality phosphate rock (STOWA, 2011). According to EcoPhos it has 25% of the European production capacity for phosphates and wants to become the largest phosphate producer in the world (Vilt, 2016). In France a full-scale plant is currently build which will also process the ash of HVC and SNB.

VNCI

VNCI (Vereniging van de Nederlandse Chemische Industrie) is the chemical industry branch organisation of the Netherlands. The chemical industry includes fertilizer producers such as ICL. The vision of VNCI for the chemical industry of 2030-250 includes reducing the dependence on hydrocarbons by increasing the use of secondary (waste) and bio-based feedstock (Deloitte, 2012). The focus seems to be on reducing fossil fuel input.

Thermphos

Thermphos was a Dutch phosphorus producer. They were one of the first to look for other type of phosphorus sources as they did not have their own mine and were depending on the phosphorus market (I6, 2016). In 2007 they made a contract with SNB to recover phosphorus from sewage sludge ash (SNB, 2013), but in 2012 Thermphos was declared bankrupt and the delivery of sewage sludge ash stopped (Boon, 2012).

2.4. History of struvite recovery

Recovering phosphate from municipal wastewater is not a new idea. At the MWWTP in Geestermerambacht phosphate was recovered since 1993, but because the process uses a lot of chemicals, this process was expensive. In 2010 Lommen did an analysis of the socio-technical network of phosphate recovery from municipal wastewater in the Netherlands. His research showed that already several actors like ICL, UvW, the water boards, STOWA, the sludge processor SNB and the government were involved (Lommen, 2010).

This research starts with looking at what happened from 2010 onwards. In 2010 STOWA published a roadmap for the Dutch MWWTPs towards 2030. The roadmap envisioned the MWWTPs to become Water, Energy and Nutrient Factories. This new vision on wastewater treatment and resource recovery is seen in the events that take place in the period thereafter. In 2011 the UvW and the government set-up a Green Deal, which was focused on sustainable energy production and recovery of nutrients. Green Deals are agreements between government and other parties with the aim to execute sustainable ideas. The ambition of the UvW was to create at least 12 energy factories and 3-5 phosphate recovery installations at MWWTPs or at sludge treatment facilities.

That phosphorus recovery was not only of interest for the water boards but also for other parties became clear with two other developments that took place in 2011. In the beginning of 2011 the Nutrientplatform was launched. Another step forward in mobilization of actors came in October 2011 when the Ketenakkoord Fosfaatkringloop was signed by 20 actors, see also Subsection 4.1.1. The Ketenakkoord Fosfaatkringloop had the goal to stimulate closing the phosphate loop with the aim to turn the surplus of phosphate into valuable export products.

While on the one hand national steps were taken to improve phosphorus recovery in general, the water boards were exploring the opportunities for phosphorus recovery from municipal wastewater. In 2011 the water board Aa en Maas installed a temporary struvite reactor from

Anphos to handle an increase of phosphate containing wastewater coming from the renovation of the wastewater treatment plant of the company Peka Kroef. After the temporary project it was decided to build a permanent struvite reactor and in 2015 the NuReSys technology won the tender for a full-scale installation (STOWA, 2011; Heijmans-van Asseldonk, 2017).

In March 2013 the first European Sustainable Phosphorus Conference was held and the European Sustainable Phosphorus Platform (ESPP) was formed through a declaration which was signed by more than 150 organisations after the conference (ESPP, 2013). In the same year a struvite installation of Airprex was built in Echten at the MWWTP of water board Reest en Wieden and an Airprex installation at the MWWTP in Amsterdam that is managed by water board Waternet.

In 2014 phosphate rock was put on the list of critical raw materials of the EU. These raw materials are of high importance for the EU and have supply risks associated with them. Green Deals and changes in legislation followed to stimulate phosphorus recycling, see Subsection 4.1.1.

In 2015 two struvite reactors of NuReSys were installed: in Land van Cuijk (water board Aa en Maas) and in Apeldoorn (water board Vallei en Veluwe) (Dutchwatersector, 2015). The second ESPP conference was organised and during the conference policy action proposals were formulated. Other countries were taking steps as well, for example Switzerland made phosphorus recovery from sewage sludge obligatory and Denmark wants to recycle 80% of the sewage phosphorus by 2018 (ESPP, 2015b).

In 2016 the MWWTP Amersfoort, under the management of Vallei & Veluwe, officially opened their struvite reactor based on the Pearl technology and the Kabinet[3] accepted two proposals related to nutrient recycling, see Subsection 4.1.3 for more information. 2016 was also the year of the Dutch presidency of the EU and the Netherlands initiated the Netherlands Circular Hotspot campaign (NLCH) in which the case of ICL using secondary phosphates was used as an example of Circular Economy. In October 2016 struvite was accepted as one of the ten test cases in the International Green Deal 'North Sea Resources Roundabout'. In this international Green Deal different countries work together to align regulations on export and use of waste as resource.

2.5. History of ash recovery

Recovery of phosphorus from ash started already in 2007, when the Dutch sludge processor SNB and Dutch phosphorus producer Thermphos made a five year agreement on bringing the sludge ash to Thermphos for phosphorus recovery.

In 2008 SNB made also an intention agreement with ASHDEC, an Austrian producer of half-fabricates of fertilizers. ASHDEC technology would be able to produce fertilizers from fly ash. The intention agreement focused on setting up a business case and looking into aspects such as permits (SNB, 2008). In 2009 more information on the costs became available. A phosphorus recovery installation at the site of SNB in Moerdijk would cost around 15-20 million which raised the question to what extent a company like SNB should pay for this. As Marcel Lefferts of SNB stated: 'the phosphate problem is a problem for all of us and maybe the financial risks for such an installation could be shared with other actors' (SNB, 2009). At the beginning of 2010 a decision was expected, but no data was found on a continuation of the installation.

As mentioned in Section 2.4, in 2011 the Ketenakkoord Fosfaatkringloop was signed and the actors formulated individual goals to support the general aim of closing the phosphorus loop

[3] The Kabinet are the minister-president, the ministers and the state secretaries of the Dutch House of Representatives. The Kabinet is in charge of the government policy.

(Ketenakkoord Fosfaatkringloop, 2011). The following three goals were directly related to phosphorus recovery from ash.

- ICL Fertilizer wants to use 15% secondary phosphorus in 2015 and 100% in 2025.
- SNB wants to use 100% of their ash in 2015 for phosphate recovery and HVC aims at phosphate recovery from 85% of their ash and wants to work with other partners on realisation of an installation to recover phosphate.
- Thermphos wants to work with only secondary phosphate resources in 2020 and in 2013 already 15-30% of the input must be recycled material.

In 2012 50% of SNB's ash was brought to Thermphos for phosphorus recovery. Due to the bankruptcy of Thermphos in 2013 this was not possible anymore (SNB, 2013; BN DeStem, 2012). Problems that led to the bankruptcy included restrictions to prevent exceedance of emission standards and the low price of phosphorus from Kazakhstan (Boon, 2012).

After the cooperation with Thermphos stopped, SNB searched for new ways to recover phosphorus. With the other Dutch sludge processor HVC, SNB signed a contract with EcoPhos in February 2015 to deliver their fly ash to EcoPhos (Waterforum, 2015). From 2018 onwards SNB and HVC will start supplying the factory that is currently built in Duinkerken[4] in France (SNB, 2016d).

The addition of phosphate rock to the list of EU critical raw materials in 2014, the conferences of the ESPP in 2013 and 2015, the NLCH campaign and the national Circular Economy program contributed positively to gain attention for phosphorus recycling, see Subsection 4.1.1.

In 2016 ICL announced the acquisition of the RecoPhos technology to be able to manufacture elemental phosphorus and phosphoric acid from sewage sludge ash (ICL Europe, 2016; I7, 2016). The final decision for the location of the pilot plant was not yet taken at the moment of the interview, this will be Germany or the Netherlands (I7, 2016). Currently ICL is already processing recycled phosphorus, but RecPhos gives the possibility to scale up and reach their 100% target (I7, 2016).

In January 2017 the German government decided to make phosphorus recovery obligatory from sewage treatment plants (SNB, 2017). The phosphorus recovery is obliged for sewage works that have sludge with more than 2% phosphorus and that are larger than 50,000 person equivalents (Kabbe, 2016a). According to Interviewee 7 the sewage sludge cannot be used on soil anymore which means the sludge needs to be processed. This will create opportunities for sludge processors and consequently for technologies using the sludge ash for phosphorus recovery (I7, 2016).

[4] The city Duinkerken lies in France, near the border with Belgium. Other notations for Duinkerken are Duinkerke, Dunkirke and Dunkerque.

3 Theoretical framework & methodology

This chapter presents a theoretical framework based on theories of Innovation Systems, Functions of Innovation Systems and Circular Economy literature. Phosphorus recycling can be analysed from various perspectives such as a system transition or as a technological innovation. To find suitable theories to analyse the system, selection criteria for theories were set up.The selected theories were used to create a list of possible barriers and this list was used for the analysis of the case study.

3.1. Selection criteria for theories

To build a theoretical framework for this research, the theories need to fulfil a couple of criteria, related to the goal of this research. Recycling includes recovery and reuse, which means barriers for both the producer and the user side need to be identified:

- Theory needs to indicate barriers towards phosphorus recovery
- Theory needs to indicate barriers to reuse of recovered phosphorus

Barriers to recovery are related to the implementation of the recovery technologies. The theory on Innovation Systems [IS] and Function of Innovation Systems [FIS] are used to identify barriers for technology implementation. Phosphorus recovery is an innovation in wastewater treatment and IS theory takes a holistic approach towards innovation processes, which connects to the principles of Industrial Ecology. FIS is based on IS and takes a closer look at the dynamics within the innovation system. The theory of FIS has been often used to research the uptake of renewable energy technologies.

Phosphorus recycling is part of the vision of a Circular Economy, see Section 3.4. Therefore it is expected that literature on Circular Economy provides general barriers that could hinder the uptake of phosphorus recovery technologies and hinder the use of recycled phosphorus. The barriers from the three fields of literature will be grouped to provide one table with potential barriers for phosphorus recycling.

- Barriers from Innovation Systems
    - Barriers from Functions of Innovation Systems
- Barriers from Circular Economy

3.2. Innovation System theories

Innovation systems are composed of networks of actors and institutions that develop, diffuse and use innovations (Markard & Truffer, 2008). An IS includes all institutions and economic structures that guide and influence the speed of the change of technologies (Hekkert et. al., 2007). Different definitions of IS can be found, depending on their function, but there are some common features of the Innovation system theories. Learning is crucial to the innovation process and learning takes place through interaction and knowledge exchange between actors (Malerba, 2002). Secondly, institutions play an important role in the innovation process. Institutions are rules and regulations but also social values and routines of actors. These influence the development of innovations. Third, the innovation system theory has a holistic approach: the innovation system is a system in which the relations and interactions between the elements influence the whole system (Suurs, 2009). Innovation is seen as a collective process where interaction between actors, such as firms or organizations, takes places and that is influenced by institutions. The aim of IS theories is to understand the innovation process and find ways to influence and guide the direction of the innovation process. In practice the theory is used to identify drivers and barriers and give recommendations for innovation policies and strategies.

Innovation systems can be defined as a National Innovation System, a Sectoral Innovation System (Malerba, 2002) or a Technology (Specific) Innovation System, depending on the chosen boundaries (Hekkert et al, 2007).

A National Innovation System (NIS) is "*a set of national institutions which contribute to generation and diffusion of new technologies and which provide the framework within which government and firms negotiate policies to influence the innovation process"* (Watkins et al, 2015). It can measure the potential of country to innovate by assessing the institutional capacities.

Sectoral Innovation System (SIS) is *"a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products"* (Malerba, 2002). It is used to analyse and follow transformations and processes of change in sectors.

A Technological Innovation System (TIS) is *"a socio-technical system focused on the development, diffusion and use of a particular technology"* (Bergek et al, 2008). TIS has a focus on a specific technology which is subject to cross- sectoral and international influences. Researchers define a set of boundaries when using TIS. These boundaries can be geographical such as focussing on the development of wind energy within the Netherlands (Kamp et al, 2004), however this is not the same as a National Innovation System.

In this case study TIS is chosen to be used in the framework. In the first step of the research in which the current state was researched, it became clear there were two types of recovery technologies currently applied in the Netherlands. The case study itself covers different sectors such as water management, agriculture and chemical industry, including fertilizer production. Because struvite technology is part of the wastewater treatment sector, the two technologies cannot be just assigned to the fertilizer industry, which makes the use of a SIS difficult. A SIS would for example focus on the use of recycled phosphorus in the whole fertilizer sector, while this study also looks at reasons to implement the technology and looks at the whole system. Furthermore, the use of TIS enables to address both technologies and has the additional benefit that there is more literature available on TIS compared to NIS and SIS case studies.

3.2.1. Structural factors of an Innovation System

Innovation systems exist of three structural factors: Bergek et al. (2008) considers actors, institutions and networks as structural factors, while Suurs (2009) uses actors, institutions and technological factors as structural elements of an IS. Networks are then a specific form of interaction between actors. In this research the categories of Suurs (2009) are used. I agree with Suurs that technology characteristics can enable or constrain actors in their actions and in this case study the technology characteristics are important. Because the two main types of technologies produce different products and are installed in different parts of the value chain, the technology factors can influence the development and adaptation of those technologies.

Actors

Actors include all parties that influence the innovation process, including knowledge developers, government, industry, investors and interest groups. The actors can contribute competences, resources or knowledge. By the actions of the actors the technology is generated, diffused and used (Suurs, 2009). The development of the TIS will therefore depend on the interactions between the various actors.

Institutions

Institutions include laws, regulations and patents but are not restricted to these formal objects. Institutions are also social and technical norms (Markard et al, 2012) which are expressed in policy making, current beliefs and social structures. Institutions can be categorized in formal and informal institutions. Formal institutions are legislation, policies and for example contracts. The formal institutions are important intervention tactics and therefore target for lobby groups. By altering these, the actors can find support for their technology development. Informal institutions can be divided in normative or cognitive rules. The normative rules include social norms and the cognitive rules are social paradigms (Suurs, 2009). A paradigm guides the thinking of the human, it is a perspective or a way of looking. For example, the thought 'the market formation will solve the scarcity problem' is a paradigm (Cordell et al, 2011).

Technology factors

Technology factors consist of artefacts and the technological infrastructure. Technological aspects such as environmental impact, safety, reliability and costs influence the IS. Other aspects are knowledge that is needed to use the technology and the characteristics of the value chain (Suurs, 2009). Technology in itself can support and hinder actions of actors and thereby influence the actors again.

Relationships and Networks

The structural elements of the TIS interact with each other. There are not only interactions between actors but also interactions between institutions and technology or technology and technology interactions. These interactions can have positive of negative influences. For example competing technologies contradict each other, but complementary technology reinforce each other (Suurs, 2009).

Networks can be categorized as learning networks and political networks (Bergek et al, 2008). Learning networks are important for knowledge creation and knowledge diffusion, while political networks can influence the politics or stimulate the creation of a shared vision between different stakeholders (Vasseur et al, 2013). Some networks are created with a special task, while others arise from interactions or around shared goals. Formal networks are easily identified while informal networks require analysis of collaborations, co-patenting or interviews with actors (Bergek et al, 2008).

3.2.2. Components and structure of an Innovation System

In an IS structural factors can be categorized in several components. Van Alpen et al. (2008) used four components: supply, demand, intermediaries and the supportive infrastructure. The supportive infrastructure includes investors and governmental organisations. Alkemade et al. (2007) and Suurs (2009) used five components, namely the government structure, supply-side, demand-side, knowledge and intermediary structure. The positive side of the categorisation of Suurs is the separation of government and knowledge structure. However, the category supportive infrastructure has the ability to include also financial supportive actors, a category of actors that is difficult to subdivide in Suurs categories. For this thesis the following categorisation is applied: Supply, Demand, Intermediaries, Knowledge and Supportive infrastructure, whereby the Supportive infrastructure includes government, see Figure 10.

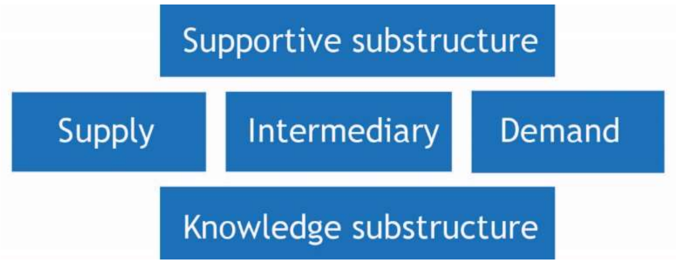


Figure 10. Five substructures of an innovation system

The IS focusses on a technology, but in this research the product resulting from the technology is also important. For that reason, an alteration is made. The supply-side supply refers to the supply of the product and therefore does not only encompass the technology providers, but also includes the technology user. The same applies to the demand-side whereby the demand relates to the use of the product.

- The supportive subsystem includes government agencies and ministries but also formal institutions issued by the government. It includes also investors and other actors that can be regarded as supportive actors.
- The supply-side encompasses all the actors that are involved in the production of recycled phosphorus products. These actors include technology developers and companies that deliver components of the technology and actors who install these technologies. Institutions are quality standards and shared visions on a future market.
- Demand-side covers all actors that use recycled phosphorus, which can be industry, retailers but also farmers and the general public. Institutions that stimulate the demand for a certain product are part of this subsystem.
- The intermediary structure encompasses institutes and other organisations that improve the relations between all the subsystems. Institutions in this subsystem are for example policy programs that stimulate collaboration.
- The knowledge component consists of organisations that support the other structures with the generation, assessment and exchange of knowledge. Public research organisations, private research institutes and organisations within the educational system are part of this structure.

According to Alkemade et al. (2007) a subsystem is well developed if it contains a diversity of actors who actively contribute to the diffusion and use of technology. Suurs (2009) defines a component as well developed if it contains a sufficient number of actors, institutions and technologies that contribute to the diffusion and use of technology. The overall system performs well if the subcomponents are well developed and the relations between the subcomponents is good. Because these definitions only mention the diffusion and use of technology, the definition is changed in this research to:

A subsystem is well-developed if *'it contains a sufficient number of actors, institutions and technologies that contribute to the diffusion and use of recycled products'.*

Barriers from IS

IS identifies barriers on subsystem level and on factor level. An example of a barrier on subsystem level would be an underdeveloped demand structure. An example of a barrier on factor level is an institution hindering the application of a technology (Suurs, 2009). The following barriers will be used for the case analysis:

- Poor functioning of the supportive substructure
- Poor functioning of the supply-side
- Poor functioning of the demand-side
- Poor functioning of the intermediary substructure
- Poor functioning of the knowledge substructure

3.3. Functions of Innovation Systems

Innovation Systems theory can be used to analyse the structure of an IS, but to understand the processes gain insight in the dynamics of a TIS, the TIS model was further developed by Hekkert et al. (2007) and Bergek et al. (2008) to include functions or activities of an IS. New technologies are not only competing with the standard technologies, but also with the evolved standards around those technologies such as infrastructure, legislation, social norms and knowledge capital. Therefore it is important to understand these structures in relation to the incumbent technology and the emerging innovation. Mapping activities that take place in the IS can explain changes that take place. Relevant activities are activities that contribute to developing, applying and diffusing new technological knowledge. In the literature several key processes have been identified as Innovation System Functions. One of the most used sets are the seven Functions of Innovation Systems of Hekkert et al. (2007).

Function 1: Entrepreneurial activities

Experiments by entrepreneurs are crucial for learning. Not only to learn about the technology but also to learn about interactions with other stakeholders such as government and consumers. Entrepreneurial activity is the prime indicator for the innovation system performance and the other six functions have influence on the entrepreneurial activity. It is important to realise the role of the entrepreneurs in the system, because one firm cannot fulfil all the functions. The entrepreneur needs to know with who he has can collaborate to perform other functions and with who he competes. Indicators for this function are the amount of experiments, the amount of new entrepreneurs in this field and activities of incumbent firms that are focused on new innovation.

Function 2: Knowledge development

Knowledge development is important for the innovation process. New innovations need to be further developed and the time and money invested in research shows the interest in the innovation. The amount of R&D projects, investments in the development and creation of patents serve as indicators for this function.

Function 3: Knowledge diffusion through networks

To improve the innovation process not only the generation of knowledge is crucial, but also getting information to the right parties. Knowledge can influence expectations and attitudes on the use of technologies, which is important for policy makers but also for public acceptance. Furthermore it can activate partners in the value chain, inspire new entrepreneurs or investors and stimulate more knowledge development. Knowledge diffusion can be measured by the amount of papers and conferences and by analysing the network size and the intensity of the interactions between actors.

Function 4: Guidance of the search

Innovation processes are guided by several institutions, such as legislation, subsidies for specific technologies but also the public opinion can guide resources to specific technologies. Expectations on technologies can positively or negatively influence available resources for the technologies as high expectations can boost R&D investment and can lead to increased cooperation between firms in the supply chain. Knowledge creation stimulates the development of several technologies while the guidance of search fulfils a role in the selection of technologies. This function is can be measured by analysing targets of the government or industries, by positive or negative expectations that can be found in papers and by analysing the public opinion in the media.

Function 5: Market formation

Market formation depends on creating a demand for the specific innovation. Available measures include tax exemptions or the obligation to use a minimum of new products such as obligatory use of renewable energy. For new innovations niche markets can be created to allow space to experiment and mature. This function can be mapped by analysing new standards, tax rules for specific technologies or the amount of niche markets.

Function 6: Resource mobilization

Resource mobilization is influenced by guidance of the search. Resources include financial resources, labour but also the availability of specific products as input. The function can be measured by analysing whether stakeholders feel they have enough access to resources.

Function 7: Creation of legitimacy/counteract resistant to change

New technologies have to compete with the incumbent industry. New actors will cooperate together to create legitimacy for their technologies, which is depending on the public opinion, resources they have and on the expectations of the technologies. The legitimacy can be analysed by researching the amount and growth of platforms, interest groups and by analysing their role in lobbying.

3.3.1. The link between structures and functions

Suurs (2009) explains the relation between structures and functions studieby using a stock and flow analogy. The substructures are the stocks, they are a snap of the time of what is currently present. The functions are the flows, they represent change and show how the structures are changing.

Events can be used to show changes that take place in a short period of time, while slowly changing structures are considered as structural factors. An example of an event is the installation of a pilot, while the general knowledge of the technology, that increases, is part of the substructure. Whether an event contributes positively or negatively to the innovation is evaluated by interpretation of the actors involved or by the judgement of the researcher.

In this research information is gathered by using an event history analysis. An event is defined as '*an instance of rapid change with respect to authors, institutions and/or technology, which is the work of one or more actors and which carries some public importance with respect to the TIS under investigation'* (Suurs, 2009). Examples of event types for the seven functions can be found in Table 1. The event types are used to search relevant information on the functioning of the system.

Table 1. Event types as indicators of system functions (Suurs, 2009)

System function	Event types
F1. Entrepreneurial Activities	Projects with a commercial aim, demonstrations, portfolio expansions
F2. Knowledge Development	Studies, laboratory trials, pilots, prototypes developed
F3. Knowledge Diffusion	Conferences, workshops, alliances between actors, joint ventures, setting up of platforms/branch organisations
F4. Guidance of the Search	Expectations, promises, policy targets, standards, research outcomes
F5. Market Formation	Regulations supporting niche markets, generic tax exemptions, obligatory use
F6. Resource Mobilisation	Subsidies, investments, infrastructure developments
F7. Support from Advocacy Coalitions	Lobbies, advice

Barriers from FIS

Barriers within the Innovation System are linked to malfunctioning of the Innovation System Functions. For example the lack of investments can indicate that the function Resource Mobilisation is low performing. For each Function several potential barriers are listed (Alkemade et al, 2007; Bergek et al, 2008; Bergek et al, 2015):

F1. Entrepreneurial activities

- Low amount of competitors or new companies
- (this function dysfunctions also if the other 6 functions are underdeveloped)

F2. Knowledge development

- Low amount of R&D projects, low investment in research
- Low amount of pilot testing

F3. Knowledge diffusion

- No platforms to share experiences
- A gap between research and practical needed knowledge
- Low cooperation between firms
- Low amount of conferences and research collaborations
- Consultants are unaware of developments
- No educational programs

F4. Guidance of the search/ Demand Articulation

- Absence of regulatory pressures
- No belief in the potential of the technology or expectation mismatch between actors
- No clear vision (of end goal)
- No demand articulation
- Negative landscape developments (for example, war, prices, economic crisis)
- Low alignment with incumbent infrastructure

F5. Market Formation

- A negative or absent tax system, hindering the technology
- Price/performance ratio is bad
- Scale of supply is too small
- Consumer potential and application is too narrow
- Incumbent companies are not willing to cooperate

F6. Resource Mobilization

- There are not enough financial resources available or accessible
- There is not enough knowledge or education to provide human capital
- There are no complementary services or infrastructure

F7. Creating Legitimacy

- There is low alignment with the current legislation
- There is no outspoken interest in the technology (by investor and user)
- There is big uncertainty or risks related to the technology
- Low level of lobby
- Low level of acceptance by users and public

3.4. Circular Economy

The previous two theories focused mainly on technology innovation. To find general barriers to phosphorus recycling and more specific on the reuse of recycled products, the literature on Circular Economy was researched.

Circular Economy (CE) is a broad concept, focused on closing material loops and reuse of material while trying to keep the value of the materials highest at all times. The concept Circular Economy is mainly based on the following schools of thought: Industrial Ecology, Biomimicry, Cradle to Cradle, Blue Economy and Performance Economy, but also Waste hierarchy, Permaculture, Natural Capitalism and Regenerative Design have contributed (Korse, 2015; Mentink, 2014; EMF, 2016a).

The definition used the most comes from The Ellen MacArthur Foundation (EMF, 2013; EMF, 2014):

Circular Economy is 'an industrial system that is restorative or regenerative by intention and design', which aims to 'enable effective flows of materials, energy, labour and information so that natural and social capital can be rebuilt'

Circular Economy 'relies on renewable energy, minimises tracks and eliminates the use of toxic chemicals and eradicates waste through careful design' (EMF, 2013). It aims to keep products, components and materials at their highest utility and value at all times (EMF, 2016b). Figure 11 visualises CE as an industrial system that is restorative by design and shows how everything is seen as part of a system by linking the biosphere and technosphere (EMF, 2013).

The five main principles of CE are (EMF, 2013, p22-24):

- Design out waste
- Build resilience through diversity
- Rely on energy from renewable sources
- Think in systems
- Waste is food

Phosphorus recycling from communal wastewater can contribute to ‘building resilience through diversity’ by introducing a different source of phosphorus. Seeing the communal wastewater chain as a source for new resources, is also according to the CE principles whereby waste is regarded as input. Therefore the waste management sector plays a crucial role in the transformation to a circular economy.

The principles ‘Think in systems’ and ‘Rely on energy from renewable sources’ should be used in implementing the phosphorus recycling. As phosphorus recycling from communal wastewater is to my opinion an end-of-pipe solution, the principle ‘design out waste’ is less applicable to the case study. The concept Circular Economy is used by many organisations and there are many different visions on how it should be implemented, probably because of the various principles and theories that are behind it. The reflection will go into the different perspectives of CE and sustainability.

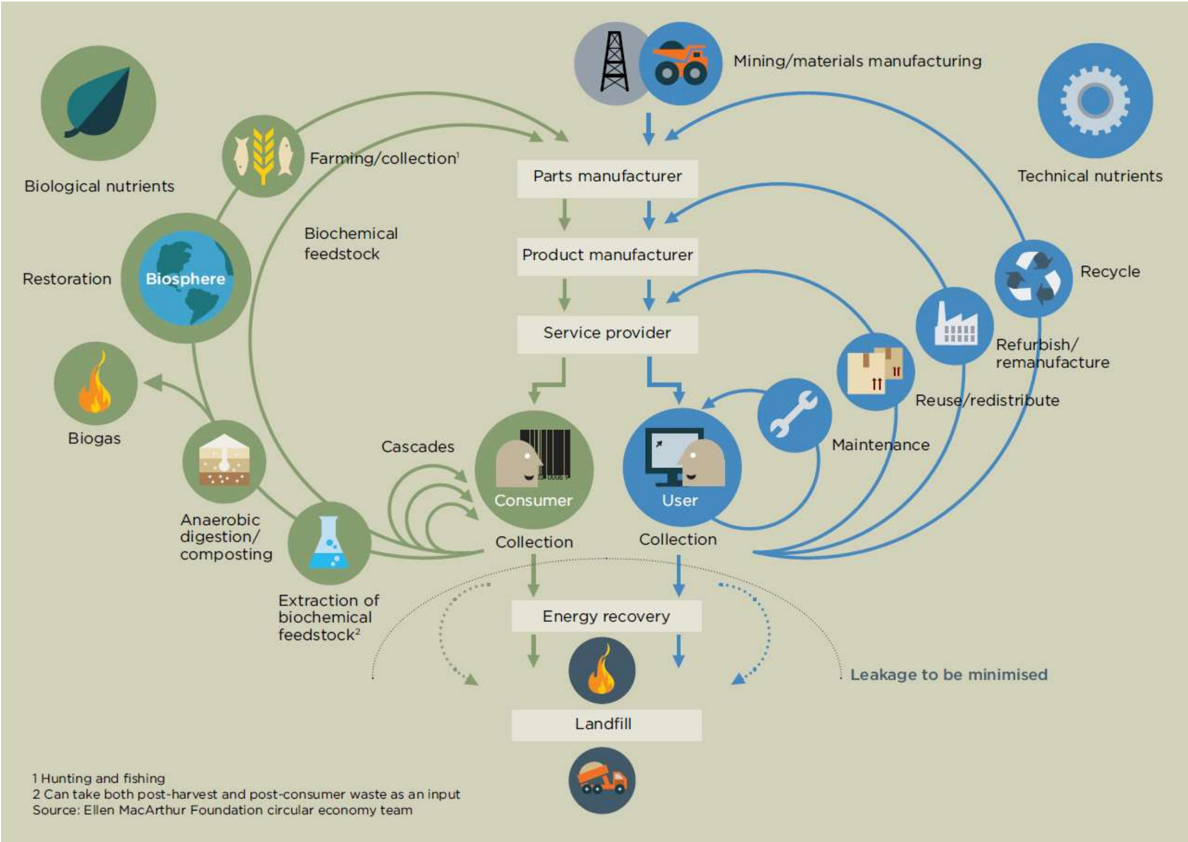


Figure 11. The interlinkage between the biosphere and the technosphere combined in a circular economy (EMF, 2013)

Barriers in CE

To go from a linear to a circular economy inevitable some barriers will be encountered. Although there is a lot of literature on Circular Economy case studies, a barrier framework for CE or a specific list of barriers for nutrient recycling was not found. For that reason, reports of organisations and institutes were used to find general CE barriers. The following barriers were extracted from literature and divided into the following categories: financial, institutional, societal, technological and infrastructural. This division was taken from the report of Kok et al. (2013).

Institutional

- A lack of government support can hinder the CE transition (Rizos et al, 2015). The government could provide specific policies, alter regulations or provide subsidies.
- There is no CE standard or metric that calculates the CE score of a product or new process (Aldersgate group, 2012).
- Financial government programs support the linear economy, for example by taxing labour instead of materials or when circularity is not integrated in innovation policies (Kok et al, 2013).
- Legislation concerning competition can hinder collaboration between companies. For example regulations on cartel formation (Kok et al, 2013).
- For new business models there are questions concerning ownership, liability and responsibility (Kok et al, 2013).
- Recycling is only measured in recycling rates, but there are no rules on the quality of recycled waste which inhibits the focus on high-quality recycling (Kok et al, 2013).
- Waste management regulation is focussing on discarding waste with minimum societal damage instead of focussing on recycling (Het Groene Brein, 2015).
- At EU level there are institutional barriers, for example the stimulation of lower taxes on materials and a lack of clarity on how to use the waste hierarchy (Het Groene Brein, 2015)
- Changing regulation can take 5 years at EU level, while circular projects often can start within a year (Het Groene Brein, 2015).

Technological

- Life cycle impact of CE principles should be better assessed to show the effect of using CE principles (Ghisellini et al, 2016).
- Small companies lack necessary skills to apply or deal with new technologies (Rizos et al, 2015).
- Products are not well designed for the end-of-life phase and linear technologies are rooted in the system (Kok et al, 2013).
- At the moment the supply and the quality of recycled materials is limited (Kok et al, 2013).

Financial

- High investment costs and payback period for new equipment, related to CE, are financial barriers, especially for smaller companies. Often these CE practices, including management and planning, are also time consuming and labour intensive which is another barrier for (small) companies to implement CE measures (Kok et al, 2013; Rizos et al, 2015).
- For smaller companies it is more difficult to have access to external financial resources such as funds, grants or bank loans (Rizos et al, 2015).
- Raw materials are often cheaper than recycled products (Kok et al, 2013).

- There is a lock-in in the procurement system, in which the investments costs of new technologies are often leading in the buying system. However, if more than one lifecycle is considered, it could turn out that the CE-investment is a better investment although there are higher initial costs (Aldersgate Group, 2012).
- Environmental externalities are not taken into account in the price of products (Aldersgate Group, 2012; Kok et al, 2013).
- Shareholders have short-term benefit thinking what can influence the long-term circular economy thinking (Kok et al, 2013).

Infrastructural

- Knowledge on the role of scavengers and decomposers in the waste management systems needs to be further researched (Ghisselini et al, 2016).
- Most companies rely on external providers to be able to adopt circular economy principles (Aldersgate Group, 2012). Working together in the supply chain can be difficult due to complex and international value chains and because of a lack of trust between companies (Het Groene Brein, 2015; Kok et al, 2013).
- More data on material flows is needed to research where valuable resources go and where valuable material is lost (Aldersgate Group, 2012).

Societal

- The knowledge and awareness of both producers and consumers on CE needs to be improved (Ghisellini et al, 2016).
- Rizos et al. (2015) named one of the barriers ‘the lack of support from the supply and demand network’, addressing the fact that small companies have low bargaining power in greening their supply chain and that consumers, although finding sustainability important, do not reflect that opinion in their buying behaviour.
- A sense of urgency is lacking (Kok et al, 2013).
- The GDP is not a good measure for welfare (Kok et al, 2013).
- For business models with service models to succeed, there need to be acceptation of consumers to not own the product but to have access to the product or service. (Aldersgate Group, 2012).
- The interests of incumbent businesses are big. Businesses with linear business models will resist changes in the status quo (Aldersgate Group, 2012; Kok et al, 2013).

3.5. Barriers from theory

The previous theories provided barriers that can occur in phosphorus recycling. The theoretical framework explains how these barriers were combined into one list of barriers.

3.5.1. Theoretical framework

The three theories have brought up various barriers for recovery and reuse of phosphorus. In order to use the input from all the theories, it was decided to create one list of barriers. Figure 12 provides the explanation of the framework. The theory of FIS provides barriers which are mostly technology oriented (I). The literature on CE provides system oriented barriers (II). The barriers from FIS and CE were combined and when overlapping, they were merged into one barrier (III). In the final barrier list an extra category 'Knowledge' (IV) is added. Adding this sixth category gives the possibility to specifically include research and knowledge related issues, which is an important part of IS and FIS theories. The substructures of IS were added as concluding barriers to be able to reflect on the whole system.

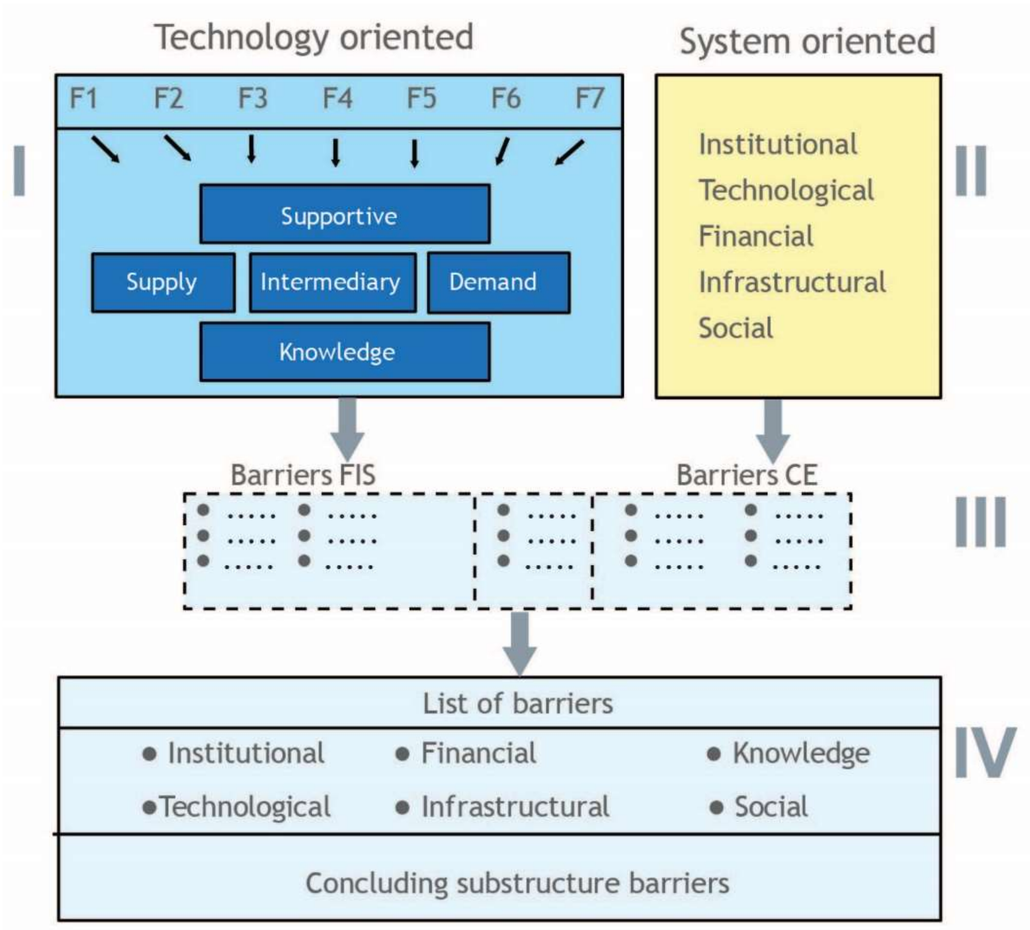


Figure 12. Theoretical framework for barrier analysis

3.5.2. List of barriers

The framework leads to one list of barriers. In phosphorus recycling two type of barriers can be distinguished: barriers hindering the installation and use of the technology and barriers to the use of recycled phosphorus. Some barriers are applicable to both producers and users while other are only relevant for producers or users, therefore a distinction has been made between those categories. This list of barriers will be used to identify which barriers are hampering the growth of phosphorus recycling in the Dutch communal wastewater chain.

	Technology user and producer (recovery)	Product user (reuse)
	• Low alignment with current legislation • Low level of lobbying • Absence of regulatory pressures • Regulations change slowly • Lack of clarity on how to use waste hierarchy • Recycling rates focus on quantity and not on quality • Cartel formulation legislation hinders collaboration between companies • No CE standards for products • CE is not integrated in innovation policies of the government • No clarity on ownership, liability and responsibility in new business models	• Absence of regulatory pressures • Low alignment with current legislation
	• Uncertainties or risks related with the technology • Lack of LCA to proof the effect of CE principles • Products are not designed for end-of-life	• Risks are associated with product • Quality of product is limited
	• Low amount of competitors and new companies in the field • Low investments in research • Negative landscape developments • Financial support for linear or incumbent systems (or absence of tax system supporting sustainable product) • Not enough financial resources available • Investment calculations are based on one lifecycle instead of more cycles • Labour is taxed instead of materials • High amount of investment costs • Long payback period	• Application is too narrow • Price/performance is bad • Financial resources for consumer are lacking • Price of raw material is lower than recycled products • Externalities are not reflected in the price
	• Complementary services & products are lacking • Scale of supply is too small • Low alignment with incumbent infrastructure • Incomplete production chain for technology or product, • Companies are relying on external providers to adopt CE principles	• Scale of supply is too small • Complementary services & products are lacking
	• Lack of knowledge dissemination • Low amount of R&D and pilot projects • Lack of human capital • Gap between research and practical needed knowledge • Low cooperation between firms • Lack of awareness by intermediaries on developments • Lack of knowledge required to develop, produce and control technology • Lack of skills or knowledge to apply/deal with technology • Lack of data on material flows • Lack of knowledge on roles of companies in circular economy	• Lack of knowledge or awareness on CE by producers and consumers • Lack of skills or knowledge to apply or deal with product
	• No believe in potential of technology • No believe in potential of product • No clear vision • Negative landscape developments • Sense of urgency is missing • Shareholders have short-term thinking (with focus on benefits) • Waste management is focussed on discarding waste with minimal societal damage instead of focussed on recycling • Incumbent industry is not willing to cooperate and resists changing status quo • GDP is not a good measure of welfare • Lack of trust between companies	• Acceptance of service products instead of ownership of products • Sense of urgency is missing • Consumers interest in sustainability not reflected in buying behaviour
Concluding	• An underdeveloped Supply side • An underdeveloped Demand side • An underdeveloped Supportive substructure • An underdeveloped Intermediary substructure • An underdeveloped Knowledge substructure	

* Icons retrieved from www.thenounproject.com. See references for acknowledgement of the authors of the icons.

3.6. Methodology based on the theoretical framework

The theoretical framework helps to guide the search for information and the analysis.

Step 1 consists of setting the focus or in other the words to set the boundaries of the Technological Innovation System. Setting the boundaries includes choosing whether a technology or a knowledge field is studied, choosing the spatial domain and making a balance between the breadth and the depth of the research. The boundaries were set by interpreting the first six interviews and collected data. The outcome of step one was used to adjust chapter two to include only relevant data.

After collecting data on phosphorus recycling in the Dutch communal water chain, the choice was made to focus on two sets of technologies: struvite recovery at the MWWTP and P recovery from sludge ash. Both types of technologies are installed in the Netherlands or in another way related to the Dutch communal wastewater chain. Technologies with the same function but with no connection to the Dutch communal wastewater chain were left out of the scope. Althoug the Netherlands is the focus area, international developments can influence the TIS. Therefore attention has been paid to the developments in Europe and were included in this research when these had impact on the Dutch system.

Step 2 is identifying the structural factors of the Innovation System. These are actors, institutions and technologies. The factors were identified by using the interviews and the desk study. The most important actors are presented in Section 2.3.

Step 3 is searching more information related to the six perspectives. The identification of institutions and technologies form the basis of the first two perspectives. The other four perspectives were used to collect information on subjects such as knowledge development, social norms, the current infrastructure and financial issues. The search for information was broadly scoped in order to be able to get a clear picture of the functioning of the whole system. Chapters 4 and 5 are the outcome of this step.

Step 4 is the identification of drivers and incentives that stimulate further development of phosphorus recycling and can be found in Section 6.2. In this research drivers are forces or developments that positively contribute to phosphorus recycling and potentially reduce barriers. Incentives are the expected benefits from an activity and are reasons for actors to be involved with phosphorus recycling. Incentives of actors have been mostly retrieved from the interviews and the driving forces have been extracted from the whole data set.

Step 5 is the barrier analysis. For this, the creation of a method to measure whether a barrier was strong or weak, was needed. This method and barrier analysis is found Section 6.3.

4 Struvite

This chapter describes the struvite recovery route from six perspectives: institutional, technological, financial, infrastructural, knowledge and social. The perspectives are described by taking the value chain as a starting point, starting from the installation of the technology to the reuse of the recycled phosphates. This approach is used to get a comprehensive overview of aspects that influence the recovery and the reuse of struvite.

4.1. Institutional perspective

The institutional perspective describes the programs and actions taken at Dutch and EU level, followed by the legislation that is currently influencing the struvite recycling and legislation related expectations for the future.

4.1.1. Context

Subsections 1.1.5 and 1.1.6 showed there are developments at EU and Dutch level that influence the phosphorus recycling. These programs are shortly discussed to give the context.

Green deals and Ketenakkoord Fosfaatkringloop

Green Deals are four year agreements between government and other parties with the aim to execute sustainable ideas. The government wants to help to take away barriers, for example by changing legislation or bringing actors together. Green Deal GD057 with a focus on sustainable energy production and recovery of nutrients was set-up in 2011 with the government and UvW. The ambition of UvW was to create at least 12 energy factories and 3-5 phosphate recovery installations at MWWTPs or at the sludge treatment facilities. According to the Green Deal several successful projects have already been done and many are in preparation, but if the (legislative) conditions will be improved, the opportunities could be better exploited. It mentions specifically the restrictive regulations for the marketing of phosphate as a point of attention (UvW, 2011).

At the end of 2011 the Ketenakkoord Fosfaatkringloop was signed by 20 actors with the aim to close the phosphorus loop (Ketenakkoord Fosfaatkringloop, 2011). The actors committed themselves to create a sustainable market with useful application of secondary phosphates within two years. These actors include the government with the Ministry of Economic Affairs, the Ministry of Infrastructure and Environment, knowledge institutes such as NMI, Deltares and Wageningen, waste stream owners such as Royal Cosun and the water boards, waste collectors and processors such as Twence, SNB, HVC, van Gansewinkel and Vion Ingredients, the fertilizer industry with ICL Fertilizers Europe and Thermphos and organisations like Nutrientplatform, InnovatieNetwerk, Aquaminerals BV and WASTE. An update on the Ketenakkoord in 2015 stated that most of the agreements were fulfilled and that attention for phosphate and the support for recycling is expanding. The export of phosphate is called crucial for circular economy and the Dutch way of working with the Nutrientplatform is called an inspiring example for the world (Mansveld, 2015a).

Changing policies

The willingness to make steps forward can be seen by changes in legislation. To reduce the legislative barriers, the government decided to change the Uitvoeringsbesluit Meststoffenwet regulations in 2015 and added a category ‘recovered phosphates’ (Dijksma, 2014). See Figure 13 in Subsection 4.1.3 for more information on this revision.

In March 2016 the House of Representatives (Dutch: de Tweede Kamer) shows again they are willing to support the nutrient recycling initiatives by accepting two proposals related to phosphate recovery. Proposal number 49 asks the Dutch Government to speed up the process of getting end-of-waste status for phosphate to stimulate export (Dijkstra & Mulder, 2015) and proposal number 52 asks for a focus on quality instead of origin and to express that vision in the Circular Economy Package that was in preparation (Mulder, 2015). Although this was a step in the right direction, the practical follow up remained vague.

Interviewee 4 puts it: 'the question remains what will happen now. Most probably the two proposals will be incorporated in the government-wide program on Circular Economy'. Interviewee 1 was not very optimistic about the proposals because he stated there are still hurdles in marketing under current legislation. Although the 'Meststoffenwetgeving' has changed, it seems there is no big effect. To make steps more concrete, the Nutrientplatform set-up a meeting with different employees of the ministries to jointly determine how nutrient recycling fits in the expected Dutch Circular Economy Package (Nutrientplatform, 2016a).

Government programs, NSSR and Circular Economy package

In June 2013 the Minister of Infrastructure and Environment informed the Dutch House of Representatives on eight operational goals of the VANG-program. This program 'Van Afval Naar Grondstof' (from waste to resource) aims to enhance the transition to a circular economy. The first goal is targeting the existing waste policy towards circular economy and innovation. This includes the stimulation of reuse of secondary resources (Mansveld, 2013). In 2015 the VANG program was evaluated and the program will continue with collecting hurdles in legislation and trying to solve these. Two of the operational objectives are making supply chains circular and increase knowledge on CE (Mansveld, 2015b; Mansveld, 2014).

Following the objectives in the VANG project, struvite was accepted as one of the ten test cases in the International Green Deal 'North Sea Resources Roundabout' (NSSR). In this international green deal between France, Belgium, the UK and The Netherlands the countries work together to align regulations on export and use of waste as resource. The involved parties are hoping that this will result in being able to export the struvite to other countries (UvW, 2016).

The Netherlands initiated the Netherlands Circular Hotspot campaign during the Dutch presidency of the EU (NLCH, 2016). The aim was to present the Netherlands as an international circular hotspot to inspire governments and international business. The City of Amsterdam is mentioned as an iconic project and the case of ICL using secondary phosphates was used as an example.

In September 2016 the Dutch Government published their (long awaited) national Circular Economy program (Dijksma & Kamp, 2016). The most outstanding aim is to realise a 50% reduction of primary materials use (minerals, fossils and metals) in 2030. The strategic objective is to substitute fossil, critical, non-sustainable produced materials with sustainable, renewable and generally available materials. There are five priorities in the program: Biomass and Food, Manufacturing, Plastics, Buildings and Consumer Goods. For these priorities transition agendas will be made before the summer of 2017. Phosphate is part of Biomass and Food. The example of phosphate recovery is mentioned when the report describes the interventions the government will use, of which stimulation of removing legislative barriers is one of them. Also the notification of the REACH revision in 2018 is mentioned, in which the government sees the possibility to make a stand for recycling. In the elaboration of the program the support for the Nutrientplatform is specifically mentioned, including 'the potential additional effective policy measures, aimed at increasing substantially the use of recycled nutrients'. The government wants to invest in a platform 'Holland Circular Hotspot' in which the Dutch Kabinet will invest in international relationships and will support more international Green Deals such as the NSRR. Because the market for phosphate lies mostly outside the Netherlands, these ambitions are important for the trade and development of the recycled phosphates. East and South Europa are mentioned as potential targets for international green deals on closing nutrient cycles. Furthermore the government will invest in strengthen the ESPP and Global Partnership on Nutrient Management (Dijksma & Kamp, 2016).

The role of the government

The water sector chain falls under Rijkswaterstaat, which is part of the ministry of Infrastructure & Environment (I&E), while agriculture falls under the responsibility of the ministry of Economic Affairs (EA). Interviewee 8 is a policy officer at the ministry of I&E. He explains how this works for phosphorus issues. Phosphate is found in wastewater and in manure and the problem of having too much phosphate in surface water can lead to problems. Interviewee 8 explains 'this part (on water quality) we have transferred to our colleagues working within the department space and water (Ruimte en Water) because the link with water quality is so big. We are on the circular economy part and work on manure treatment but for this we work together with the Ministry of Economic Affairs because agriculture is part of that ministry' (I8, 2016). Hoppe et al. (2016) noted that the fact that the responsibility for those two sectors is at different departments, is a hurdle in overcoming legislative barriers.

The interviews show the role of the government is subject to different viewpoints. Interviewee 3 thinks the actions of the government imply a facilitating role and sees they do not imposing anything[5] (I3, 2016). Interviewee 2 perceives the government as risk avoiding and thereby inhibiting innovation. He calls upon the government to think along with innovation instead against it (I2, 2016). Interviewee 1 thinks the government could stand up and guide the development. He also says that there is good communication with the government and setting up Green Deals are making it easier to work on their goals because it creates a shared interest. He thinks that 'getting the decision makers along is actually the most difficult. When that is done, the level which is under that, the executives, know on what they can work' (I1, 2016).

Interviewee 7 thinks the Dutch government was helping ICL a lot more than the government in Germany and especially Arnoud Passenier from the ministry of I&E helped to create possibilities. However, he fears that the financial cuts at the ministries will endanger the delegation of the ministries in the Nutrientplatform, while it is a crucial aspect for innovation to sit with officials around the table (I7, 2016). But Interviewee 7 sees also possibilities for improvement: The government has a lot of information on who is doing what. If they use this information, they could create clusters or shared initiatives, but the mind-set of the officials is not in this direction (I7, 2016). Interviewee 8 says there is a difference between what the government does and what he thinks. He thinks 'the government can reach a lot with Green Deals and covenants but as a government you can be critical. You can change legislation if it hinders innovation, but the rules are not there for nothing so you have to be aware of what you are doing'. He adds to this: 'but if needed, you should not be afraid to make new rules but the current Kabinet wants deregulation'. Interviewee 8 thinks a lot can be reached if barriers are removed and the government helps, but he also explains that 'helping' used to be giving money while nowadays there is less money and other parties are asked to step in. He sees an active role for the government to help society and guide them in the right direction. On the question whether the government should stimulate the demand side he answers 'this should not initially be done by the government but we can help. That is a facilitating role. Like using our embassies to bring the right actors together'.

Developments at EU level

[5] The interviews took place before the publication of the national CE program

The EU decided to put phosphate rock on the list of critical raw materials in May 2014 (European Commission, 2014). The list includes raw materials that have a high economic importance to the EU and have high risks in their supply. Being on the list does not imply an expected phosphate shortage, because the report also shows that a surplus is forecasted up to 2020 (European Commission, 2014). However, the dependency of the EU on other countries for phosphate is a potential risk for supply security.

The EU influences Dutch developments through regulation such as the EU Fertilizer Directive, see Subsection 4.1.4. Several of current policies related to nutrient management are coming from European Directives such as the Nitrate Directive and Water Framework Directive (Hoppe et al, 2016). The European Directives create the framework in which the Netherlands can set national legislation to reach the environmental objectives from the Directives. The Directives give therefore a kind of flexibility, in contrast to specific regulations coming from the EU. There is no specific Directive related to phosphorus but the Water Framework Directive includes targets for phosphorus in water (Sutton et al, 2013).

4.1.2. Supporting policy

In the Netherlands the Kaderrichtlijn Water sets goals for water quality of the water bodies. The Kaderrichtlijn Water comes from the EU Water Framework Directive (2000/60/EC) which states that the surface and ground water quality should have a good chemical and ecological status. The concentrations of phosphorus and nitrogen have influence on this ecological status (Gaalen et al, 2015). In 2021 80% of the water quality problems need to be solved (Groenkennisnet, 2016 but in 2015 only 45% of the water bodies meet the nitrogen and/or phosphorus norms. Especially in the regional water bodies, the norms are exceeded, of which two third is due leaching of agricultural soil and 20% of the total load comes from the MWWTPs (Gaalen et al, 2015). As a consequence there are regulations on the allowed phosphate concentration in the effluent. Most of the MWWTPs have phosphate removal installations, but it does not mean phosphate is recovered in a usable form.

4.1.3. Certification and lack of clarity in policies

One of the barriers most often mentioned by the interviewees is the legislation around the production and valorisation of struvite. This Subsection will describe the legislation that has to be followed to get a marketable product and how the current legislation influences recycling.

The function of the water board

Section 2.3 described the role of water boards. Because the water board is a public authority they should not pursue profit. The question arose whether selling waste resources or energy to other parties is in conflict with the public function of the water board and research was done to answer this question. The European legislation has some restrictions but there are also exceptions possible, allowing the researchers to conclude that the European law creates possibilities for sustainable initiatives (STOWA, 2012).

Waste status and certification

To be able to determine the status of struvite, the following scheme can be followed:

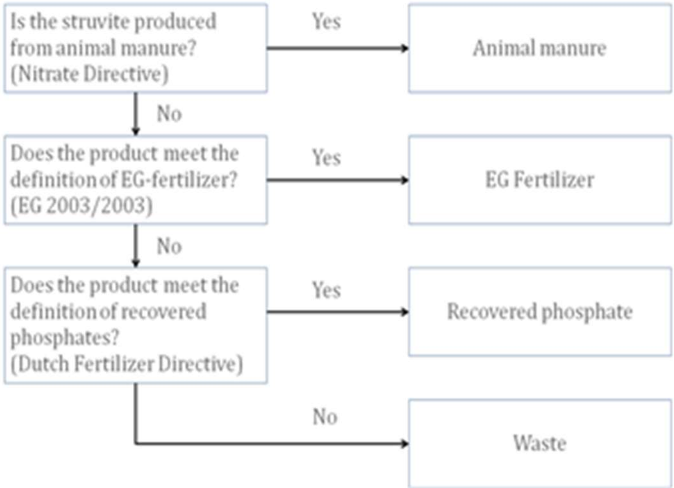


Figure 13. The status of struvite (STOWA, 2015)

One of the biggest hurdles is the 'Waste' status of the recovered materials. In the Netherlands municipal wastewater is considered a waste product according to the 'Wet Milieubeheer' (Law on Environmental Management) which means every material coming from wastewater treatment is waste. According to Aalke Lida de Jong of Aquaminerals not many companies are interested in waste products. To be able to process waste, a special permit is needed. Also the transport of waste needs to be done by registered carriers and registration is needed. To be able to bring waste products to other countries, the EVOA procedure needs to be followed. The EVOA procedure is timely, costly and a bank guarantee is needed. The procedures requires work of specialists and most of the companies have no experience with this. The consequence is that a waste product often has a negative value and that there are not many potential buyers. The motive for a company, to buy waste products although the paperwork is demanding, is often the low price (De Jong, 2017).

However, if the product recovered from wastewater meets the requirements of the EG-2002/2003 Directive, the product gets automatically the status EG fertilizer, loses its waste status and can be sold (STOWA, 2015). This is the case for the struvite produced by the Pearl technology of Ostara.

In February 2015 a revision of the Uitvoeringsbesluit Meststoffenwet went into force and the category 'recovered phosphates' was added (Mansveld, 2015a; Dijksma, 2014). Recovered phosphates include struvite coming from wastewater, magnesiumphosphate from drying of struvite and dicalciumphosphate coming from wastewater.

The following categorization is used in the Dutch fertilizer regulations:

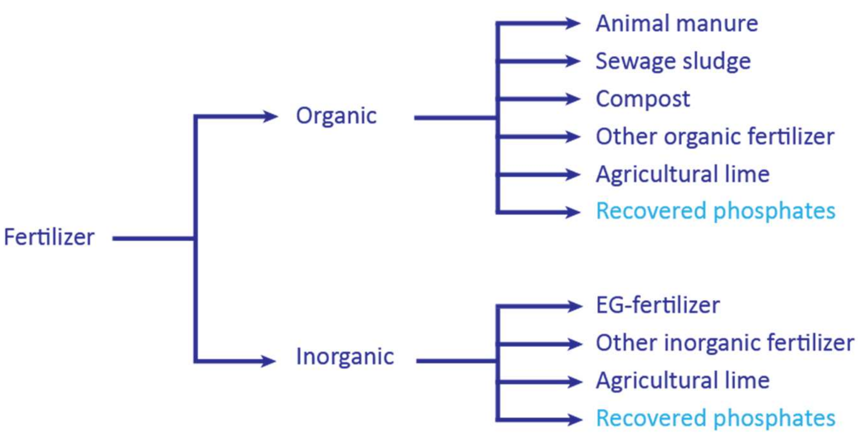


Figure 14. Schematic overview of the different fertilizer categories (STOWA, 2015)

If the recovered phosphate does not contain organic material, it is an inorganic recovered phosphate. If the struvite contains organic material, it has to meet the criteria on maximum amounts for heavy metals and arsenic and fulfil the standards on organic micro pollutants. Most of the Dutch struvite contains organic material and therefore will have to fulfil the standards on organic micro pollutants (STOWA, 2015).

Pathogens

There is one difficult paragraph in the revision of the Uitvoeringsbesluit Meststoffen which relates to pathogens.

"By ministerial order it can be determined that recovered phosphate from municipal sludge needs to be treated with a procedure that has as a consequence that most of the pathogens present in the sludge will be killed, in view of the risks for public health and environment"

Recovered phosphate from sewage water cannot be treated as being risk free because there could be still pathogens in the end product. At the time of the revision STOWA was still doing research on pathogens in struvite. Therefore the revision included the possibility to make extra treatment obligatory. Although legislation specifies a treatment step to reduce risks associated with the presence of human pathogens in recycled phosphates, there are no standards for acceptable concentrations and therefore it is unclear whether the treatment step is necessary.

STOWA researched the quality of the struvite and found pathogens in the struvite (STOWA, 2015). The values of pathogens in cleaned struvite were found to be lower than values found in animal manure, so STOWA recommends to use the same user guidelines which are used for animal manure as fertilizer. Interviewee 2 tells about the renewed discussion with the Dienst Leefomgeving[6] on pathogens and drug residues in the struvite and that they have no idea on how to measure or how to set standards for the struvite because there is no legislation. Interviewee 12 who works at a water board experiences the same problems: they are in contact with RIVM on what the water boards need to prove and what the criteria are to put a safe product on the market.

End-of-waste (EoW)

If the product does not fall in one of the categories of Figure 14, the material is regarded as waste. The procedure for end-of-waste (EoW) can be followed but the regulations are complex. There are no European EoW criteria for products recovered from municipal wastewater. If there is no European legislation, then the member states can decide per waste product whether the material is waste or non-waste which means the minister of I&E can decided that a product that meets the Kaderrichtlijn Waste Products, gets an EoW status. In 2014 there were no national EoW criteria for products recovered from wastewater, in which case the minister of I&E should decide per material whether the product meets specified criteria and is granted the EoW status. In that case the producer has to show the product meets specified criteria. The EoW status is based on the individual case per end-user, per location and per application. If the product gets this EoW status, it can only be exported if the receiving country also regards the product as end-of-waste. The Rijkswaterstaat made a portal where can be researched whether an EoW status is applicable (I4, 2016).

There are four criteria for getting an EoW status:

- The recovered product has a useful application and this useful application is fulfilled
- The recovered nutrient has a usual application for specific purposes
- There is a market or demand for the material

[6] Dienst Leefomgeving is part of the division Water, Verkeer & Leefomgeving of the Rijkswaterstaat.

- The material meets the technical requirements for the specific purposes and the product meets the applicable legislation and standards?
- The product has in general no negative effects on the environment or human health when using the product.

If the product wants to get an EoW status, it needs to fulfil the REACH. REACH is the European regulation no 1907/2006 for chemical compounds. It concerns the Registration, Evaluation, Authorisation and Restriction of Chemicals (Sloover & Klootwijk, 2014; Dijksma, 2014). According to the REACH declaration all chemical materials that are brought on the market in Europe need to be reviewed on their risks and be registered. The declaration is not applicable to waste, what means the declarations becomes applicable when an EoW status is obtained. On the other hand, for obtaining an EoW status, the material needs to meet the current legislation and regulation. In practice, both trajectories are done parallel (De Jong, 2017). The costs for the registration are high, see also Subsection 4.3.2. However, some materials are exempted from getting the actual REACH registration (REACH, article 2.7d). In 2015 the ESPP filed a formal question at the ECHA to request clarification on this subject (STOWA, 2015)[7]. The European Commission decided that struvite was exempted for the actual registration but to be able to get an EoW status, it still needs to comply with the declaration.

Interviewee 12 explained the REACH procedure for his struvite installation. First the water board had to give money to Berlin Wasserbetriebe, the lead registrant for Airprex technology, because they did research and have the documents. After that there was the real registration at the European Chemical Agency (ECHA) in Finland. The other water boards cannot use the registration of Waternet because they are a different legal entity (I12, 2016). This means the water boards have to follow the procedure themselves. Interviewee 7 said they are interested in struvite but the water boards needed to work according to the rules and deliver REACH declarations for their products (I7, 2016). The company has in its permit written they can only use products with REACH certificate (I12, 2016). Before the REACH declaration Waternet was not able to sell its struvite due to the regulatory hurdles and stored the struvite until it could find a buyer (Aquaminerals, 2014). Only after Waternet completed their REACH registration, Aquaminerals signed a contract with ICL to provide yearly minimal 500 ton struvite of Waternet to ICL (Aquaminerals, 2015). After the reaction of the European Commission to exempt struvite for registration, ICL could accept struvite that was based on this exemption (De Jong, 2017).

When the legislative status of the product is not an issue anymore, there is also legislation that influences the potential of using struvite. The application of phosphorus to soil is regulated by the Nitrate Directive. This EU regulation sets maximum limits for nitrogen application in soil. The Netherlands has an exemption until the end of 2017 to be able to apply 230 kg/ha of nitrogen instead of 170 kg N/ha. The conditions for the exemption include a prohibition on the use of chemical phosphorus fertilizer (Hari & Riiko, 2016).

In March 2016 Timac Agro introduced a fertilizer with recycled phosphate from agricultural waste (Boerenbusiness, 2016; Timac Agro, 2016; Nutrientplatform, 2016d). This fertilizer is promoted as specifically for livestock farmers that are not allowed to use mineral phosphate because they are part of the derogation. Interestingly, the RVO[8] report published in June 2016, concludes that the derogation is a barrier for using struvite because phosphate fertilizer, including struvite, cannot be

---

[7] In the mean time, the European Commission has decided that struvite is exempted for REACH registration (European Commission, 2015c). This means the producer still has to comply with the REACH regulation, by doing the needed analyses, but does not have to pay for the registration.

[8] RVO, Rijksdienst voor Ondernemend Nederland is the government service for enterprising Netherlands. It is part of the Ministry of Economic Affairs and stimulation can consist of subsidies, helping with aligning to laws and regulations, knowledge and finding business partners (RVO, 2017).

used at farms that fall under the derogation rules (Graaff & Naber, 2016). The contradiction between these two events shows that the execution of the Directive can lead to confusion.

4.1.4. Future policy impacts

The revision of the EU Fertilizer Directive and discussions on adjusted cadmium regulations can influence the phosphorus recycling in the Netherlands.

The EU Fertilizer Directive is currently revised and there are plans to add struvite to the Fertilizer Directive. The revision is mentioned by several interviewees as a potential step forward in making trade of recovered phosphates easier. Interviewee 3 has the hope that within 2-3 years the main legislative hurdle, regarding the EoW status, will be dealt with (I3, 2016). Interviewee 4 hopes European criteria can lead to a generic approach to resources. At the moment there are different quality standards by country what means there is no level playing field. There are different obligations for the various nutrient and you need documents for every material, every application and therefore she advocates an easier way (I4, 2016).

The ESPP is committed to getting struvite in the revision. The ESPP sent a proposal for the EU fertilizer regulation on the criteria for recovered struvite to the EU Commission (ESPP, 2015a). The proposal focuses only on struvite (magnesium ammonium phosphate) and looks at the use of struvite as direct fertilizer and as ingredient for fertilizer production. If the struvite will be authorised by the EU Fertilizer Directive, it will open up the way for changing the EU Organic Farming Regulation 889/2008. In February 2016 an expert Group for Technical Advice on Organic Production, that was set up to provide advice to the European Commission, published a response on proposals for authorisation of recycled phosphate products as fertilizers in the organic agriculture under the EU Organic Farming Regulation (EGTOP, 2016). The committee concludes that struvite should be authorised for organic farming, if the production method ensures hygienic and pollutant safety. Also phosphates from ash should be authorised for organic farming if the heavy metal content is within approved limits. However, both products cannot be included in the organic farming legislation until they are authorised under the EU Fertilizer Regulation.

The revision is expected to become effective in January 2018. In the annex of this revision struvite is not yet included, because the Joint Research Centre of the EU should first give advice on this. Currently experts are working on this in the Strubias project, so struvite, biochar and ashes will be added later. The first results are expected in the summer of 2017 (De Jong, 2017).

Next to potential supply risks due to political situations, the quality of the phosphate rock is seen as a risk for phosphate supply (Ridder et al, 2012). The rising level of cadmium, a toxic element, in the phosphate ores leads to concerns. There are discussions on lowering the allowed limit of cadmium (I9, 2016). However, the phosphate ores of Morocco are high in cadmium what means Europe will become more dependent on Russia’s ores if standards are lowered. A decision to lower the allowed concentration of cadmium can therefore impact the industry.

4.2. Technological perspective

The struvite route was viewed from a technical perspective. Factors influencing installation, the technical characteristics of the technologies and information on the sustainability of the technologies can be found in the first Subsection. The product quality and related issues are found in the second Subsection.

4.2.1. Technology context

Technical characteristics

According to Interviewee 3, struvite is easy to recover as the technologies are not so complicated (I3, 2016). The P-REX project, an EU project on phosphorus recovery, identified at least 13 technologies that produce struvite (Kabbe, 2015). They are in different stages of development as some are tested on lab scale while others have been installed already in full-scale. Of these technologies, there are currently three types implemented at full-scale in the Dutch communal wastewater chain. These are the Airprex, Pearl and NuReSys technology. The Anphos technology has been implemented in a temporary setting to handle an increase of phosphate containing wastewater coming from the renovation of the wastewater treatment plant of the company Peka Kroef (Heijmans-van Asseldonk, 2017). All these technologies work on biological P-removal systems. The Phosphaq technology which is also implemented at full-scale in the Netherlands, works on a mixed waste stream of both municipal wastewater and potato processing wastewater (Nutrientplatform, 2016e). These five technologies are shortly described[9].

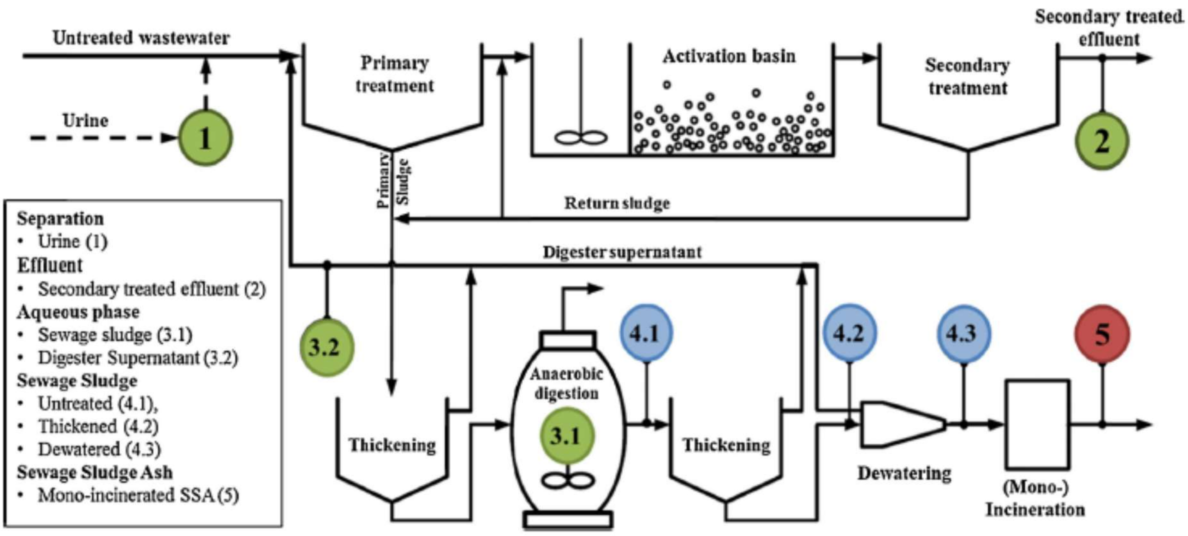


Figure 15. Possible access points for P-recovery in the communal water chain (Egle et al, 2015)

The Airprex works on digested sludge (3.1 in Figure 15) and uses a crystallization and precipitation process. Magnesiumchloride is based on the P load and added in a 1.1-1.2 Me:P ratio. The efficiency related to the P-flow is 80-95%, but because the struvite removal from sludge is only 30-35%, the recovery of P compared to the total MWWTP influent is only 10-15% (Egle et al, 2015; STOWA, 2011). According to Egle et al. (2015) the struvite is sold as a fertilizer Berliner Planze after a cleaning step. The heavy metal content is low and there are no pathogens present. In combination with other techniques a higher P recovery can become possible (Egle et al, 2015).

NuReSys and Ostara Pearl both work on digester supernatant (3.2 in Figure 15) and only use a crystallization process. Their P-flow efficiency is 90% and related to the total P in the MWWTP inlet this is 10-25% recovery. NuReSys uses magnesium chloride and sodium hydroxide for the crystallisation. In Belgium the technology is used on potato process water and the struvite can be sold as fertilizer (STOWA, 2011). The Pearl technology can, in combination with WASSTRIP technology, increase the total efficiency up to 45% (STOWA, 2011). Magnesium is added in a ratio of

[9] For more in-depth information on other types of phosphorus recovery technologies, the following documents are recommended: Egle et al, 2015; P-REX, 2014; STOWA, 2011.

1.05 Me:P. After drying a commercial fertilizer is obtained and sold under the name Crystal Green Fertilizer (Egle et al, 2015).

Anphos is based on rejection water (3.2 in Figure 15) and uses a precipitation process. Magnesium(hydr)oxide is added to achieve struvite precipitation (STOWA, 2011). Anphos claims a P-flow efficiency of 85-95% (Colsen, 2014). 20% of the phosphate inlet could be recovered as struvite (KNW, 2011).

Phosphaq works on digester supernatant (3.2 in Figure 15) and secondary treated effluent. Magnesiumoxide is used in the crystallisation process. The P-flow efficiency is 90%, which leads to a 10-25% efficiency related to the MWWTP influent (Egle et al, 2015).

In conclusion, the current technologies for struvite recovery are able to recover 10-40% of the P-inlet. 15% of the P-inlet is discharged in the effluent and the residue of the P ends up in the sludge.

Factors influencing installation

Interviewee 11 works at a water board and explained several factors that influence the choice for installing a struvite recovery technology. First, the water boards have to fulfil discharge limits to meet water quality requirements as explained in Subsection 4.1.2. If meeting the discharge standards is a problem, this creates an incentive to recover phosphorus (I11, 2016). According to Interviewee 11 there are two main options when looking at installing phosphorus recovery technologies: before or after sludge dewatering. The first has the advantage that it improves the sludge dewaterability and thereby decreases the sludge transport and treatment costs, while the other technology provides more phosphate as a separate grain and therefore more recovered material (I11, 2016).

Second, the space that is available to set up an installation influences the choice of technology. Waternet installed an Airprex installation in Amsterdam. Interviewee 12 explains that although Amsterdam is the second biggest MWWTP in the Netherlands, there is little space and an installation such as the Pearl technology would not fit within the existing area (I12, 2016).

A third factor of influence is the proof-of-principle. According to Interviewee 12 one of the supporting reasons to choose the Airprex installation at that time, was the fact that the Airprex technology was already installed in Germany (I12, 2016). Interviewee 11 says also you are not likely to invest in something that still has to be made if you have a properly functioning installation available.

A fourth factor is the price and business case. This point is elaborated in Section 4.3.

Fifth, the beliefs and priorities of a water board contribute to the decision whether nutrient recycling has priority. This factor is described in the social perspective, Section 4.6.

Sustainability of technologies

Recovered phosphorus is seen as a sustainable alternative to mineral rock phosphate. To be able to calculate and proof the sustainability of the technologies, actors have tried to measure the environmental impact. The Agentschap NL[10] commissioned CE Delft, an independent research company, to calculate the GER-values of struvite from communal wastewater and phosphorus recovery through sludge asses. The GER-values give the total energy that is needed to produce the product. These calculations can be used to calculate energy-efficiency or can be used in lifecycle assessment (LCA) studies. Crystallisation from rejection water is taken as example for struvite and

[10] The Agentschap NL merged with Dienst Regelingen into the Rijksdienst voor Ondernemend Nederland (RVO) and is part of the ministry of Economic Affairs

the Thermphos process was taken as ash-example. The numbers show that if the positive side-effects of struvite recovery such as reduced maintenance, are taken into account, the produced struvite has a better GER value than normal fertilizer. Also recovering phosphorus from sludge ash has a better GER-value than phosphorus from phosphate ores (Croezen et al, 2012).

STOWA carried out two LCA's: one on struvite produced by the Pearl technology and one on phosphorus from ash recovered by the EcoPhos technology (STOWA, 2016b). This LCA shows also the struvite route has a better environmental performance compared to the ash route but the percentage of recovered phosphate is higher in the ash route. However, the Pearl technology produces a ready fertilizer while struvite of other technologies needs additional treatment steps. Such differences can influence the outcome of LCA's. Interviewee 1 mentions in his interview the difficulty of comparing and making LCA's and he takes the LCA of EcoPhos as an example. 'The LCA of the EcoPhos is influenced by the nature of the HCl that is used in the process. If the HCl is bought on the market, the LCA scores low on material use but if the HCl is classified as waste or by-product from another process, the LCA has a more positive outcome' (I1, 2016).

The P-REX project delivered LCA's of various types of technologies (P-REX, 2015a). Cumulative energy demand, global warming potential, metal depletion potential, terrestrial acidification potential, eutrophication, ecotoxity and human toxicity are indicators for the LCA. These LCA's show that there is not one most sustainable option. It depends on the local conditions and on the weight that is added to the different LCA indicators. There is a big variation in the recovery ratios and in the amount of resources required for the processes such as chemicals, the energy demand and needed infrastructure. The side-effects on further sludge treatment and the quality of the recovered P in terms of heavy metal content influence the outcome of the LCA and the varying P content in the MWWTPs has impact on the efficiency of the processes. The struvite technologies have lower energy demand and toxicity of used chemicals and the improved dewaterability of the sludge brings energy benefits, but the P-recovery efficiency is low. Recovery via mono-incineration has a higher environmental impact due to the chemicals used, energy demand and the waste disposal, but the P-recovery is higher (P-REX, 2015a).

4.2.2. Product

Product quality and output

The struvite technologies produce different qualities of struvite. Not every technology leads to a product with direct applicability in agriculture which means an extra treatment step is needed to make the struvite directly usable. For Interviewee 11 this is a factor that is taken into account in the multi-criteria analysis, which is used to choose a phosphorus recovery technology for their treatment plant in Den Helder (I11, 2016).

Airprex produces a struvite slurry with finely dispersed particles that needs to be washed to remove sludge residues (STOWA, 2011; STOWA, 2013). The slurry can be used as input for fertilizer production. The usability of Anphos struvite slurry was still under research at the time of publication of the STOWA report in 2011. It is recovered as a slurry, contaminated with digested sludge (STOWA, 2013). The NuReSys is able to produce a certified fertilizer for Belgium (STOWA, 2011), but in 2011 not yet in the Netherlands. The struvite is recovered as a slurry, contaminated with digested sludge (STOWA, 2013). The Pearl technology produces struvite pellets with several sizes between 1,5-4,5 mm (STOWA, 2011). It is pure struvite, directly usable as a fertilizer. The product is called Crystal Green and can be sold since it has an EG-certification, see Subsection 4.1.3. Phosphaq produces a struvite slurry and the struvite from the site in Olburgen is used for the fertilizer Vitalphos. The wastewater is mostly potato processing wastewater with 15% rejection water of the municipal wastewater treatment plant (Nutrientplatform, 2016e; STOWA, 2013).

According to Interviewee 2 and Interviewee 1 are keeping the quality constant and keeping the production constant a challenge (I2, 2016; I1, 2016).

Another aspect of quality is the usability of the phosphate in the product. If struvite is used in agriculture, the farmer wants a product that can be taken up by the plants. As Interviewee 7 states 'the small amount of phosphate they are allowed to apply should be an effective product and not a kind of gambling game of when the phosphate is released by the product' (I7, 2016).

Pathogens, drug residues and heavy metals

The struvite that is obtained by a struvite slurry can be polluted by pathogens and drug residues and as explained in Subsection 4.1.3 the lack of standards for these pollutants creates problems.

This means it is difficult to know how the struvite should be measured and standardized. Interviewee 2 suggests it would be better to calculate the actual risks for exposure and make a choice. 'The drug residues are a risk but you have to bear in mind what the risks are during the whole value chain. The struvite will be processed into fertilizer and applied to a large area. How big is the risk? And are the drug residues taken up by the plants?' (I2, 2016). Interviewee 12 says Waternet has done analysis on struvite but 'the laboratory does not measure anything or they do measure something and that could indicate that there are perhaps worm eggs in it. Thus the laboratory is careful in their conclusions[11] (...) The RIVM, Dutch institute of health and environment and part of the government, doubts the results so we have asked them to tell us which laboratory we have to send the product to or do research on it'. Interviewee 12 says the current analysis methods are insufficient, but maybe in three years from now the methods will be more refined and it will possible to measure drug residues (I12, 2016). Interviewee 5 says they have detected pathogens, but he wants to research the effects of pathogens, especially if the struvite is used in food production (I5, 2016). Interviewee 7 told he received struvite made of urine from festivals and it contained a considerable amount of drugs. For that reason, he thinks the concerns of people are not completely unfounded (I7, 2016).

The heavy metal content is also a parameter for the struvite quality as they pose a risk to health. Egle et al. (2015) researched the heavy metal content of recovered P products and P mineral fertilizers. The samples of the Pearl and Airprex technology showed heavy metals values that are lower than the values found in mineral fertilizers, except for the amount of copper.

4.3. Financial perspective

In our society money plays a crucial role in getting things done. Therefore the financial perspectives looks at the finances regarding installation, the expected monetary benefits of struvite production and at the market potential.

4.3.1. Financial context

Investments, subsidies and fiscal system

New innovations require investments for knowledge development, pilots and full-scale installations. The investments can come from the actors themselves, government or external investors. A European policy framework could stimulate investments (ESPP, 2015b). The EU can also provide subsidy programs, an example is the LIFE+ program. The water board Vallei & Veluwe was able to get subsidy to make their struvite installation in Amersfoort possible (OmzetpuntAmersfoorI2, 2016a). In contrast to the possible European subsidies, Interviewee 3 says that there is no Dutch subsidy for sustainable resources recovery, there is only subsidy for sustainable energy by the SDE+

[11] Dutch: Ze houden enorme slagen om de arm

subsidy program (RVO, 2016; I3, 2016). “Maybe this is not a barrier but changing the regulation could stimulate the recovery of resources” (I3, 2016). Interviewee 10 of a water board mentions the lack of subsidy for resources recovery as well (I10, 2016). Interviewee 10 even goes further and calls the fiscal system a barrier because it does stimulate energy recovery but energy production has often as consequence destroying valuable resources (I10, 2016). Another barrier coming from the fiscal system according to Interviewee 10 is the levy system for treating waste. A water board can gain benefits by creating biogas through treating sludge of others. However, the water boards have to charge for the waste treatment according to the levy system (I10, 2016). The levy costs could be a reason for companies to treat their sludge in another way, preventing the benefits of treating the sludge by the water board. This problem was also mentioned in the Green Deal 057 (UvW, 2011).

Interviewee 5 of the research institute says it is difficult to find funding for research on nutrients. At European level, they did some attempts but were unsuccessful. The water boards have a drive to implement and that is noticed in the questions they ask to the research institute. There are technologies available, but questions on the applicability of struvite, on the choice for the most optimal route and about pathogens still exist (I5, 2016). In 2016 the government published its National Circular Economy program. To stimulate research on closing the loops and circular economy, a NWO-program (Dutch Science Research Centre) with 5 million euro will be made available for research projects (Dijksma & Kamp, 2016).

To stimulate the recycling of nutrients including phosphate the Nutrientplatform published their ambition plan at the end of 2016. The financial feasibility issue is addressed in this ambition plan by the following aims: to stimulate the creation of an innovation fund for sustainable resources, to organise matchmaking between technology developers and potential investors, to research other possibilities of financial incentives for sustainable use of resources and to stimulate financial support for pilot projects (Nutrientplatform, 2016b).

4.3.2. Costs

Installation costs, sludge costs and payback period

The payback period of struvite reactors depends on the cost reductions and on the profit made by recovering struvite. The investments cannot be recouped by only the revenue of the struvite. The related cost reductions because of lower sludge disposal cost, lower maintenance costs due to minimising struvite nuisance in equipment and reduced chemical consumption will determine the financial advantages of struvite recovery (STOWA, 2013). Vaneeckhaute et al. (2016) estimated that currently struvite recovery is economically feasible on side streams from wastewater treatment if the P-load is more than 20% by weight. The operational costs and payback periods are highly dependent on the composition of the input.

Systems based on precipitation, such as Anphos, are relatively easy processes and the investment costs for these technologies are relatively low. The operating costs are in the same order of other struvite recovery systems. Research showed that for a MWWTP of 300,000 IE (inhabitant equivalent) a payback period of 2 till 6 years is possible (STOWA, 2011).

The installation costs differ on the scale of the treatment installation. Interviewee 11 says that the installation in Amersfoort costed probably a couple of million but on a location such as Den Helder, the costs will be in the order of 1 million (I11, 2016). The installation costs of the Airprex technology in Amsterdam were 4 million in total and it saves around €400,000 per year (Waterforum, 2013). In a presentation of Alex Veldman of Waternet during the events on Opening Omzetpunt Amersfoort, he said the investment was 3 million euro with savings of €500,000 and a return on investment in 6 years. Interviewee 12 said that the business case of the Airprex installation was built on the lower treatment costs of the dewatered sludge and not on selling the struvite (I12, 2016).

The MWWTP in Amersfoort of water board Vallei & Veluwe installed the Pearl technology. The total payback period of this new treatment plant is expected to be 7 years and the project got an EU subsidy of the LIFE+ program to make the project possible. The technology provider, Ostara, signed a contract with the water board to buy the struvite back for the next 10 years. The sale of the struvite is an important element of the business case as it covers 20-30% of the costs of the new sludge treatment plant they have installed (Dutchwatersector, 2016; OmzetpuntAmersfooI2, 2016a).

The Pearl technology has higher investment costs but the guaranteed returns on the product will at least cover the operational costs. After the payback period is reached, the savings of the Pearl technology (in combination with WASSTRIP technology) will be higher than with the Airprex system (STOWA, 2011). The costs per P over a lifecycle of 15 years are for Pearl 5 times lower than the Airprex system, due to the higher revenue and a high recovery rate (STOWA, 2011).

REACH

The REACH-procedure is costly and takes some time. According to Interviewee 12, the registration is expensive (I12, 2016). A REACH registration costs around 20,000-25,000 euro (De Jong, 2016). The costs consist of (1) the ECHA registration fee, (2) buy-in at the lead registrant, which is a letter of access (LoA) to the research outcomes of the lead registrant and (3) the costs for the analysis of the material. The registration costs for 100-1000 ton dry material are around €10,000. The buy-in costs around €6000 for struvite with a production volume of 100-1000 ton. Hiring a consultancy for the registration and analysis can easily lead up to €5000 (De Jong, 2017). When asking Interviewee 7 about the REACH declarations he says that not everyone bought themselves in at Berlin Wasserbetriebe. 'That is a possibility, for a small amount you can do that'. His words imply he thinks the costs should not be a barrier towards registration. The comments of Interviewee 12 and Interviewee 7 show the costs are experienced differently by the actors. But ICL is not the company who has to pay for the registration as the water boards such as Waternet have to obtain the REACH registration.

Whether the benefits of getting a REACH declaration outweigh the costs depend on the amount of struvite produced at the STP (I12, 2016). Interviewee 12 mentions Land van Cuijk as an example: 'They have struvite or at least produce phosphate but they have such low amounts that a REACH registration makes little sense. You would have higher costs than the product value' (I12, 2016).

4.3.3. Market

Struvite profit

The projections for the price of struvite differ. In 2011 STOWA estimated that the struvite slurry of the temporary installation in Anphos was equated with the disposal transportation costs. A value of €20 or €30 and even up to € 100 per ton can be expected (STOWA, 2011). These revenues are not high. For example, the production of struvite from the NuReSys installation in Land van Cuijk does not lead to profit as the transport costs outweigh the benefits (Heijmans-van Asseldonk, 2017). The struvite in Tilburg also does not bring high profits. €100,000 on magnesiumoxide is put into the process, which results in 430 ton of struvite. Currently the struvite is sold for €60 per ton on the market what will bring €130.00 revenue and 'that will not make you rich' according to Interviewee 1 (I1, 2016).

In the discussion during the event of opening Omzetpunt Amersfoort (16-17 June 2016), attendees in the room said 200 euro/ton for green struvite would stimulate the struvite production. But the current price for phosphate from Morocco was estimated at €100 per ton and the price of P influences the market price of struvite (OmzetpuntAmersfooI2, 2016b).

Niche application

Struvite is seen as a product with a niche application for two reasons. Firstly, because the manure surplus in the Netherlands and secondly, because of the product characteristics of struvite. Due to the manure surplus, a structural economic attractive sale of struvite is unsure (STOWA, 2013). The manure surplus leads to the use of manure as fertilizer in conventional agriculture. As a consequence there is low demand for phosphate fertilizers, except for phosphate fertilizer as a ‘start fertilizer’. Struvite would be usable for this application and for applications where animal manure is poor applicable or not desired. The leisure sector and public green were named as potential markets in 2013 (STOWA, 2013), but later research of STOWA abandoned the application for public green due to a low nitrogen concentration (STOWA, 2016a). Other applications of struvite would be as input for the production of various types of phosphate fertilizer (STOWA, 2013).

In May 2016, STOWA released a research report on the agricultural value of struvite (STOWA, 2016a). Several experiments with crops such as iceberg lettuce, gladiolus and dykes grass were performed. This research showed that struvite has comparable functions as mineral fertilizer. However, crystal struvite or ungrained struvite cannot be used immediately in regular fertilizer spreaders and is only usable as resource in the fertilizer production. The grained struvite has a wider applicability, but the ratio of nitrogen and phosphate needs to match the plant requirements (STOWA, 2016a). Especially potatoes and corn are P-needing crops. Pot trials showed that the availability of P in struvite is comparable with triplesuperphosphate (TSP) fertilizer (STOWA, 2013).

The struvite can be used in sport fields under construction or during large maintenance, but due to the low nitrogen concentration the struvite is not suited to be used in public green areas. The maximal market demand of grained struvite is estimated to be 6400-8300 ton/year, excluding the potential of struvite as input for fertilizer production. Because of the needed market introduction, a more realistic market demand is estimated to be 465-1400 ton/year, what is lower than the current production of 1500 ton annually (STOWA, 2016a). If the struvite can be enriched with nitrogen or other plant nutrients, the potential demand could grow. The market value of struvite for fertilizer production is estimated to be €5,50 per 100 kg. If the struvite can be used as fertilizer replacement, the product could be worth €35 per 100 kg (delivered at the user) (STOWA, 2016a).

Interviewee 12 sees that compared to the amount of fertilizer and manure that is used, the recovered phosphate from sewage is only a small amount. It is a niche market for the more environmentally conscious consumer (I12, 2016). Interviewee 2 uses the sustainable image of the product as an advantage and tries to find companies that are involved with sustainability. He sees many companies value the green origin of the product (I2, 2016). Interviewee 1 sees potential for struvite in local projects in the Netherlands (I1, 2016). If struvite cannot be used as a direct fertilizer, it can still serve as input for fertilizer production. The company, Ostara, of the Pearl technology sells their struvite also to blenders (Omzetpunt AmersfooI2, 2016b).

External markets

Germany has provided a market for the struvite produced by the Airprex system. Although it was classified as waste under Dutch regulations, the product could be used in Germany for fertilizer production (STOWA, 2011). External markets have been mentioned as a potential business case, but Interviewee 3 noticed that not all these markets have recycled phosphate as their priorities. Countries with surpluses are problem owners. Countries in East and South Europe are more likely to have shortages but are not eager to get phosphate from North West Europe. He mentions Poland as an example; ‘I have been in Poland which has places with shortages but there is barely awareness and the focus lies on other problems such as climate change, drought and they do not have the same mind-set as we have’ (I3, 2016).

Contracts

Contracts can give long-term security and stimulate developments, but on the other hand it can limit possibilities. As an example: The Pearl-system produces a certified fertilizer and the sales are guaranteed by a long-term contract of 10-15 years with the technology provider Ostara. The returns on Crystal Green cover at least the operational costs, but could be higher than the operational costs, depending on the situation (STOWA, 2011). The contract is obligatory when the technology is installed what means you have the sell the struvite to Ostara. This fact played a role in the decision to build an Airprex system in Echten (GoI2, 2016). According to Roelof Gort of EFGF the Phosphaq installation also comes with a five-year contract what means the water board is dependent on the prices of the provider (GoI2, 2016).

Market outlook

Demand for controlled and slow release fertilizers such as struvite is expected to grow because they are environmentally friendly and the application can reduce labour costs due to decreased application frequency. If costs can be reduced by larger production scales, the struvite can become more competitive with conventional fertilizers and be used for commodity crops (Vaneeckhaute et al, 2016). According to Interviewee 2 more parties are getting interested in struvite. ‘In the past, there was only one party interested, but now you see more manure processors who think it could be an interesting product to add to their product to increase the phosphate concentration. With a higher phosphate concentration it becomes economically attractive to sell their product in a wider transportation distance’ (I2, 2016). ‘The logistic costs are expressed in costs per volume of phosphate, what means if you can put more phosphate in a truck, you can drive further whereby you can distinguish yourself from competitors’ (I2, 2016). Interviewee 12 thinks that because of the growing number of producers, the price of struvite will rise (I12, 2016).

There are also counterarguments and less positive expectations. Interviewee 8 mentions that the market for recovered phosphate is limited. There are some niches but if the recovery of phosphate grows, the demand market won’t be enough to use all struvite (I8, 2016) or as Interviewee 10 says: ‘if the niches are filled, you have another problem’ (I10, 2016). Interviewee 7 thinks companies such as Ostara can make nice products but that those companies are getting a problem; they get more capacity, make more contracts but the niche markets are becoming saturated. The consequence is that they have to go commodity with a product which has a high price and that will be a challenge (I7, 2016).

The further development of the market will be affected by the changes in policy such as the EU Fertilizer Directive, see Subsection 4.1.4.

4.4. Infrastructural perspective

The infrastructural perspective looks at the integration of the technology in the incumbent industry. This involves the installation possibilities, the total potential of production and the link with the incumbent industry. This Section gives an overview of these factors for the case of struvite recycling.

4.4.1. Supply

Type of MWWTP

There are two types of MWWTPs: with biological and with chemical treatment. In the Netherlands there are 70 MWWTP installations with chemical phosphate removal, 4 with a separate installation, 112 with biological removal and 113 with a mix of chemical and biological phosphate removal. 38 MWWTP have no specific phosphate removal systems (CBS, 2016a).

STOWA calculated the potential amount of recovered struvite from municipal wastewater, see Figure 16. In the calculation it is assumed that the installations with biological P-removal and with sludge digestion possibilities are available for struvite production and the scale of the MWWTP have not been taken into account (STOWA, 2013). This means that smaller MWWTP are expected to be able to recover struvite as well. The division on the amount of biological and chemical treated sludge was taken from CBS figures of 2010 (STOWA, 2011). But in the same report phosphorus recovery at the MWWTP is only regarded worthwhile when the concentration and the amount of phosphorus in the waste stream is high enough. The best chances for phosphorus recovery are in bio-P treatment plants with sludge digestion (STOWA, 2011). Phosphorus recovery at MWWTPs with chemical P-removal can be done, however the costs are high as the phosphate from the sludge needs to be dissolved again (STOWA, 2013).

Sludge treatment such as fermentation and dewatering is increasingly done through central sludge treatment at bigger MWWTPs. Without sludge fermentation, the amount of P in the rejection water is negligible (STOWA, 2011). This trend lowers the amount of locations where P-recovery is feasible, because technologies such as Airprex and Pearl work on MWWTPs with sludge fermentation. But installing these types of technologies on central treatment facilities increases the scale of phosphorus recovery and favours the economic feasibility (STOWA, 2011).

Potential

The amount of P in imported fertilizer (in 2008) is estimated at 12 kt P/year (STOWA, 2013) and is comparable with the amount of P in sewage sludge (almost 12 kt P/year), see Figure 16 (STOWA, 2013). Because the Netherlands has a manure surplus, most of the phosphate used in agriculture comes from applying manure (70 kt P/year). STOWA (2013) calculated the potential of struvite from Dutch communal wastewater. The maximum amount that could be recovered through struvite production would be 2.5 kt P, see Figure 16. This number is based on the amount of P entering the MWWTPs, the different types of MWWTP there are in the Netherlands and the efficiency of the technologies. In these calculations a maximum of 40% efficiency is used, but often the efficiency is lower. (STOWA, 2013). Struvite recovery only takes place at biological MWWTPs, what means that phosphate from chemical MWWTPs will end up in the sludge and go through the ash route in this scheme. If all the P is recovered through mono-incineration of sludge, this could produce 11.6 kt P/year (STOWA, 2013). Mono-incineration means the sludge is burned separately and not combined with other waste sources. Not all the MWWTPs work on a scale that would make struvite recovery economically viable. Interviewee 7 thinks the potential amount of struvite is peanuts: 'If you add all the struvite that becomes available in the Netherlands, you talk about 5000 ton struvite, that is nothing, you can throw that in two days in our installation' (I7, 2016).

Scale of supply

According to Interviewee 2, an economy of scale is needed. By having a higher struvite production, more parties get interested. A larger scale is also important because 'the government then starts to think along and you have the power of having a collective entity' (...) The water boards are actually too small' (I2, 2016). Aquaminerals calls upon struvite producers to cooperate and collectively address the market (Nutrientplatform, 2016b). Some of the interviewees suggest central post-treatment for the produced struvite. This could include washing and hygienisation, depending on the "sales channel". Then it would be possible to make a good product on a central location according to Interviewee 12 (I12, 2016).

For market parties it would also be interesting if the phosphate concentration in the product can be raised because this would enable a profitable business case for higher transport distances (I2, 2016).

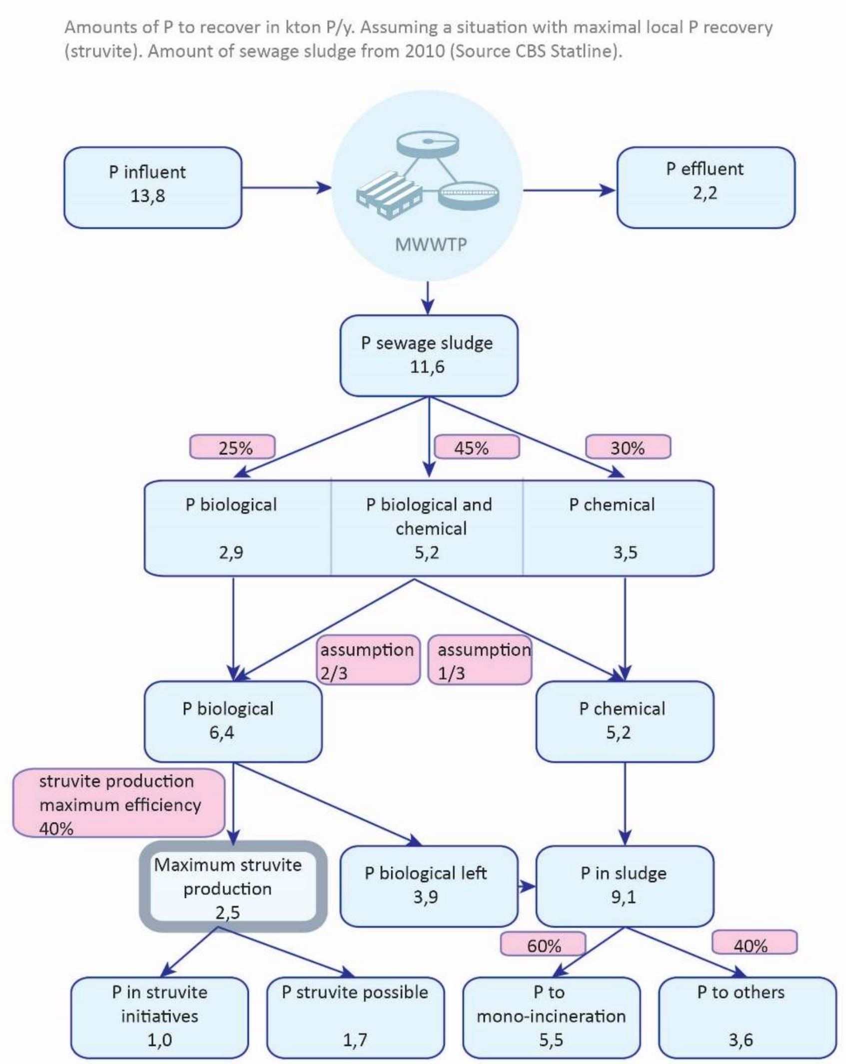


Figure 16. Potential recovery of P in kt (Adapted from: STOWA, 2013)

4.4.2. System integration

Complementary technologies

To be able to use struvite as a direct fertilizer, it must be compatible with existing machinery in agriculture. Many fertilizer 'dispersers' are adjusted to traditional fertilizer that have grain sizes between 2- 5mm. For food production, where liquid or water soluble fertilizers in irrigation systems are used, struvite is not suitable as struvite is difficult to dissolve in water (STOWA, 2016a).

Incumbent system

The technologies for struvite recovery are compatible with the MWWTP in the Netherlands. However, the available space for installations can influence the decision whether a technology and which type of technology will be installed, as Interviewee 12 pointed out: 'We have, although we are one of the biggest MWWTP in the Netherlands, very little place. It is really limited and everything is tight to one another. And then I wonder whether a Pearl installation would fit and then I think the answer is "No"' (I12, 2016).

To market struvite as fertilizer, it will have to deal with the incumbent fertilizer industry. There is only one phosphate fertilizer production site in the Netherlands, this is ICL Fertilizers in Amsterdam. The fertilizer companies have a lobby organisation for the fertilizing industry. Meststoffen NL is a branch organisation who represent producers, blenders and suppliers of mineral fertilizers (Meststoffen NL, 2015). Meststoffen NL is member of the Nutrientplatform and according to Interviewee 3, partly to show they do something about sustainability and partly to see what is happening and in what way it influences the fertilizer industry (I3, 2016). ICL stands out as frontrunner of using recovered phosphates by their ambition to use 100% recycled phosphates in 2025. Before ICL bought the RecoPhos technology, they looked at other ways of using recycled phosphates and currently they buy struvite from Waternet. Interviewee 7 said in his interview ICL encountered technical problems due to the provisional way they applied the recycled phosphates in their production process, therefore ICL decided to build a new process installation and asked the company Tauw to engineer the final system (I7, 2016). Another company in the fertilizer industry that uses recycled phosphate is Timac Agro, they use struvite from agricultural waste in one of their products (Nutrientplatform, 2016d).

4.5. Knowledge perspective

The knowledge perspective includes knowledge development and the dissemination of this knowledge. It looks at the research that has been done and to which initiatives stimulate the knowledge development and sharing of knowledge.

4.5.1. Knowledge development

Research in the last years

In the last years several reports with research related to phosphorus and struvite recycling have been published. The research institute STOWA has produced the most research relevant for the Dutch situation as STOWA answers knowledge questions of water boards. In short the timeline of research will be described, starting from 2011, to give insight in how the research subjects have evolved over time.

At the end of 2011 STOWA published an explorative report on phosphate recovery at communal wastewater treatment plants. It focused specifically on the possibilities of phosphate recovery from wastewater and from sludge ash. Four technologies that were available at that time were studied more in-depth and some scenario's for phosphate recovery were elaborated. Technologies that fit in the existing infrastructure were favoured over others. The report emphasizes the need for sustainability, closing the loops and the opportunities this creates for the water boards (STOWA, 2011).

In 2012 a report on legislation was published (STOWA, 2012). The research was triggered by questions that arose on the role of the water boards as a public body and the wish to produce goods such as struvite and energy, see page 38 of the institutional perspective.

In 2012 the research institute CE Delft was commissioned by Agentschap NL to publish a report on GER-values of struvite from communal wastewater and phosphorus recovery through sludge asses. These GER-values give the total energy that is needed to produce the product and can be used to calculate energy-efficiency (Croezen et al, 2012).

In 2013 the STOWA continues with a report on barriers and possible amounts of phosphorus that can be recovered from communal wastewater and from the sludge. The research did not only focus on the technical details but also looked into the legislation and market aspects and the consideration at which place in the wastewater chain phosphorus recovery would be the best option (STOWA, 2013).

In 2014 a juridical guide on sustainable energy and resources from wastewater was published (Sloover & Klootwijk, 2014). This report was needed because after the first struvite reactors were running in 2013, it became clear that the complex legislative field around valorisation of materials from wastewater acted as a big hurdle towards market creation. An update was made by the EFGF after the addition of the category ‘recovered phosphates’ to the Meststoffenwet (EFGF, 2015a).

Concerns on pathogens in struvite led to research by STOWA to measure the quality of the struvite (STOWA, 2015). Interviewee 5 of the research institute says more demonstrations and research are needed to show the working and the safety of struvite (I5, 2016). This research can influence the acceptance of the product. See also Subsection ‘pathogens’ in 4.1.3,‘pathogens, drug residues and heavy metals’ in Subsection 4.2.2 and ‘waste acceptance’ in Subsection 4.6.2 for more information on this issue.

The relevance of STOWA’s research became even more evident after the interviews. Interviewee 1 stated in his interview that struvite is still an unknown product and the value needs to be demonstrated (I1, 2016). One month after the interview STOWA published their research on the agricultural value of the struvite. The main result is that the market for struvite as direct fertilizer is quite small but there is a bigger potential for struvite as input for fertilizer production (STOWA, 2016a).

Current knowledge need

As said in the previous paragraph, research on product safety is still needed. The report of STOWA on agricultural value showed that the market for struvite as direct fertilizer is quite small (STOWA, 2016a). Anticipating on that, the research institute is looking for project partners who can mix the struvite to create a product that is directly applicable (I5, 2016). But finding companies as direct customers is difficult: ‘Especially with new materials that literally have a smell and there is not much experience’ (…) ‘and because you don’t have the product yet or only a small sample, it is difficult to get those parties interested. As the industry is working with relatively large volumes and they do not want a small amount’. Secondly, it is not easy to find financial resources for projects (I5, 2016).

A big report on Nutrient Recycling in Europe identified the following knowledge gap: There is not enough data to do benchmarking for the sector. Most full-scale installations have taken place in the last years so there are no figures on likely operating costs or plant scale economics. As a consequence there is little insight in what type of infrastructure is needed for new fertilizer products and what the costs are (Buckwell & Nadeu, 2016).

4.5.2. Knowledge dissemination

In the case study several collaborations between companies, research institutes and networks have been found that stimulate the exchange of knowledge. These are discussed hereafter.

Research projects

P-REX

In the P-REX project, which ran from 2012-2015, life cycle assessment of technologies and comparative assessments of crystallization technologies have been done and market barriers and market potential were analysed (P-REX, 2015b). In the project new technical solutions were demonstrated at full-scale and the aim was to increase the European phosphorus recycling rate from municipal wastewater to 80%. In this EU project 15 partners from Germany, France, Swiss, Austria, Finland and Spain were involved.

ARREAU-SRRLA

ARREAU is a project on Accelerating Resource Recovery from Water Cycle and is part of the European Innovation Partnership on Water. The ARREAU Struvite Recovery & Recycling Learning

Alliance (SRRLA) is set-up to share experiences related to struvite recycling and to bridge the gap between recovery (technology providers and MWWTP operators) and recycling (downstream users) (Kabbe, 2016b). SRRLA started in 2016 as follow-up from the P-REX project.

SusPhos

In this project PhD's are working on utilizing phosphorus in a sustainable manner. Three industrial partners and nine academic partners worked together in this project (SusPhos, 2016). The focus was solely on sustainable phosphorus in the industry and none of the involved partners is member of the Nutrientplatform.

Green Deals

The Green Deal Resources was signed by the Unie van Waterschappen, STOWA and the Government (UvW, STOWA & Rijksoverheid, 2014). One of the aims of the Green deal was to stimulate knowledge exchange between the water boards.

Network organisations

Nutrientplatform

The Nutrientplatform tries to develop knowledge that can be used by the members of the network, see also Section 2.3 on relevant actors.

European Sustainable Phosphorus Platform (ESPP)

The ESPP contributes to knowledge dissemination by for example organising conferences. The ESPP was also in de advisory board of a big study on Nutrient Recycling in Europe (Buckwell & Nadeu, 2016). The report focuses on three main sources of phosphate and nitrogen: manure, sewage and food chain waste and elaborates on the scope, scale, technologies, potential for nutrient recovery and policy measures.

One of the conclusions was that the information exchange through the nutrient platforms should be kept and could be further developed. For example by establishing information on the Best Available Technologies. Also research, training and skills development are activities that are well-established. According to the report 'it does not appear that there is a lack of public support to identify and pilot nutrient recovery technologies' (Buckwell & Nadeu, 2016).

4.6. Social perspective

The social perspective includes visions, beliefs and general landscape developments that influence the struvite recovery. Also the problem perception and the risk perception influencing public acceptance are described here.

4.6.1. Context

To get an understanding of the social context, it is useful to understand who the problem owners are, what social aspects influence decisions to install struvite recovery technologies and how movements in the Netherlands contribute or hinder recycling of phosphorus.

Problem perception

One of the barriers found in the data is the awareness and the perception of the phosphate problem. According to Interviewee 3 the government and the waste stream owners are the problem owners, not the consumers. 'You could say the Netherlands is the dirtiest boy in the class concerning water pollution by phosphate. Farmers do not ask for recycled phosphate and regions outside the Netherlands that have phosphate shortage do not have the same mind-set (as the

Netherlands). In those regions there barely is awareness, the focus lies on other problems' (I3, 2016). The words of Interviewee 7 are in line with Interviewee 3: 'we tried to involve southern and eastern countries but that doesn't work yet because issues are different there. They are interested in phosphorus recycling, but do not have a phosphorus surplus and in our case everything went quite fast of course because we have a surplus (phosphate) problem and even in such a way that the phosphorus surplus affects the stock of cattle. Then there is an economic aspect to stir the discussion' (I7, 2016). In other words he says the phosphate surplus acts as a driver to look at phosphorus recycling in general. In the opinion of Interviewee 3 are 'the waste stream owners, government and water boards the problem owners because of water quality or problems with struvite scaling in treatment plants' (I3, 2016). This means the supply side is the one that has problems.

On the other hand there is the perception of the phosphate scarcity. According to Interviewee 9 'phosphate is not seen as experiencing a shortage, because there are still many sources. It can last for another 300-500 years until these sources are exhausted and after that there is still a lot of phosphate at the bottom of the sea. Ten years ago they expected a phosphate problem but the exporting countries also need their consumers. If those don't deliver, their market goes downs. We need each other' (I9, 2016). Interviewee 8 thinks phosphate will last another couple of hundred years (I8, 2016). Shortage is not being considered a problem, is also stated by Ridder et al. (2012) in the report of the Hague Centre for Strategic studies. 'Peak phosphorus' is not so much of a problem but the rising prices and the quality of phosphate rock are creating risks for the phosphate supply (Ridder et al, 2012).

'The product (struvite) has been developed because it is possible but not with the idea to think of who can use the product' (I3, 2016). This situation creates a supply push, in which products are put on the market but the demand side is less developed.

Drivers and trade-offs

Sustainability is often mentioned as a driver for decisions that are made. Sustainability is a broad concept and within the concept of sustainability there is more than one route to follow. This means that preferences and priorities of actors influence the 'sustainable' choices.

Interviewee 3 expresses the idea that drivers for closing the phosphorus loop are not only environmental impact due to mineral phosphate use. Drivers for phosphorus recycling are local production, fluctuating phosphate prices, the perspective of shortage and the water quality of surface waters in the Netherlands (I3, 2016). Interviewee 11 of a water board explains why water boards want to be active in struvite recovery. The water boards are a public body. He says 'you (the water board) do it to show it is possible. As government you are a role model and with that you hopefully stimulate phosphate recovery in other places, where it can have more impact' (I11, 2016). Interviewee 6 sees the water boards are enthusiastic to show they contribute to addressing the phosphorus challenge by recovering struvite, but he has some critics on this. Struvite recovery has big advantages for wastewater treatment, but falls short to recover phosphorus on larger scale. Too much publicity on struvite recovery can give the impression that not much is left to be done and according to Interviewee 6 this latter aspect deserves more attention. On the other hand he points out that the water boards are contributing to recovering phosphorus from ash when they treat their sludge by SNB and HVC.

When the motivation is sustainability, the individual priorities or perception of the concept sustainability become important. For example, Interviewee 11 mentions that in the installation of Beverwijk phosphate is recovered from the effluent, but is left in the sludge. The sludge will be dried and used in a biogas digester. The phosphate can be left in the sludge to recover it at a later stage from ash (I11, 2016). This is still a sustainable choice but the focus lies on energy recovery at the

MWWTP and not on nutrient recovery. In the Netherlands the focus seems to lay more on sustainable energy recovery as can be seen in Subsection 4.3.1.

Interviewee 2 points out that choices for sustainability are playing further along the value chain as well. His company looks at what type of actors are interested in their recycled materials as they look for companies who value sustainability. ‘We will not sell our materials to the shale gas sector and we prefer to market our products locally’ (I2, 2016).

Next to sustainability, cost reductions such as reduced maintenance costs are drivers for struvite recovery (I1, 2016; I12, 2016).

Flexibility

The wish to be flexible is mentioned by Interviewee 11 as an important barrier in phosphate recycling. ‘The wish for flexibility of the individual water boards will be the biggest barrier. The question is to what extent a water board wants to be free and to what extent they want to commit themselves to central phosphate recovery?’ (I11, 2016). Some of the struvite installations are contractually bound, such as Pearl technology and Phosphaq, see Subsection 4.3.3. Interviewee 11 sees the following ‘at the moment the water boards are seeing for themselves what are convenient methods and chances and I think this will come together again’ (I11, 2016). The wish to be flexible can lead to decisions that are maybe suboptimal from a sustainability perspective.

Landscape developments

With the VANG, CE package and changes in legislation, it seems the Dutch political situation stimulates nutrient recycling as part of the Circular Economy. Society itself shows examples of willingness to move towards a more sustainable use of materials and looking at ways to reuse waste. Examples are Rotterzwam[12] that produces mushrooms from coffee-grounds, The Plastic Whale Foundation[13] that collects plastic from the Dutch canals to produce plastic products and the Chocolatemakers who want to bring struvite to their chocolate plants. The attention for climate change, expressed i.e. by the Paris climate agreement[14] and the critical attitude towards the use of fossil fuels contributes to reconsidering the use of non-renewable resources. Furthermore, Germany and Swiss have made phosphorus recycling from communal wastewater obligatory (I6, 2016; ESPP, 2017). Despite these positive (inter)national developments, Carabain et al. (2016) concluded that the behaviour and attitude of Dutch citizens was stable in the last years what means they have become neither more nor less sustainable.

4.6.2. Social acceptance

The social acceptance of struvite is related to risk perception and to acceptation of waste as resource. These two subjects have been mentioned by interviewees as barriers and are here elaborated in more detail.

Risk perception

Risks related to struvite have been shortly discussed from a policy perspective in Subsection 4.1.3 and a technical perspective in Subsection 4.2.2, Safety is not only a technical discussion but also has a social component related to risk perception. Waternet hoped they could sell their struvite to other parties than ICL when the revision of the Meststoffenwet went into force, but that didn’t work

[12] https://www.rotterzwam.nl/
[13] https://plasticwhalefoundation.com/
[14] The Paris Agreement is the first universal legally binding global climate deal, adopted by 195 countries in December 2015 in Paris with the aim to set out a global action plan to limit global warming to 2°C (European Commission, 2017)

because there were debates on ‘that it was taken up in the Meststoffenwet but actors were still not sure the product complied with the rules’ (I12, 2016). According to Interviewee 12 the risks are limited and ICL also sees no problem in using the struvite. But the Rijkswaterstaat, institute on public health and environment, questioned the safety and asked questions on whether it has drug residues in it. As Waternet is not sure how to measure the drug residues nor how to norm/standardize it, the reaction of the government is according to him is ‘if we don’t know what to do, then maybe we should not do it’ (I12, 2016). This attitude inhibits further developments. But Waternet also does not want to bring an unsafe product to the market, ‘we cannot allow ourselves to put a product on the market which is a risk to public health’ (I12, 2016). Therefore the struvite producers need to know what safe criteria for struvite are. As Interviewee 1 puts it: ‘The struvite needs to be clean and unsuspicious’ (I1, 2016). Interviewee 6 thinks that it can ‘of course help to get the fertilizers qualified according to the law but that doesn’t mean the consumer will get trust in the product on a large scale’. ‘It must be proven that it is a good product as people often choose for safety’ (I6, 2016).

Life cycle costing is another form of risk acceptance. Interviewee 11 uses LCA’s to measure the sustainability of their decisions. ‘But these LCA’s are often translated in costs related to risks. Taking risks can lead to costs, but safety also costs something. You are going to look whether you meet the norm if a treatment installation is overloaded or a machine breaks down and what the financial costs of such an event are. We look at this from a risk perspective and not from an opportunity perspective while if you talk about sustainability, you talk about chances instead of risks’ (I11, 2016).

Interviewee 11 tells in the past Geestmerambacht plant was producing phosphate grains that were used in the chicken industry. After diseases such as swine and bird flu occurred, all such materials were banned from the food industry. Everything that was used in the value chain needed to be certified and the origin needed to be known. For sewage water it is difficult to determine, although you can measure the quality by taking samples. His perception is that after these diseases more monitoring took place and these materials were not allowed in the food production process anymore (I11, 2016). Interviewee 11 thinks the mind-set has not changed since then, because if you want to use struvite in agriculture, you have to follow the end-of-waste procedure and show that the product is safe with respect to hygiene (I11, 2016).

Waste acceptance and awareness

Interviewee 12 says: ‘if you produce struvite and have arranged everything on institutional level, there is still a communication hurdle: does the general public want recovered phosphates from sewage wastewater on their soil? This could be a psychological barrier’ (I12, 2016). Also Interviewee 5 says public acceptation is a hurdle: ‘you have to be careful with the public opinion. Wastewater is dirty and we don’t want to use it’ (…) ‘agriculture preferably uses conventional methods because that does not put the marketing in danger. If the farmer uses waste and the public opinion is against him, he has a product which he cannot sell’ (I5, 2016). Water board De Dommel tried to create more awareness among the general public on the importance of closing the loop and of phosphorus recovery by letting people urinate in jars at the annual fair in Tilburg and telling phosphate would be recovered from it (De Jonge, Weijers & Van Veldhoven, 2015). From his experience the people responded enthusiastic, but also because ‘it does not affects them personally’ (I1, 2016). The phosphate problem is not of direct influence in their lives. Interviewee 3 also thinks the general public should be more involved to address the phosphate problem in general. ‘People first need to know about the phosphate problem and then they are able to make choices’. For example, product labels have phosphate on it but you don’t know what it exactly means’ (I3, 2016).

4.6.3. Guidance of the search

Guidance of the search leads to selection of technologies. Targets, visions and public opinion can give guidance to the development of struvite recovery.

Vision

Interviewee 8 says the ministry of I&E does have a vision on phosphate recovery, but does not have a quantitative goal, because it is difficult to formulate such a target. The current targets are formulated as actions. 'The core idea is to ensure that all the ways to recover phosphate become reality and to create a marketable product' (I8, 2016). The Nutrientplatform formulated an ambition plan that includes common goals and individual ambitions of the members of the Nutrientplatform. In this ambition plan the government plans to develop more international Green Deals and support circular agriculture in East and South Europe (Nutrientplatform, 2016b).

Missing actors

Several interviewees have mentioned more actors could be involved to stimulate phosphorus recovery. The chemical industry and retailers are missing according to Interviewee 3. 'We talked with the FNLI, the federation of the food industry and they say it still has to become a hot topic in the industry. They see the importance but have not been working on it nor promoted it. More could happen on awareness' (I3, 2016). Retailers could play a role by demanding sustainability requirements (I3, 2016). The chemical industry worked on phosphorus recycling in the SusPhos project, but none of these actors is active in the Nutrientplatform (SusPhos, 2016). Interviewee 5 sees opportunities for the chemical industry to become involved in two ways; as waste stream owners and as consumers (I5, 2016). Interviewee 7 says there are not many collaborations with the industry as colleagues are not willing yet to step in. 'They keep distance and are mentally not as far but I think they could play a bigger role. I think a change of mentality is needed' (…) 'And as chemical industry we should be more aware of the role we can play in circular economy' (I7, 2016). Interviewee 8 thinks it would be good if the LTO, the Dutch employers' organisation for agriculture and horticulture, joins the Nutrientplatform again, as they have done before (I8, 2016). Also Interviewee 11 thinks the agricultural sector could be more committed to phosphorus recycling (I11, 2016). Interviewee 7 thinks the retailer plays an important role in getting agriculture involved: 'do not underestimate the power of Unilever on the quality assurance. They can dictate that they want a certain amount recycled material is used. If you can get these (companies) active, I think it will be good for the market' (I7, 2016).

5 Ash

This chapter elaborates on the ash case study from six different perspectives: institutional, technological, financial, infrastructural, knowledge and social perspective. The value chain is followed by presenting information on factors influencing installation up to consumer acceptance of the product. As there is some overlap with the case of struvite, some of the perspectives are described only briefly and there will be referred to the chapter on struvite for more information.

5.1. Institutional perspective

5.1.1. Context

The context of the institutional perspective includes several elements that are described in the context for struvite, such as the Ketenakkoord Fosfaatkringloop, the CE program, the two proposals of the Kabinet, the addition of phosphate rock to the list of EU critical raw materials and the EU Fertilizer Directive. This information can be found in Section 4.1. Additional information relevant for the ash route will be described hereafter.

The Ketenakkoord update

In the Ketenakkoord of 2011 SNB expressed their vision for using their ash for phosphate recycling in 2015. This aim was not met in 2015 but the contract of SNB and HVC with EcoPhos will probably result in meeting their targets in 2017 or 2018. The aim of ICL was to use 15% of secondary phosphate in their fertilizer production and wanted to build an installation to be able to process secondary phosphate. These goals were not yet met due to technical problems in their processing.

The cadmium regulation

According to Interviewee 9 there are currently discussions on lowering the allowed concentration of cadmium in phosphate rock. This would mean the cadmium must be removed from the ores, which is expensive. Interviewee 9 says that ‘this is on its own not a problem if it would happen on international level’. ‘But studies have shown that cadmium does not accumulate in the soil so why should you lower it, our message is to keep it on 60mg. In that way you keep the mines in Africa open, because the only products that would meet the lower standards are in Russia. Then you would become dependent on them’. When the author concluded that the branch organisation of the chemical industry was putting their effort on preventing more stringent cadmium regulations other than on promoting the use of secondary resources, Interviewee 9 said ‘yes, it is for the short and longer term. If next year the cadmium standards would change, we hang. And the recycling is for the medium term’ (I9, 2016). At the time of the interview the new guidelines were not yet in a legislative proposal. However, in October 2016 a proposal was send from the Council to the delegations. Page 91 of the proposal describes the objective to reduce the cadmium (Cd) limit to 20 mg Cd/ kg P_2O_5 within 12 years after the Regulation would go into force (Council of the European Union, 2016). The Irish website the Independent wrote an article about the discussion on the draft proposal, indicating the fear exists that Europe becomes more dependent on Russia for phosphate rock and prices of fertilizers will rise (Collins, 2017). Rising prices and increased dependency due to the lower cadmium limits could serve as an incentive to increase phosphorus recycling from other sources.

5.1.2. Supporting policies

As states in Section 2.1, it is not allowed in the Netherlands to apply sludge from municipal WWTPs on soil. The sewage sludge needs to be disposed of or exported to other countries where it is allowed to apply on land. There are five routes taken for sludge disposal in the Netherlands. In 2007 was 50% of the sludge treated by sludge processors, 25% was dried and co-incinerated in power plants or in cement kilns, 15% was composted, 6% was co-incinerated in a waste incinerator and 4% went to other destinations (Ellenbroek, 2008).

5.1.3. Inhibiting policies and lack of clarity

The implications of the ETS system in Europe causes uncertainty with ICL. ETS is the Emission Trade System of the EU with the aim to reduce greenhouse gas emissions. The ETS sets a cap on the total emissions of the installations which are part of the system. Over time the cap is lowered to reduce the total emissions. Within the cap companies are able to buy or receive emission allowances for their emissions. If a company is emitting more than the amount of allowances he has for that year, a fine will be imposed (EU, 2016). Interviewee 7 explains ICL is trying to see whether they fall under the rules of the CO_2 trading system. In his opinion they should be exempted because with recycling of phosphate they prevent CO_2 emissions and mining in other countries. However, these countries are not part of Europe and fall therefore outside the ETS system. According to his opinion a local system (ETS) should not hinder reducing global effects which is less CO_2 reduction by having a factory in Europe.

Permits

Interviewee 7 talks in the interview about their plant in Ludwigshaven in Germany. On the question whether Ludwigshaven can process the ash, he explains that is not yet possible. 'It is a remarkable story. In Berlin everybody talks about recycling but when you come to the local officer, he says not in my backyard. He is delaying the process already for 2,5 years'. According to Interviewee 7 the Netherlands is doing better in that sense. Especially with the aid of Arnoud Passenier, board member of the ESPP and part of the ministry of I&E, the company ICL was able to start experiments (I7, 2016).

Heavy metals

At the moment the recovered phosphorus from ash must meet the regulatory levels for heavy metals. However, some elements such as copper (Cu) or Zink (Zn) are measurable in high concentrations. These elements are not considered in current mineral fertilizers regulations but recommendations have been given to review these elements critically (Egle et al, 2015).

5.1.4. European developments

Not only Dutch developments influence the ash route, but European developments also play a role. The ash route is more internationally oriented with SNB and HVC cooperating with the Belgium company EcoPhos but also because ICL sees market potential outside the Netherlands. The current ashes they are using comes from slaughter waste from England, but the new German ordinance on sludge provides also opportunities for ICL. In January 2017 the new sludge ordinance of Germany has been passed by the German cabinet. The ordinance makes phosphorus recovery obligatory for sewage works that have sludge more than 2% phosphorus and which are larger than 50,000 person equivalents (p.e.). The phosphorus recovery can be through phosphorus recovery from the sludge or by P-recovery from mono-incinerated sludge. If the phosphorus content is lower than 2% (dry solids), then co-incineration is still allowed. Application of the sludge on farmland is only allowed for sewage treatment plants that are smaller than 50,000 p.e. (Kabbe, 2016a; ESPP, 2017). Interviewee 7 expects more ash from Germany will be available for them to process (I7, 2016). Although ICL asked the struvite producers to comply with the REACH, for the use of ash there seem to be less problems. On the use of German ashes Interviewee 7 says ‘the product can go over the border as product, it can go over the border as waste. Our environmental permit states we can process this type of products as waste’. Also SNB thinks the new factory of EcoPhos in France is of importance for Germany because it can play a role in German phosphorus recycling (SNB, 2016c).

5.2. Technological perspective

5.2.1. Technology context

From phosphate rich ashes phosphorus can be recovered by several technologies that are currently in development. In this research only the technologies that are linked to the involved actors are described. In the Netherlands SNB and HVC have a contract with the company EcoPhos for their ashes and the company ICL has acquired the RecoPhos technology to recover phosphorus from different types of ashes.

Ash as input for phosphorus recovery

Not all ashes are suitable for phosphorus recovery. Ash, produced by sludge co-incineration with other waste, has a lower P concentration than ash from mono-incineration. In addition, the mixture of substances can make the nutrient recovery more difficult (Buckwell & Nadeu, 2016).

In the Thermphos-route the ashes needed to have a low concentration of iron (Fe/P<0,2 mol/mol) which means that if chemical phosphate recovery is used in the MWWTP, preferably no iron but aluminium salts should be used for phosphate precipitation (STOWA, 2011). The RecoPhos consortium who developed the thermal RecoPhos project was able to use iron-containing sewage sludge ashes in their pilot (European Commission, 2015b). Whether EcoPhos needs ash with a low concentration of iron could not be deduced from the data.

The concentration of P in the ash is also important for the business case. Marcel Lefferts of SNB says their fly ash contains approximately 20 to 25% of phosphate (Waterforum, 2015). Buckwell and Nadeu (2016) talk about a percentage of 2-12% of phosphorus in fly ash.

HVC says a low P-concentration in the ashes reduces the economic feasibility of the ash recovery technologies. Recovering struvite at the MWWTP reduces the amount of P in sludge and therefore in the ashes. For that reason, the water boards which are shareholders of HVC have agreed upon not recovering struvite. If struvite recovery is needed due to problems in the water treatment, HVC will receive the struvite to be able to keep the P-concentration in ash high enough to sell the ash to EcoPhos. In the individual ambitions of the Ambition plan of the Nutrientplatform, SNB also mentions the maximization of phosphate in the sludge to be able to use their sludge ashes for phosphorus recovery (Nutrientplatform, 2016c). In the interview Interviewee 1 talks about an initiative of four companies to build their own WWTP, which may include a struvite reactor. Interviewee 1 was asked whether struvite recovery at those companies would influence their business case of recovering phosphorus: ‘No, because the contract with SNB states the P-concentration should be at least 20% phosphorus and we are already on 19,6%. And EcoPhos says it does not matter whether it is 19% or 20% as long as it is constant quality. So, not 18% and the next time 20% and then again 17%, but preferably a constant quality as input. That is why they have taken the number 20% in the contract’ (I1, 2016).

Technology characteristics

EcoPhos is a wet chemical process. Ashes are dissolved in hydrochloric acid (HCl) after which phosphoric acid is produced. Most of the by-products can be sold such as $CaCl_2$, gypsum and other salts such as ferric chloride (Egle et al, 2015). The process was originally designed to extract phosphoric acid from low quality phosphate rock (STOWA, 2011).

RecoPhos[15] technology is a thermo-reductive process in which sewage sludge ash is heated to approximately 1300-1600 degrees Celsius. Phosphate in the ash reacts with carbon and silicon dioxide and is reduced to phosphorus. P and CO leave the reactor in the gaseous phase. The reduced phosphorus can be retrieved as white phosphorus or oxidised into phosphoric acid. The process produces as by-products liquid slag, molten metal and an iron P-alloy (Maurer, 2016; RecoPhos, 2017a; Egle et al, 2015).

Sustainability of technologies

For a note on sustainability of ash recovery technologies, see Subsection 4.2.1 in the chapter of struvite.

5.2.2. Product

Product quality and output

As both technologies, EcoPhos and RecoPhos, are still under development, no research could be found on the quality of the recovered phosphates from full-scale plants. Both companies will use the recovered phosphorus to produce fertilizers or other type of products.

Interviewee 7 explains they treat the recovered phosphates chemically like they do with their own phosphate. ‘Because before you give it to the plant, you need to chemically treat it to convert it to an absorbable form of phosphate. We don’t want to stimulate the direct valorisation of those products, because you don’t want to sell ashes to the farmer as those are not effective. We use it only as a resource and convert it to useful materials with a known absorption pattern’ (I7, 2016).

Pathogens, drug residues and heavy metals

Pathogens do not seem to be an issue in the ash recovery technologies. Interviewee 7 states that ‘through our processing, we can guarantee that, even if the used struvite contains pathogens, the used technologies will produce a sanitized product’. Egle et al. (2015) confirms this opinion with stating that technologies using sewage sludge ash (SSA) are able to destroy all pathogens and persistent organic pollutants (POPs), because the organic matter in the material is destroyed. But the quality of the ash can vary due to the different P concentration and heavy metal content in the sewage sludge (Egle et al, 2015).

5.3. Financial perspective

5.3.1. Financial context

Investments and subsidies

Adapting the system of ICL for the use of recycled phosphates, to make the aim for 15% recycled phosphorus input feasible, was a two million investment (I7, 2016). But building full installations for phosphorus recovery from ash requires a higher investment than struvite recovery technologies.

[15] There are two RecoPhos technologies on the market as noted by Egle et al. (2015). In Egle’s article RecoPhos® and RecoPhos InduCarb are mentioned. RecoPhos InduCarb is the process of ICL.

In 2009, Marcel Lefferts of SNB estimates the installation of a phosphorus recovery plant would cost 15-20 million euro (SNB, 2009). ICL wants to invest 150 million in RecoPhos technology installations (I7, 2016) and the investment of EcoPhos in the first phase of their plant in Duinkerken is estimated to be 60-75 million (Nord France Invest, 2015; SNB, 2016b).

High investments costs bring risks. As Marcel Lefferts of SNB states in 2009 on the possible installation of phosphorus recovery technology; ‘The question is whether we *alone* should take the risks. Perhaps there is another way of sharing the risks. After all we are talking about a problem that will affects us all’ (SNB, 2009). Also Interviewee 7 sees problems in taking high risks. As he phrases in Lommen (2010): ‘where our initiative fail is the fact that if we make investments, no one gives guarantees if a problem appears such as a company who cannot deliver their ashes anymore’. Lommen follows that ICL could make delivery contracts with companies, but here occurs a bottleneck as companies do not dare to make such contracts over longer periods, such as 10 years. And ICL wants at least to recover their investments when a company cannot fulfil their delivery contract (Lommen, 2010).

SNB and ICL have both applied for European subsidies, SNB for research on a fertilizer installation with Ashdec and ICL for an installation for using recycled phosphates (SNB, 2009; Nutrientplatform, 2015). No formal communication was found on whether the subsidies were granted or turned down.

5.3.2. Costs

Installation costs and payback period

According to Interviewee 6, costs are often the bottlenecks the industry encounters: ‘There is a gap between what is around and what is needed. You have to make costs to get from A to B and that is a barrier. It turns out to be cheaper elsewhere. You could say that for a couple of specialized processes phosphate is too cheap. It makes a lot of recovery processes less interesting’ (I6, 2016).

For the installation costs, see previous subsection. No information was found on the estimated process costs of the technologies or the payback period of the technologies from the case study.

5.3.3. Market

Profit

No data could be found on the estimated price of the phosphorus from ash. However, according to a news article, the price in 2016 was 180-200 dollar per ton phosphate (Vilt, 2016). Rock phosphate (from Morocco) was around 118 US dollars in January 2016, 110 dollar in October 2016 and around 98 US dollars per ton in March 2017 (World Bank, 2017).

As Interviewee 6 stated in the previous Subsection, phosphate is too cheap for certain processes. On the question whether the price should be three times higher, he answered that ‘having the price doubled would bring us already a lot further. It would initiate a lot of things’ (I6, 2016).

Application

White phosphorus can be extracted from ash. Although most phosphorus is used in fertilizers as phosphate, elemental phosphorus can be used in many other industrial applications, such as animal feed, detergents, fuel retardants, lubricating oil or feed additives (Schipper, 2013; I7, 2016).

Market outlook

Interviewee 7 says they expects that the future market demand of phosphate will grow 2% globally, with regional differences. West-Europe is stable and could experience a small decline due to precision agriculture and maybe East-Europa will grow a little (I7, 2016). During the interview he told about the expected enactment of the sewage sludge ordinance in Germany in the spring of 2017. In January 2017 the enactment was done (SNB, 2017). Interviewee 7 says ICL expects this ordinance presents opportunities. At the moment the company imports English ash from slaughter waste. In England there is a surplus of ash while the price of Dutch ash from slaughter waste is too high due to the fact that Dutch ash is used in the Netherlands for other purposes, such as the cement industry (I7, 2016). He emphasizes that it should be economically attractive for ICL to use such products. Their preferred cost price of phosphate is lower than the market price because ICL uses the cost price of their own phosphate from the mines as reference (I7, 2016). He expects to be able to use the Germans sludge ash in their factory and if ICL builds commercial units of RecoPhos, they can process all the available ash from Germany (I7, 2016).

Furthermore, Interviewee 7 does expect that the discussion on Circular Economy, which currently takes place in Europe, also is going to play in the USA. ‘It is already starting there but also in the Far East because all those big cities with wastewater, they are going to do something with their phosphates as they are going to realise that phosphate is an ending resource’. ‘We think we don’t only have the technology for our own needs but also something that can expand in the future. I think in the USA it is going to play in the coming five years, as we already had a discussion with the governor of New York who was really interested in the Circular Economy thinking’. ‘So in South-East Europe with all the big cities, there it will also start within 10 years, really’ (I7, 2016).

5.4. Infrastructural perspective

5.4.1. Supply

Scale of supply

The scale on which ash recovery takes place is larger than struvite. As Interviewee 7 states it: ‘For the water boards struvite is a big thing, but for us it’s peanuts (…) 5000 ton struvite of which 24% is phosphate so say 1000 ton phosphate. We work on a different scale’ (...) the current production of ICL is 900,000 tons of products’. According to Interviewee 3, also SNB sees phosphate recovery at the MWWTP as having a marginal contribution, compared to recovering phosphorus from ash (I3, 2016). The opinion of Interviewee 7 is that ‘the market needs in the first instance a bulk solution and next to that it is nice to create some niche markets’. Interviewee 9 sees the advantages of ICL in this market: ‘They have export channels, a market and can scale up. Big is not a problem’ (I9, 2016).

With the factory that is currently build by EcoPhos their total production capacity is estimated to be 600,000 phosphates (Horckmans, 2014). This includes the use of phosphate rock with low quality as input for their production process. The cooperation of HVC, SNB and EcoPhos has the intention to deliver 50,000-60,000 tons of fly ash per year (Waterforum, 2015).

On the question on how Interviewee 7 sees the coming five years, he answers: ‘Hopefully 150 million euro on the table and with that building RecoPhos units in Europe. Because with that, we can process 400,000 ton ashes and are we taking a big step forwards’ (I7, 2016). Then they can process all the available sewage sludge ash from Germany (I7, 2016).

5.4.2. System integration

Incumbent industry

The incumbent industry plays a role from an infrastructural perspective and from a social perspective. The latter is described in the Subsection 5.6.3.

Using sewage sludge ash as substitution of phosphate rock as input for fertilizer production can be integrated in existing infrastructure and can use the sales to existing markets (Egle et al, 2015). EcoPhos is able to deal with almost all types of ashes, with the only restriction of a minimum amount of phosphorus. However, the fertilizer industry is vulnerable for the varying ash quality (Egle et al, 2015). This was also mentioned by Interviewee 1, see Subsection 5.2.1, who said that EcoPhos needs a constant quality. And the case of ICL shows the use of recycled phosphates in current systems does require a little adaption. In the ICL factory in Amsterdam pilot tests were done on the use of secondary phosphates. However 'the provisional way the phosphate was put in the process, has led to a technical breakdown of several machines and the production process was interrupted' according to Interviewee 7. 'Now we have said we stop with the provisional way of working and we will create a definitive solution. At the moment the new design is engineered, which is a project of two million euro'. This is needed to make the aim of using 15% recycled phosphates feasible. 'But the system is set-up in such a way, that with that you can go to the 100% covenant agreement' (I7, 2016).

The ash recovery is depending on the sludge input which means the sludge processors are depending on the water boards for their phosphorus. If the water boards are recovering struvite, the amount of phosphate in the sludge lowers. The sludge processors can get problems with their phosphorus concentrations, because SNB and HVC made agreements in their contract with EcoPhos on minimum phosphorus concentration (Nutrientplatform, 2016b).

5.5. Knowledge perspective

5.5.1. Knowledge development

Research in the last years

Not much publications of research on the two ash technologies were found. EcoPhos is a technology developed and patented by EcoPhos (Vilt, 2016), while RecoPhos has been developed in a consortium of several companies and institutes (RecoPhos, 2017b).

Current knowledge need

No general knowledge need was identified, except for the benchmarking which has been pointed out in Subsection 4.5.2. Company specific several examples of knowledge need were identified. ICL experienced some technical problems due to the use of recycled phosphates in their standard process, see also Subsection 4.4.2. 'The final design is currently engineered, the company Tauw is working on that, we have outsourced that' (I7, 2016). And furthermore is the RecoPhos technology is not completely mature but ICL is working with several consultants who, according to Interviewee 7 'have a great deal of expertise in this field'. 'We try to build up our own group of knowledge and we hired these people for the duration of the project' (I7, 2016).

5.5.2. Knowledge dissemination

Knowledge dissemination has been described in Subsection 4.5.2. ICL and EcoPhos are member of ESPP. Furthermore SNB, ICL and HVC are members of the Nutrientplatform.

Interviewee 7 points out the value of platforms such as Nutrientplatform as he explains that 'the Nutrientplatform is an important instrument as you meet people from the value chain' (I7, 2016). Also organisations such as EFGF and Aquaminerals are important because 'it makes talking easier than communicating with individual water boards' according to Interviewee 7 (I7, 2016).

5.6. Social perspective

5.6.1. Context

The context includes the social aspect of the problem perception and drivers for involvement with phosphorus recycling. The information in Subsection 4.6.1 on the context is also relevant for the ash route, but additional information related specifically to the ash route is given here.

Problem perception

Not only new entrants have to legitimate their actions, also within the incumbent industry the ‘problem of phosphate’ is perceived differently. As part of the incumbent fertilizer industry and with their own phosphate mines, Interviewee 7 had to convince his own company to get active in recycling phosphorus. ‘We had a long internal discussion. You can imagen that for a lot of people it is a strange move you are doing when you, as a production company of its own phosphate from Israel decides to invest in alternative sources. That means closing your own mine. In Europe we have a different mind-set but I can guarantee you that for somebody who has never been confronted with recycling or phosphorus surpluses, this is a strange story’ (I7, 2016).

The perception of the problem can also lead to going in a certain direction or in other words on how the actors perceive a solution for the phosphorus problem. Interviewee 7 believes ‘the market needs in the first instance a bulk solution and next to that it is nice to create some niche markets. But first ensure that at any time your bulk is in order’ (I7, 2016). He relates it to what he sees in the market. ‘There are struvite producers that make really nice products such as Ostara (the Pearl technology) but they are starting to get a problem. They are getting more capacity but the niche markets are getting fulfilled which means they will have to go commodity with a product with a high price and that is a new challenge for them’ (I7, 2016).

Even if the problem is acknowledged, priorities can differ. Interviewee 7 explains they talks with other companies (such as food industry) and try to make a connection with them by using other topics that are more important to those companies such as CO_2 emissions. ‘But they have of course their plate full with all the things they are working on. I understand their situation also. They are not only busy with the fertilizer industry, they have a thousand things on their plate’ (I7, 2016).

Drivers and trade-offs

In Subsection 4.6.1 sustainability was mentioned as a driver for phosphorus recycling. Interviewee 9 has another opinion. ‘No company is really sustainable, they do it only to make money’. Sustainability is more a strategy. ‘There are two successful companies at the top of the Sustainability Index, they see sustainability as a chance. There is no chemical company that doesn’t think we should do something with it’ (I9, 2016). Interviewee 7 thinks you see at Dutch companies the mentality of seeing chances. ‘Maybe the legislation around CE and recycling is complex, but it also offers opportunities. And Dutch people try to grab those opportunities’. His colleague agrees: ‘It is indeed noticeable that here it is perceived more as an opportunity rather than something that needs to be done (I7, 2016).

The interview with the fertilizer producer shows the phosphorus recycling is also moved by strategic motivations. The fertilizer producer is using 30-36,000 tonnes of elemental phosphorus per year but does not have elemental phosphorus production themselves. This means that downstream processing depends on a couple of suppliers from ‘not the most ideal countries, such as China, Vietnam and Kazakhstan’ as Interviewee 7 puts it. ‘There is a limited group of players and clear coordination, but you cannot accuse them of cartel formation. Nonetheless it stays a small market involving distant countries which means long distances for logistics and uncertainty. In Vietnam and

China because of the political environment for example'. 'If the Chinese have a wild idea, they can raise the export tax with 20% and the day after they can lower it again. You are the ball in game of the political system in a country far away and that is not a nice idea. That is also our strategic motivation, if we are able to produce P_4 ourselves that would be good. Our own phosphate sources cannot be used for that, but if we can make a high value product from waste, we are a good example of Circular Economy. And this fits the whole EU discussion' (I7, 2016).

Interviewee 6 explained the driving force behind the actions of Thermphos. 'They were the only company that produced phosphorus but did not have their own mine. Which means once every few years the phosphate rock needed to be acquired and it was getting more expensive and the quality was getting lower. Thermphos started to think why they imported phosphate when phosphorus could be found in waste. For a long time it was an ideology "maybe we should do something with it" and lets map it. Until the phosphate price suddenly exploded and it became economic viable. It was the only way to keep the industry alive in West-Europe so it become the policy' (I6, 2016).

Landscape developments

See struvite Subsection 4.6.1 for more information.

5.6.2. Social acceptance

Waste acceptance

When talking about the public perception and awareness of recycled phosphorus, Interviewee 7 explains that they does not advertise with having recovered phosphate in their products. 'At this stage of development recovered phosphate is not a wish of the client. Actually, if you don't take care, it could even work the other way around. And from that perspective you can see that also in the Netherlands the mind-set still needs to shift' (I7, 2016). He says 'in Germany they have a nasty slogan which states "Kein brot aus kot", which means no bread from shit. That is where the mind-set starts, so you need to make clear you are talking about very normal products. For example the buyer of pure phosphoric acid for the coke (cola) industry: we are not sure whether they want this phosphoric acid recovered from ashes' (I7, 2016). Interviewee 7 says 'transparency is very important. Be open, to both government and consumer, on what we do and in no way put our reputation at stake. Reputation has too much worth for us, because we are fertilizer farmers' (I7, 2016).

5.6.3. Guidance of the search

As there is overlap with the struvite case, see also Subsection 4.6.3.

Incumbent industry

Both Interviewee 7 and Interviewee 9 characterise the fertilizer industry as conservative (I7, 2016; I9, 2016). As an example, VNCI lobbies to prevent more stringent Cadmium rules for phosphate rock. Interviewee 9 admits that prevention of Cadmium regulation is short-term thinking while the actions of ICL are more long-term oriented (I9, 2016). On the question what the other members of Meststoffen NL, the branch organisation of the fertilizer industry, are doing, Interviewee 7 answers: 'it goes slowly, but for example Yara is starting thinking circular'. 'We try to be transparent with respect to our colleagues because we do not mind if colleagues are also becoming active in this field. The other way around, we see it as an advantage but there are not yet colleagues who want to step into it yet. They are mentally not as far' (I7, 2016).

6 The analysis

This research has the aim to identify barriers that hinder phosphate recycling via the communal water chain. First, a recap on the Dutch situation is given. Second, drivers and incentives for phosphorus recycling are extracted from the available data in chapter 4 and 5 and described in Section 6.2. This section is followed by a comparison of the theoretical barrier list with the collected data in Section 6.3. This results in identifying the most important barriers for both routes in Section 6.4.

6.1. Summary of the Dutch situation

Hereunder a short overview is given on the phosphorus recycling methods that have been identified in the last two chapters.

The wastewater enters the MWWTP which can have biological treatment system, chemical treatment system or a combination of both. The phosphate entering the biological treatment system can be recovered in the form of struvite from the aqueous phase or from the sludge phase. The efficiency is 10-40% of the phosphorus inlet. Some of the phosphorus, about 20%, will leave the MWWT in the effluent. The quality of the struvite produced depends on the technology used. So far only the Pearl technology delivers an EG-certified struvite that can be used directly as fertilizer in agriculture. To be able to use the other types of struvite in agriculture, an EoW status and compliance with the REACH regulation is needed. At the moment Waternet has their struvite REACH certified and is selling the struvite to ICL as input for fertilizer production. Water board Vallei & Veluwe has almost completed their REACH registration for the struvite produced in Apeldoorn (I12, 2016). The struvite of Apeldoorn is also commercially sold (Peters, 2017).

For both treatment systems, the phosphate that is not recovered ends up in the sludge. The sludge can be used among others in electricity production, cement kilns, but for phosphorus recovery the sludge will need to go to HVC and SNB, the sludge processors. The sludge that is burned via mono-incineration will be sold to the company EcoPhos, with whom SNB and HVC have a contract. ICL will also be able to process sludge ash with their RecoPhos technology that is currently further developed, but has no contract with the Dutch sludge processors. ICL is currently processing English slaughter waste ash in their facility. Both ICL and EcoPhos can extract pure phosphorus from the sludge ash, which can be used in the chemical industry or further processed into fertilizers for agriculture. Figure 17 shows the current phosphorus possibilities with the involved actors.

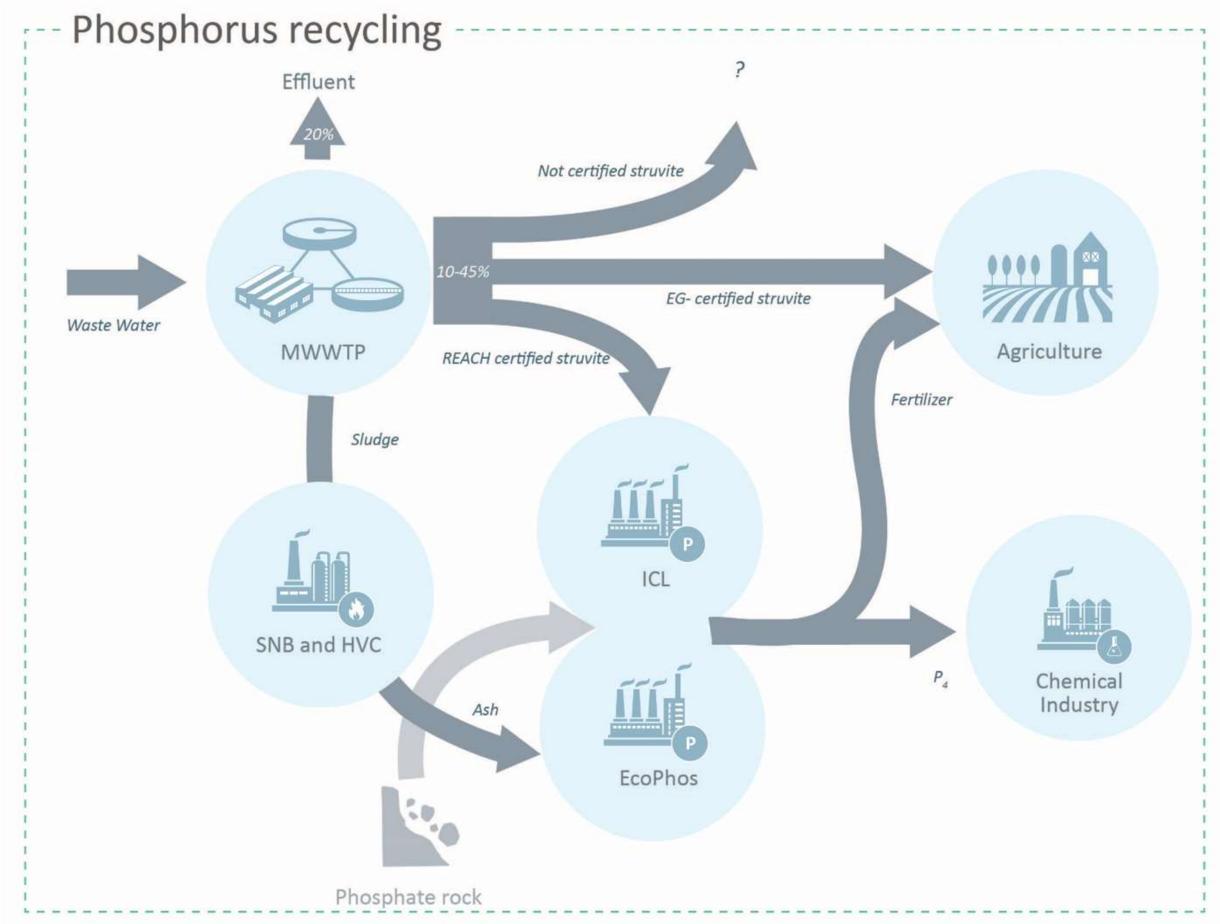


Figure 17. Summary of two routes including important actors in the value chain

6.2. Driving forces

In the introduction three main motivations were given on why phosphorus recycling is needed. These were the scarcity perspective, the dependence of Europe on non-EU countries for phosphate and the environmental impact of mining. In this Section the stimulants and incentives that enable phosphorus recycling in the Dutch communal water chain are identified more in-depth. These stimulants are both on international and Dutch level and the actors themselves have incentives to be active with phosphorus recycling.

6.2.1. International context

At EU level there is a growing awareness of the need for sustainable practices. The interviewees noticed this as well. Interviewee 10 'sees a growing movement in that area. 5-6 years ago companies said a lot but did not do much and now you notice that companies really want sustainability'. He mentions the climate agreement of Paris[16] as an example where many parties advocate for climate actions and are take a step further than the government (I10, 2016). Interviewee 8 sees phosphorus developments in Europe and points out that Germany and Denmark are working on phosphorus recycling and France and Belgium a bit. He thinks Germany is technological very strong but for Germany it is more difficult to get things started, so the Netherlands is further in the development. The European developments such as the addition of

[16] The Paris Agreement is the first universal legally binding global climate deal, adopted by 195 countries in December 2015 in Paris with the aim to set out a global action plan to limit global warming to 2°C (European Commission, 2017)

phosphate rock to the list of critical raw materials and the initiatives to get recycled phosphates such as struvite in the EU Fertilizer Directive are a sign the European Union is acknowledging the importance of phosphate and supports recycling of phosphate. Swiss and Germany have even made phosphorus recycling from communal wastewater obligatory (I6, 2016; ESPP, 2017). The foundation of the ESPP and projects such as SusPhos, P-REX and consortium around the RecoPhos technology show phosphorus recycling in general has attention within the EU and not only by government or institutes, because also many companies are involved.

6.2.2. Dutch context

Interviewee 3 sees several drivers for closing the phosphorus loop. 'These are independence of phosphate from mines, reducing the environmental impact related to mining and of transport. Local phosphate would be better. Another driver is the fluctuating price of phosphate and the scarcity perspective. The fourth pillar is the environment, because due to the phosphate surplus the water quality is leading to eutrophication and we need to do something about that' (I3, 2016). The Dutch context gives two more stimulant for phosphorus recycling; the attention for CE and the manure surplus as one of the sources of the phosphate surplus in the Netherlands. Interviewee 8 says he sees CE is really a point of attention for companies. Also big companies are looking what they can do with it. 'I think the Netherlands is strongly encouraging CE, especially for phosphorus recovery. They enable that and apply it'. He believes Dutch companies are in general willingly and are able to see opportunities. Furthermore he states that Dutch companies have a lot of knowledge in this area, so it would be good to look if the Netherlands is able to get real economic advantage of the situation. The Netherlands should go international, to start with Europe but he also says Canada and the USA are interested (I8, 2016). Interviewee 7 points out that it was not only the wish for sustainability that stimulates the phosphorus recycling in general. 'In the Netherlands everything happened rapidly because we have a surplus problem and even to such extent, the surplus problem is threatening our stock of cattle. There is an economic incentive to lead the discussion' (I7, 2016). The awareness of the subject led to policy actions such as the revision of the Uitvoering Meststoffenwet, see Subsection 4.1.3, but also to the creation of Green Deals and the Ketenakkoord Fosfaatkringloop. These two in itself became drivers for the involved actors to stay committed. One of the tasks of Interviewee 4 is to see whether the ministries and the UvW are keeping themselves to the agreements in the Green Deal (I4, 2016).

6.2.3. Incentives of the actors

An incentive is the expected benefit of an activity, for example struvite is recovered to prevent scaling in the pipelines and thereby reduces maintenance costs. The incentives of the actors to be involved with phosphorus recycling are varying but most of the actors are motived by social, financial or institutional drivers.

<u>Water boards:</u> The water boards have several incentives for phosphorus recycling. Interviewee 11 formulates it as follows: 'You have to show that it is possible, that is the role you have as a government. And maybe with that, you stimulate the phosphorus recycling at other places where it can have more impact'. But the incentives are not only socially motivated. The Green Deal is an institutional driver, as Interviewee 11 mentioned the Green Deal as a driver to take action and look for opportunities to recover phosphorus at their MWWTP. Also the discharge requirements for discharge treated wastewater on surface water acts as an institutional incentive. As Interviewee 11 explains about their plans for struvite recovery at Den Helder: 'Den Helder has central dewatering and a collective place for sludge, you can expect a high concentration of phosphorus. And that was the case and such high concentrations we were not able to meet the discharge requirements. And then you combine the chance to do something with the need to meet the standards'. Interviewee 6 shows another perspective on the incentives of the water boards. He says the water boards see it as a form of creating legitimacy for their existence. With phosphorus recycling the water boards can

show they are important and needed (I6, 2016). Interviewee 1 says struvite recovery is pure a necessity for maintenance, because if you don't do it, the pipes will get obstructed with struvite (I1, 2016).

Industry: For the industry the drivers seem different. According to Interviewee 6 the driver for the industry is 'the battle to survive or also to show they are useful, and anything in between'. But he also mentions Thermphos as example. 'For Thermphos it was a long time an ideology to do something with phosphorus from waste until the phosphate price enormously increased and it became economically viable' (I6, 2016). His sayings show there are both social and financial incentives. Interviewee 7 gives in his interview also two types of incentives. On the one hand he says: 'You can throw the phosphorus away, you can put in cement, do nothing but it is better to recycle it', which shows there is a social motive to be active with recycled phosphate, but on the other hand he clearly states there is a financial aspect. Our company uses elemental phosphorus in their fertilizer production, but does not have their own production of elemental P. This means they are depending on suppliers of 'not the most ideal countries such as Vietnam, China and Kazakhstan. You are the ball in the game and that is not a nice idea. That is our strategic motivation' (I7, 2016). Interviewee 10 mentions that for industrial parties with waste streams the motivation to recover struvite at their plants is driven by the wish to reduce discharge costs related to phosphorus concentrations in their effluent and not the recovery of struvite itself' (I10, 2016).

Government: Interviewee 8 told the new building of the Ministry of I&E will have a toilet with phosphorus recovery. He says: 'You should see it as an example project. It does not have much impact, but you have to show the government is also doing it. Corporate social responsibility also applies to the government' (I8, 2016). 'We think it is important to operate together with society, with parties that want the same and the most important actors around the recovery of phosphate are in the Nutrientplatform'. The latter is also the reason why the Ministry of I&E is member of the Nutrientplatform.

Others: Different type of companies and institutes have joined the Nutrientplatform, but the drivers are divers. Some (of the new) members join from a personal ambition related to phosphorus recycling, while others join to show their sustainability vision. The first members were mostly the owners of the waste streams, while now also smaller parties join who see other types of business opportunities (I3, 2016).

6.2.4. Conclusion

The current amount of struvite installations, the developments on ash recovery and the examples of cooperation, such as Waternet and ICL, are showing the phosphorus recycling in the Netherlands is on the right track. The attention for Circular Economy and the Green Deals led to action and as the history in Section 2.4 shows the last years 5-6 struvite installations has been build. By the acquiring of RecoPhos by ICL and the contract of HVC and SNB also steps are taken to recover phosphorus on larger scale. Furthermore has phosphorus recycling gained attention in the political arena as can be seen by the proposals of Dijkstra and Mulder and the revision of the Uitvoeringsbesluit Meststoffenwet, see Subsection 4.1.1. Furthermore there is an active Dutch network created in the form of the Nutrientplatform of which producers, government and other interested parties are member. When looking at these aspects, it seems there are enough reasons to believe phosphorus recycling will grow in the coming years. However, despite these driving forces, the phosphorus recycling is only growing slowly. Therefore in the next Section the barriers are analysed to find opportunities to increase the use of recycled phosphorus.

6.3. Barrier analysis

Although there are driving forces for phosphorus recycling and the current involved actors are motivated to take action, there is still growth potential for both routes. Therefore an analysis of the barriers hindering the further growth of phosphorus recycling has been done. This analysis will answer the third research question:
"Which barriers are experienced in recycling of phosphorus through the Dutch communal water chain?"

6.3.1. Method for interpretation of barriers

In Chapter 3 a list of barriers was compiled with the aid of theoretical literature. The complete table can be found in Section 3.5. This chapter compares the barriers found in literature with the findings from the case study. If the barriers are experienced differently for the struvite or ash route, the barrier is described more in-depth per route. Per barrier is first described what the barrier means, secondly data of the case is given and thirdly the data is interpreted on whether the barrier is experienced as weak, medium or strong in the case study.

The interviewees have a broad range of backgrounds. The interviews were aimed at their field of expertise. As a result the interviews had different subjects and not all barriers type have been addressed in each interview. Secondly, the barrier list itself was not used in the interviews. This means no quantitative measuring of the barriers is possible and the analysis requires often an interpretation of the author. To guide the assessment of the strength of the barriers, the following guidelines are used.

The following criteria are used to rate the barriers:

First, did the subject come up in the interview? If yes:

- To what extent do the interviewees denote the barrier as being a problem:
    - If the interviewee mentions the words 'barrier, problem or negative effective' the barrier is rated as highly relevant for the actor. If these words were not specifically used, the author assesses its significance.
    - The following two criteria, if applicable, contribute to deciding whether the barrier is 'medium' or 'strong'.
        - Does it influence the whole value chain or only specific actors?
        - The scale on which the barrier is active. In other words, whether the barrier plays on regional, national or European level.
- If the barrier topic is brought up in the interviews, but the barrier is not mentioned as a problem and the data shows no indication of the presence of that barrier, the barrier is 'weak'.

If the barrier topic was not addressed in the interview:

If the barrier is not addressed in the interviews nor specifically mentioned in the desktop study, there are two options:

- When the barrier did not come up in the interview, though it could be expected to be brought up, and there is no other data indicating this barrier exists, the barrier is regarded 'weak'.
- When it is plausible the barrier did not come up in the interviews and is therefore not discussed, while there are reasons to believe the barrier could play a role, the barrier is rated 'unknown'.
- When the barrier seems to have no link at all with the case study or is not applicable, the barrier is also rated 'unknown'.

6.3.2. Institutional barriers (I)

Barrier 1: Low alignment or non-compliance with current legislation

Low alignment with current legislation can create legislative hurdles towards market entrance.

Struvite

In the case study several examples of low alignment with current legislation or unclear complex legislation were found. The legislation around pathogens and drug residues in products, the End-of-waste (EoW) status, the REACH declaration and the EU Fertilizer Directive are priority issues that have been mentioned by actors in the struvite value chain. These regulations are interlinked, as explained in Subsection 4.1.3. The lack of clarity on criteria for pathogens and drug residues in struvite lead to problems with getting a national EoW status. There are no European criteria for EoW status for products from wastewater treatment. A revision of the EU Fertilizer Directive could lead to a new category for fertilizers and if criteria of this new category are met by the recycled phosphates, the product would have automatically an EoW status. The pathogens issue does not play a role for struvite reactors of the type Pearl technology as they produce an EG-certified product. For the other technologies such as AirPrex and NuReSys, an EoW status and REACH declaration must be obtained to be able to sell the struvite, although the presence of pathogens is not a problem when the struvite is sold to ICL as the pathogens are killed in their processing. The revision of the EU Fertilizer Directive is seen as a solution that can bring struvite recycling further by the addition of struvite as a fertilizer. The revision would in addition also enable the change of the Organic Farming Directive and allow recycled struvite to be used by organic farmers.

The interviewees say the following about these topics: Interviewee 5 mentions the unclearness of the guidelines on pathogens and drug residues and says ‘for the use in agriculture this plays a role and you want clear requirements’. In the same line Interviewee 4 says ‘the problem is that there are no official criteria for drugs. At the moment we encounter the problem that we do not know how to deal with this’. Interviewee 8 says: ‘you also face the European regulations and for struvite that is already a problem, because at the moment it is not in the European Fertilizer Directive. There are two hurdles for struvite; can you use it as a fertilizer and does it has a waste status? And in the slipstream of the latter you will find related obstacles’. Interviewee 8 says it would help if ‘you can put it as a free marketable product in the European market’. Interviewee 3 mentions also the EoW status by stating that ‘applying for the EoW status is quite complex, the idea is this should be harmonised between countries in Europe’. Interviewee 1 gives an example of the effects of having a waste status: ‘If that is the case, you can try to get it back in the cycle but there is no one who wants to buy it or it ends in a certain cycle where it is a waste product while actually it is a valuable product (...) it is important to look at the legislation to be able to market our products outside the Dutch borders and therefore is it important that it is not seen as a waste anymore’. Interviewee 12 tells about his experiences at the water board and said: ‘When the new (Dutch) Meststoffenwet was adjusted, we thought we could sell our product. However, that did not succeed as there was quarrelling on whether the product fulfilled the criteria although the product was included in the Dutch Meststoffenwet. You have to show your product is not waste anymore and then you are really depending on the EoW status. We are talking with the ministry of I&E about the criteria for the EoW status to be able to get that status. Everything dependents on the EoW to put the material on the market’. Interviewee 4 states there are three barriers for struvite: ‘the current EoW status, because it hinders the reuse and valorisation. Secondly the quality standards differ per member state of the EU which leads to an unequal playing field. And thirdly, there is no generic approach for resources as there are different obligations for different nutrients’. Interviewee 7 who wants to use the struvite for their fertilizer production says ‘the capacity is there, but we want them (the water boards) to work according the rules and then you need to come with REACH declarations’. Interviewee 6 is more sceptic about the impact of the legislation: ‘well, for sure it will help, but in the Netherlands it is not something where we can expect a lot from, although it is always better if it's allowed than if it's not'. The report of the EU on circular approaches to phosphorus states 'the complexity of existing regulation concerning recycling and reuse are a significant obstacle to developing a market for nutrient recovery technologies and for recycled nutrient products' (European Commission, 2015b).

The interviews show the low alignment of struvite with the current legislation is hindering the marketing of struvite. The actors have specifically named the low alignment a problem and a barrier. It regarded relevant by different types of actors along the value chain of struvite. It influences the whole value chain as it concerns the marketing of struvite and this barrier plays at European level as it influences the European market.

In conclusion, this barrier is rated strong for struvite recycling.

Ash

The EoW regulation does not give problems for Interviewee 7: 'the ash can go over the border as a product, it can go as waste, and we are allowed to use the material as waste in our environmental permit'. Interviewee 7 gave an example of permit problems in Ludwigshaven: 'everyone wants recycling but if you come to the local officer in Ludwigshafen who has to give the environmental permit, he says not in my backyard. He is already hindering the process for 2,5 years'. But Interviewee 7 praises the attitude of the Dutch government, especially Arnoud Passenier, who supported them in creating space to experiment with legislation'.

For the ash-route the low alignment does not seem to be a big barrier. Only one actor in the ash value chain has been interviewed and therefore it is unclear to what extent these issues play for the other routes. But the lack of permits can have a big influence as they are required for the installation of technologies.

In conclusion, the low alignment for the ash route regarded as a medium barrier.

Barrier 2: Low level of lobbying

Lobbying 'allows citizens groups, associations, labour unions, corporations and others to be heard in the political arena' (Berg, 2009). Lobbying is important for reducing formal institutional barriers such as legislation, but it also important for increasing resources directed to phosphate recovery. Active lobbying can speed up the progress of changing legislation but lobbying of incumbent industry can hold back policies changes.

Struvite

The UvW represents the water boards and they keep in contact with the ministries of Infrastructure & Environment and Economic Affairs. They urge the government to adjust the legislation, thereby referring to the agreements in the Ketenakkoord Fosfaatkringloop and ask the Kabinet to adopt a similar point of view when addressing the European legislation, specifically the revision of the EU Fertilizer Directive (Glas, 2013). The Nutrientplatform is member of the ESPP and the ESPP lobbies on international level for phosphorus recycling. As an example sent the ESPP a proposal for the EU fertilizer regulation on the criteria for recovered struvite to the EU Commission (ESPP, 2015a). During the ESPP conference in 2015 policy action proposals were formulated including: *Carry through the revision of EU Fertilizer Regulation, define national/regional objectives and action plans for phosphorus efficiency, reuse and/or recycling and in particular a target for phosphorus recycling from sewage, and add phosphorus-in-general as EU critical raw material, in addition to phosphate rock*. *Harmonise EU regulatory framework and policies. And implement data monitoring of phosphorus mass flows at regional and national levels*. At the moment of the interviews Arnoud

Passenier of the ministry of I&E was the president of the ESPP and did his best to stimulate the removal of obstacles (I4, 2016). It seems the current lobby is mostly focused on the EU Fertilizer Directive as the revision can stimulate the recycling as seen in institutional barrier 1. On the question who is involved with the EU Fertilizer Directive, Interviewee 4 answers: ‘Agriculture is involved, we are involved. The Joint Research Centre is researching struvite if it can be taken up in the revision and the UvW tries to contribute to that with providing information. Everyone who has some interest is involved’.

No actor has mentioned lobbying as a problem. Lobbying is done by water boards through UvW and by all the actors via the Nutrientplatform, on national and European level.

In conclusion, the current level of lobbying does not seem to be hindering the recycling of struvite and the barrier is regarded as weak.

Ash

The collaboration of SNB and HVC is actively promoting their technology by press releases and news articles. ICL and EcoPhos are part of the ESPP and through this channel involved in EU lobbying. Interviewee 7 said ICL is lobbying for ETS- exemption, but this discussion is still in Brussel and ‘there is still a bit of lobby to do’. Interviewee 9 says the VNC I is trying to change legislation and open subsidy programmes for sustainable initiatives. On the question how lobby takes places he answers ‘with VNCI, Meststoffen NL, Nutrientplatform and the EU equivalent. On different levels lobby takes place’. On the other hand Interviewee 9 tells the chemical industry branch organisation lobbies to prevent getting more stringent limits for cadmium in phosphate rock because it will impact the industry. But more stringent standards could support phosphorus recycling so indirect the lobby against the more stringent limits could be seen as counterproductive for phosphorus recycling. Interviewee 7 points out that they don’t have a big lobby organisation but that the story of the recycled phosphate is attractive and they use that. He said they had never before so much visits of ministers and officials.

No actor has mentioned lobbying as a problem and the interviews and data show that lobby takes place on national and European level. The lobbying is done both by the actors themselves and via Nutrientplatform and ESPP.

In conclusion, the barrier for the ash case is considered weak.

Barrier 3: Absence of regulatory pressures

Regulatory pressures can create direct demand for certain products or stimulate the supply side.

There are regulatory pressures to remove phosphate from the effluent by means of the Kaderrichtlijn Water which stimulates phosphate extraction from the wastewater, but there is no obligation to recover this phosphate to be used for other purposes. From a user perspective there is also no regulation making the use of recovered phosphate obligatory. Other countries have targets such as Switzerland that wants to make phosphorus recovery from sewage sludge obligatory and Denmark that wants to recycle 80% of the sewage phosphorus by 2018 (ESPP, 2015b). Also Germany is making phosphorus recovery obligatory through the sewage sludge ordinance. The phosphorus recovery can be through phosphorus recovery from the sludge or by P-recovery from mono-incinerated sludge (Kabbe, 2016a). These examples can stimulate setting objectives for the Dutch Government. The Nutrientplatform is talking to the ministries of I&M and EA to talk about mandatory blending of a certain percentage of recycled phosphates for the fertilizer production, but Interviewee 3 is not sure such a rule would be possible and what the impact of this measure would be and whether it is really needed (I3, 2016).

Interviewee 7 sees potential for the use of regulatory pressures. As he formulates it ‘you can create a good reputation with quality and transparency and build up a pull-situation. On the other side you can start a push movement with changing the legislation like in Germany. Together they can bring about a considerable impact’. ‘The government could guide by stating that phosphate producers should at least use 10% recycled phosphate’. When he was asked such a target was desired, Interviewee 7 answered ‘yes, but a couple of colleagues do not want that because they are not as far’. On the question whether more regulation for secondary materials is needed, Interviewee 9 answers ‘yes it can help but it should be done at European level or on global level’. Interviewee 6 says it is a shame that phosphate in fly ash can end up in concrete and sees a role for the government to state that such practices are not allowed anymore. The P-REX project concluded that for wide-spread implementation a realistic and reliable European phosphorus recovery target and an obligation for national action plans for phosphorus recovery is needed (P-REX, 2015c). These statements imply the absence of regulatory pressures is inhibiting the growth of phosphorus recovery (European Commission, 2015b).

There are currently no EU or Dutch regulatory pressures for recycling phosphorus. The interviewees did not formulated this barrier as a problem, but they do think the regulatory measures could speed up recycling. One interviewee doubts whether it would be necessary as the effect of such measures can vary. Not all interviewees know what the impact of such measures would be and there seems to be preference for EU regulation instead of Dutch regulatory measures.

In conclusion there are no regulatory pressures identified. The interviewees imply regulatory pressures could stimulate the phosphorus recycling, but it is not mentioned as a requisite for phosphorus recycling. For that reason the barrier is considered medium for both routes.

Barrier 4: Regulations change slowly

Slowly changing regulations inhibit phosphorus recycling if change of legislation is needed.

Struvite

From institutional barrier 1 it became clear change of legislation is desired to stimulate the growth of phosphorus recycling. Three examples of how slowly changing legislation is affecting the phosphorus recycling were found. First the revision of the EU Fertilizer Directive which is taking several years. Interviewee 3 is hoping that this main legislative hurdle, regarding the end-of-waste status and CE-labelling, will be dealt with in 2-3 years (I3, 2016). Second, the introduction of the category ‘recovered phosphates’ in the Uitvoeringsbesluit Meststoffen which took one year longer than expected. When the Airprex installation in Echten was realised in September 2013 a delegation of the ministries Economic Affairs and Infrastructure& Environment visited the site and stated they expected to have struvite accepted as fertilizer by the 1st of January 2014 (Das Mooi, 2013). Eventually this took one year longer as that didn’t happen until 2015. Interviewee 10 mentions the fiscal system as a barrier. He says ‘the revision of the tax system is a lengthy process. Adjustment of fiscal systems takes years’.

Ash

For the ash route, the slow procedure for receiving a license to build the ash installation was mentioned as a problem. Interviewee 7 explained that the local official in Ludwigshafen (Germany) who has to give the environmental permit is holding up the process already for about 2,5 years (I7, 2016). Interviewee 7 was more positive about the Dutch government and the role of Arnoud Passenier: ‘Things went quite fast. They have done that good I must say’ (I7, 2016).

The interviewees did not specifically name the slow changing regulation as a problem, but they did mention the fact that the legislation is changing slowly when talking about inhibiting policies. The slow progress of regulatory issues is experienced at EU, national and regional level. The slow changing policy is affecting the marketing of struvite and the installation of the ash recycling technologies.

To conclude, although the slow change is not specifically mentioned a problem, the impact seems to hinder the recycling. Therefore the barrier is rated medium for both routes.

Barrier 5: Lack of clarity on how to use waste hierarchy

The waste hierarchy is a strategy from the Waste Framework Directive (Directive 2008/98/EC). The waste hierarchy is used in policy strategies and applies the following priority order: prevention, preparing for re-use, recycling, recovering and disposal. Member states of the EU are encouraged to choose the options that deliver the best overall environmental outcome. Life-cycle assessment may require departing from the waste hierarchy if lower strategies are more environmental friendly.

The only data on the waste hierarchy impacting phosphorus recycling was the notion of Buckwell and Nadeu (2016) that using the waste hierarchy can lead to policies aimed at reducing waste flows. The risk for phosphorus would be the decrease of high phosphorus containing waste streams. Although the waste hierarchy in itself did not came up in the interviews, it can be expected that this barrier could play a role for further growth of phosphorus recycling, therefore the barrier is rated unknown.

Barrier 6: Recycling rates focus on quantity and not on quality

Obligatory recycling rates are an example of regulatory pressures. In waste streams such as paper, metal, glass and plastic are minimum recycling rates defined by the EU Waste Directive (2008/98/EC). Setting a high recycling rate on phosphorus can have effects on the chosen technologies and strategies. In practice this can lead to trade-offs between a high-quality product with low recycling rate or a high-recycling rate of low value products.

Struvite recovery technologies can provide direct substitutes for a certain type of fertilizer while for the ash route more steps are needed to come to the end-product. Struvite has a lower recycling rate than phosphorus via ash recycling.

At the moment there are no obligatory recycling rates present for phosphorus and therefore the strength of the barrier is unknown.

Barrier 7: Cartel formulation legislation hinders collaboration between companies

A cartel is a group of firms that make agreements, for example on prices, at the expense of competitors. Making agreements between companies in order to enable or stimulate recycling could be hindered by legislation on cartel formation.

The interviews and desktop study did not provide information on this barrier, what means the barrier strength is unknown.

Barrier 8: No CE standards for products

In the literature this barrier means the lack of standards to what extent a product is contributing to Circular Economy. In this case study, the lack of standards on the quality of recycled products came forward. Hence this barrier is described according to the second interpretation of this barrier.

In general there is a lack of uniform standards in the recycling market according to Interviewee 4. ‘There are different quality standards by country, which means there is no level playing field. There is also no generic approach for resources. There are different obligations for the various nutrients'. 'At the moment you need documents for every material, for every application'. She understands that quality assurance is the most important but she pleads for an easier way. The UvW was hoping there would come European criteria on this subject, but the EU put it back in the hands of the member states (I4, 2016).

Struvite

As described in 4.1.3 the missing standards on pathogens and drug residues in struvite are creating problems with certification and trade. The vague regulations cause uncertainty for the involved actors, both supply and demand, on the safety of the product. Waternet experienced problems with the vague standards for struvite as described in the Uitvoeringsbesluit Meststoffenwet, because although the struvite was taken up in regulation, there was quarrelling on whether the product qualified. Because there were no clear standards for pathogens and drug residues, it was unclear which criteria need to be fulfilled to put a safe product on the market. With the consequence, as Interviewee 12 stated, 'eventually we were tired of the fuss because the amount of struvite in the storage grew and choose to get a REACH declaration and sell the struvite to ICL' (I12, 2016). In institutional barrier 1 Interviewee 5 and Interviewee 4 noted the problems with not having clear criteria on pathogens or drug residues standards. Interviewee 4 explicitly says 'the problem is there are no legislative criteria for drug residues'. Further Interviewee 1 mentions the missing quality criteria; 'The worry is of course on the moment you have a product, that it is clean and unsuspected. And then you have those quality criteria, a kind of certification, or how should you do that because it has not been done before'.

The EU noted also the need to have quality criteria set, especially regarding the thresholds for impurities (European Commission, 2015b).

The lack of standards is described by several interviewees as a problem in struvite recycling. It influences the direct marketing of struvite to agriculture and also plays a role in receiving an EoW status for struvite. This problem plays EU-wide as there are no European guidelines.

In conclusion, this barrier is strong for reusing phosphate via struvite production.

Ash

For ash no problems were mentioned by the interviewees. Although there are concerns about heavy metals in ash, the phosphorus from ash is used in fertilizer production. For those fertilizers there are regulatory standards. Nonetheless, not for all potentially hazardous elements there are regulations and Egle et al. (2015) ask for a critical review for other elements such as Cu and Zn.

So far none of the interviewees mentioned the lack of CE standards as a problem and this barrier is rated weak for the ash route.

Barrier 9: CE is not integrated in innovation policies of the government

The lack of integration of CE in innovation policies can hinder CE initiatives.

Interviewee 4 explains: 'the CE package of Brussel (the European CE package) states we think CE is very important. Everyone thinks CE is important but the concrete legislative proposals are proposed in other legislation, such as the Fertilizer Directive'. 'CE is very broad. Everyone has an opinion, everybody knows about it but it is difficult to make it concrete'. Interviewee 2 sees the government is acting risk avoiding when there are uncertainties. 'That is understandable but if you keep doing that and not making a step at a certain point, you will turn any innovation down'. The ESPP thinks this is an important barrier, they state : ‘without a European policy framework, companies will not have confidence to invest and recycling economics will not enable job creation’ (ESPP, 2015b).

The interviewees did not mention the lack of CE in innovation policy, although Interviewee 4 points out it is difficult to get clear CE policies. The remark of Interviewee 2 is related to the attitude or role of the government and not necessary the lack of CE in innovation policies.

In conclusion, to what extent CE principles are good integrated in innovation policies is unknown and therefore this barrier is rated unknown for both routes.

Barrier 10: No clarity on ownership, liability and responsibility in new business models

New business models are selling a service such as ‘providing nutrients’ instead of selling products. In the case of phosphorus recycling such new business models could raise questions on who is liable for negative side effects of the product or who is responsible for leaching of nutrients.

In the case study no indication of the use new business models was found. Therefore is concluded that for both routes this barrier does not play a role in the current situation and as a consequence the barrier is unknown.

Conclusion institutional barriers

Table 2. Conclusion of institutional barriers

Institutional	1: Low alignment or non-compliance with current legislation	2: low level of lobbying	3: absence of regulatory pressures	4: Regulations change slowly	5: Lack of clarity on how to use waste hierarchy	6: Recycling rates focus on quantity and not on quality	7: Cartel formulation legislation hinders collaboration between	8: No CE standards for products	9: CE is not integrated in innovation policies of the government	10: No clarity on ownership, liability and responsibility in new business models
Struvite	+	-	+-	+-	?	+-	?	+	?	?
Ash	+-	-	+-	+-	?	?	?	-	?	?

6.3.3. Technological barriers (T)

Barrier 1: Uncertainties or risks associated with the technology

Technology uncertainties can reduce the belief in the technology and prevent further development or investments in installations.

Struvite

In the collected data nor in the interviews uncertainties about the functioning of the installed technologies were mentioned. Technologies such as Airprex and Pearl have been installed in other countries before they were implemented in Dutch projects. This proof-of-principle was one of the reasons to choose the Airprex technology in Amsterdam and in Echten (I12, 2016; GoI2, 2016).

The data and interviews also didn’t indicate any risks associated with the technologies. The technologies implemented in the Netherlands use magnesiumchloride and magnesium(hydr)oxide for their crystallisation process, which are both safe products.

To conclude, this barrier is weak for struvite production.

Ash

The technologies for ash recovery are still under development and not yet implemented at full-scale. Although they are still under development, uncertainty about the functioning of the technology was not mentioned in the interviews and in the collected data no indication of this barrier was found. The EcoPhos project uses HCl (hydrochloric acid) and H_2SO_4 (sulfuric acid) in their process. The RecoPhos uses high temperatures to create pure phosphorus. The interviewees did not mention a perception of risk related to those technologies.

Because there is no indication this barrier plays a role at this moment, the barrier is weak.

Barrier 2: Risks are associated with product

Risk associations can have negatively influence the consumer acceptance of recycled phosphates.

Struvite

There are concerns about the safety of the product due to possible effects of drug residues or pathogens in struvite. As described in Subsection 4.1.3 and Subsection 4.2.2 several actors mention having problems with proving the safety of the product. This is partly due to the methods used for measuring, but mostly with the fact that there are no criteria for pathogens and drug residues in the product. Institutional barrier 1 and 9 have touched upon this issue. According to Interviewee 2: 'Struvite is, from a legal perspective, ready but now you need to convince people that it is like that' (I2, 2016). The interviews indicate the risk perception is related to consumer acceptance, which has an effect on the marketing. As Interviewee 12 states 'a farmer and especially an organic farmer is very careful with what products he brings on his land'. And also Interviewee 1 says 'a product needs to be clean and unsuspected'. But concerns on the presence of drug residues are not ill-founded. Interviewee 7 tells ICL received struvite from urine collected at festivals and there was a significant amount of drugs in the struvite. Interviewee 8 explains the opinion of the government. He says the Rijkswaterstaat can judge whether the product is safe for the environment. 'We thought that was easy, but is turned out to be complicated. Struvite is relatively clean, with possibly some pathogens, but now the RIVM points at the drug residues. And these are barely measured. The water boards think it's not such a big problem, but it can be a big problem, just like they have problems with drug residues at their MWWTP. But are there drug residues in struvite? That is what we should measure' (I8, 2016).

The barrier is mentioned by several actors. The risk perception hinders the direct route to agriculture, but the struvite can still be used as input for fertilizer production. The problems with drug residues in struvite play with several technologies.

Therefore, the barrier is rated as strong for struvite recycling.

Ash

For phosphorus from ash the discussion on pathogens is less relevant. According to Interviewee 7 they can guarantee, because of their process, that even if the struvite contains pathogens, the treatment steps will lead to a sanitized product. For ash, the presence of heavy metals is possibly an issue, as Egle et al. (2015) pointed out with the recommendation to review the mineral fertilizer regulations critically.

The interviewees did not specifically mention the risk of the product as a problem, but the risk of heavy metals in ashes has been pointed out in other data.

Taking this into account, this barrier is regarded medium for the ash route.

Barrier 3: Lack of LCA to proof the effect of CE principles

Life cycle assessments (LCA) are used to measure the environmental impact of products and services. For companies these LCA's are important to show how they reduce their environmental impact and contribute to sustainability goals. More information can help technology installers to make choices based on these outcomes or in more abstract terms: this type of knowledge development can give guidance to the search. David Sears of the European Economic & Social committee says LCA is needed to provide scientific data to support policies on for example energy use and environmental impact (ESPP, 2015b).

As described in Subsection 4.2.1 several LCA's have been done in order to measure the impact of struvite and ash recovery through various technologies. STOWA and P-REX project concluded that there is not one most sustainable technology as the most sustainable technology depends on the context (STOWA, 2016b; P-REX, 2015a). Both alternative routes are more sustainable than current practices.

To conclude, LCA's are regarded as important, but so far there has been no sign that LCA's or the lack of LCA's hinder the development of phosphorus recycling in the Dutch communal wastewater chain.

Barrier 4: Products are not designed for end-of-life

Recycled phosphorus is taken up by plants and there is no defined end-of-life phase for fertilizers. To what extent the technology installations themselves are built for an end-of-life-phase was outside the scope of this research. Therefore it is concluded that this barrier is rated unknown.

Barrier 5: Quality of product is limited

Struvite

The perception of the quality of struvite is partially influenced by the risk perception. This is related to the presence of impurities and pathogens, as elaborated in technical barrier 2.

Besides the pathogens and drug residues discussion, the quality or cleanness of the product is a point of attention. Interviewee 2 says the quality is a difficult point. 'Wastewater treatment is built for treatment and now they have to make a product. Some have problems with constant production while others have problems with the quality staying behind'. Due to the characteristics of the technology, this point is valid for slurry producing technologies, but not for the Pearl technology. Interviewee 4 mentions the quality in relation to the market situation: 'Companies have no market certainty and do not invest, because there is uncertainty about the quality of struvite and that is a problem'. Vaneeckhaute et al. (2016) concluded that the important technical challenges are the reduction of chemical requirements, the guarantee of a pure product and the constant and controlled production of struvite.

The interviewees acknowledge there is a problem with the quality of struvite, although this is not valid for all struvite reactor types. The quality issue has a big effect on the direct marketing, but less effect on the use of struvite in fertilizer production. However, the uncertainty about the quality can lead to reduced investment, thereby hindering the recycling in a clear way.
For that reason, the barrier is rated strong for struvite recycling.

Ash

The quality of the end products cannot be tested yet because the full-scale plants are still in development. Therefore this barrier is rated as unknown.

Conclusion technical barriers

Table 3. Conclusion of technical barriers

Technical	1: Uncertainties or risk associated with the technology	2: Risks are associated with product	3: LCA to proof effect of CE principles	4: Products not designed for end-of-life	5: USER: Quality of product is limited
Struvite	-	+	-	?	+
Ash	-	+-	-	?	?

6.3.4. Financial barriers (F)

Barrier 1: Low amount of competitors and new companies in the field

According to the theory of Functions of innovation systems, competitors and new companies are needed to stimulate learning and innovation and to do experiments.

Struvite

The last years the amount of struvite producers and the amount of available struvite recovery technologies have increased. Interviewee 2 emphasizes the importance of a larger number of struvite producers: 'As more water boards are recovering struvite, you see the government starts to think along instead against. That is the power of a collective, at that moment people start to think' (I2, 2016).

The amount of competitors has not been a specific subject in the interviews. The interviewees have not mentioned the barrier by themselves. The only indication to this barrier was found in the interview with Interviewee 2, but his comments are related to the valorisation of the struvite and the importance of working together. Furthermore have the amount of technology providers grown during the last years.

On these ground the barrier is rated as a weak barrier for the current situation.

Ash

In Europe there are many technologies in development of which two are related to the Dutch case study. These two technologies, RecoPhos and EcoPhos, are in the phase of upscaling to full-scale plants.

No indication was found in the case study that a low amount of competitors is hindering the development.

The interpretation of the author is that this barrier is currently no obstacle in the growth or development of the ash technologies, but could be a barrier towards further innovation and process optimisation when the first technologies are implemented.

Barrier 2: Low investments in research

Low investments in research can hinder the further development of the technology or of the product. See also knowledge barrier 2 in Subsection 6.3.6 for the effects of little research.

At European level there are calls for research funding for analysis and risk-assessment on contaminants in nutrient recycling (Buckwell & Nadeu, 2016) and the need for financing of demonstration projects is expressed (European Commission, 2015b). Yet these comments are about nutrient and phosphorus recycling in general.

Struvite

The experience of Interviewee 5 as a researcher is that it is not easy to find financing for nutrient research. Interviewee 8 from the government agrees that from the government funding for research is limited. He says, ‘the financial support has been lowered and more is asked from other parties’. In spite of this, a lot of research on phosphate recovery and specifically struvite has been done in the last years by STOWA, see Subsection 4.5.1. These projects were done by request of the water boards.

Ash

In the Netherlands there is no clear research on phosphorus from ash. RecoPhos has been developed in a consortium with funding from the EU, but no Dutch parties were involved (RecoPhos, 2017b). Currently, the RecoPhos technology is further developed by ICL.

No interviewee mentioned the low investment in research as an obstacle for further growth. Only Interviewee 5 as a researcher made a comment about financing research.

To conclude, although financial support for research is desired, the data do not indicate this barrier is hindering further development of phosphorus growth for either routes. This barrier is rated as weak in the current situation.

Barrier 3: Negative landscape developments

The landscape is a stable external structure which includes cultural norms and political coalitions, but also external factors such as war, the economic situation and environmental problems that are present (Geels, 2011). In this paragraph only landscape developments from a financial perspective are described, in Subsection 6.3.7 the social perspective on landscape developments is analysed.

Struvite

The awareness of Europe on problems such as food security, material scarcity and the attention for circular economy can enhance the support for phosphorus recycling. A specific landscape element of the Dutch context, is the phosphate and manure surplus, as described in Subsection 6.2.2. This situation stimulates phosphorus recovery but hinders the application of phosphorus in the Netherlands. As Interviewee 12 explains; ‘There is a phosphate surplus in the Netherlands and struvite contains phosphate. There is a manure surplus so to get rid of the phosphate in agriculture, I think that is difficult’. Interviewee 8 sees the same development and says ‘We already have here a lot of phosphate, so the market for recovered phosphates is limited’.

Ash

To conclude, from the authors perspective the current landscape offers drivers for phosphorus recovery. The manure surplus leads to decreased market opportunities for the Netherlands but international markets are available. As struvite production takes place on small scale and aim for local markets, this barrier is of medium strength for struvite. As this barrier does not seem to hinder the more international oriented ash route, the barrier is expected to be low for the ash route.

Barrier 4: Financial support for linear or incumbent systems (or absence of tax system supporting sustainable product)

Financial support for the incumbent system will make it more difficult for new initiatives such as recycled phosphorus to compete with existing products. Financial support can be subsidies of favourable tax systems.

No data was found on financial support for the incumbent system with mineral phosphates or other types of phosphates, but the lack of financial support for phosphorus recycling is mentioned by the interviewees. Interviewee 10 expressed criticism on the structure of the fiscal system. 'What we see as a big hurdle is the fiscal system that is not aimed at resource recovery. For example the SDE+ subsidy (subsidy for sustainable energy production; RVO, 2016) is not available for resource recovery. And if you produce energy, often you destroy resources'. He says, 'this is why not many companies join'. In line with that he also mentions the negative effects of the waste levy system, see Subsection 4.3.1. The consequences of the current fiscal system seem to imply the stimulation of energy production instead of resource recovery. The SDE+ subsidy has been mentioned by more interviewees. Interviewee 3 says: 'The market is an obstacle and you could say financing is a problem. At the moment there is from the government mostly stimulation for sustainable energy through the SDE+ subsidy, but there is actually no stimulation for sustainable resources, whereas a lot of effort is put into CE. But if you want to realise the CE, you should not only look at energy but at the total picture, to energy, resources and climate. Whether it is a real problem such an incentive arrangement is not in place I am not sure, but it could be of great help' (I3, 2016). The potential added value of subsidy programs is mentioned as well by Interviewee 8. 'Making struvite is possible, but try to scale it and make serious production is already a lot harder. You are going from something innovative to business and there lies the famous Valley of Death in between and subsidy programs could be of great help to overcome this'. But when asking him about the SDE+ regulation and nutrient support legislation he says politically it is very difficult to open up the SDE+ regulation and there is not just money to create a new subsidy regulation for resources.

Another example is the ETS system. ICL is trying to get permission to be exempted from the ETS system. To Interviewee 7's opinion the use of RecoPhos decreases CO_2 emissions in other countries and the ETS system should therefore not hinder setting up local factories if in the end it reduces global emissions.

The subject of financial support came up in at least three interviews, whereby one interviewee sees the fiscal system as a problem, while the others phrase the financial support not as necessary but at as a method to stimulate phosphorus recycling. The comments on subsidy seem to be all made in relation to struvite recovery. Actors of the ash route did not mention the SDE+ regulation. The levy system is only a barrier for the water boards and acts more as a barrier towards energy production. The ETS systems can be a barrier for the ash route, but the impact of it is unclear.

For those reasons, this barrier is regarded as medium strength for both routes.

Barrier 5: Not enough financial resources available

This barrier is interpreted as a lack of financial resources that prevent the installation of phosphorus recovery technologies.

Struvite

One of the interviewees said the financial resources for the struvite installations are not the problem, as Interviewee 11 states that struvite is not such a big market and not a high cost item. As an example, Interviewee 11 names the possible struvite reactor for Den Helder which will be in the order of a million while their sludge dryer installation would cost around 50 million (I11, 2016). Furthermore, the water board Vallei & Veluwe was able to get subsidy to make their struvite installation in Amersfoort possible (OmzetpuntAmersfooI2, 2016a).

The interviews did not indicate that financial resources for the installation are a problem, so the barrier is rated weak for struvite.

Ash

The comment of Marcel Lefferts of SNB, as described in the history of the ash route in Section **2.5**, indicates a problem around finance. The problem was not per se the lack of financial resources but the question arose whether they, as a company, should carry the financial risk for such a big installation while it contributes to solving a bigger problem, namely phosphorus scarcity. In 2010 Interviewee 7 was interviewed and he had the same message as Marcel Lefferts of SNB. 'Everywhere our initiatives are brought to stop is the fact that if we do investments, no one gives us a guarantee if a problem appears such as a company who cannot deliver their ashes anymore'. Interviewee 7 thinks the government could give such a guarantee for the long-term (Lommen, 2010). In his interview Interviewee 6 makes a stand for subsidy for ash installations. He states 'there is no problem to get subsidy for academic research but that is not what we need. I would like to see that someone who builds the first factory is getting support'. The comment of Interviewee 8 on the Valley of Death, see the previous barrier, is also applicable to this barrier.

To conclude, the installation costs of ash recovery technologies are seen as a barrier due to the financial risk related to it. Despite that, the developments are still going on. Therefore this barrier is rated as medium strength.

Barrier 6: Investment calculations are based on one lifecycle instead of more cycles

Information on this barrier was not available in the collected data. As a consequence the strength of the barrier is unknown for both routes.

Barrier 7: Labour is taxed instead of materials

Material taxing instead of labour taxing is often mentioned as a stimulator for CE as it could stimulate material efficiency.

No indication could be found to what extent this barrier plays a role in the phosphate recycling case and the barrier is rated as unknown for both routes.

Barrier 8: High amount of investment costs

This barrier is related to payback period (barrier 9) and the availability of financial resources (barrier 5). High investment costs bear a higher risk, especially with a low availability of financial resources and a longer payback period.

Struvite

The investment costs are varying for the different struvite technologies and with the scale of the plants. The comments of Interviewee 11, as described in financial barrier 5, lead to the conclusion that the investment costs are weak barrier for struvite recovery.

Ash

The investment costs for the phosphorus recovery installations are higher than the struvite installations. As explained in barrier 5, the investments costs are a problem due to the financial risks associated with it. Therefore, this barrier is rated the same as barrier 5, with medium strength.

Barrier 9: Long payback period

A long payback period can make actors less willingly to invest in recycling installations.

Struvite

In the discussion at the event opening Omzetpunt Amersfoort the average payback period in the commercial sector was said to be 3-5 years (OmzetpuntAmersfoorl2, 2016b). Payback periods between 2-10 years for struvite technologies have been found in the data, see Subsection 4.3.2. Although for normal companies such payback periods are often too long, the longer payback period did not seem to hinder the water boards and the struvite installations were build.

For that reason, the barrier is rated as low.

Ash

Payback periods have not been mentioned in the interviews with the ash actors. But as the high investment costs have been mentioned as a barrier, the assumption of the author is that the long payback period plays a role.

Hence, this barrier is of medium strength, the same as the barrier on high investment costs.

Barrier 10: Application is too narrow

The reuse potential will be lower if the application possibilities of the product are low.

Struvite

The composition of struvite makes the product only for a niche market direct applicable, as described in Subsection 4.3.3. This barrier is acknowledged by actors. Interviewee 8 states it as follows 'Maybe there are some niches where you can sell it, but if it becomes big, you are not going to make it with that'. Interviewee 6 is also critical on the product struvite. 'The product that you get, struvite, is not so much the material that somebody wants. It can be allowed by law but it is different than that somebody really wants the material on large scale. Therefore, I don't have high expectations'. The words of Interviewee 7 are even clearer as he states 'there are currently struvite producers such as Ostara who make a nice product, but they are getting a problem. They start to get more capacity, make more contracts and the niche markets are starting to get saturated'. And Interviewee 10 says about struvite: 'Everyone is busy with it, so the market gets saturated and then you have a problem again'. He thinks that within 5 to 10 years nobody wants struvite anymore.

The interviewees state very clearly the niche application of struvite is a problem for struvite production on larger scale, although the niche application is only for the direct marketing of struvite a problem as the product can still be used by phosphate processors such as ICL.

To conclude, this barrier is rated as strong for the direct use of struvite.

Ash

Pure phosphorus and phosphoric acid can be extracted from ash. Pure phosphorus can be used as input for fertilizer production but also for other applications, see Subsection 5.3.3. The problem of having a narrow application was not mentioned by any of the actors. From the words of Interviewee 7 not only the broader application itself was found to be an advantage, he also says ‘the fertilizer industry is bound to the different seasons but with an industrial application you have the whole year a demand, thus it makes demand guarantee easier’.

Therefore this barrier is regarded as low.

Barrier 11: Price/performance is bad

Struvite

For the price/performance ratio both price and performance are important. The impact of the price is described more in-depth in other barriers such as barrier 14. The performance of struvite is only limited tested. Interviewee 1 thinks that the added value of the product is not clear and needs to be shown to end-users (I1, 2016). For the end-user it must be clear whether the phosphate in the struvite can be taken up by plants or, in other words, the effectiveness of the product must be clear. Interviewee 6 explains ‘for the farmer you need a product that is better and cheaper. They are still entrepreneurs who are often walking a tightrope (“ze werken op het scherpst van de snede”) and whether it is recycled, they do not care’. The farmer has also little possibility to pass on the higher costs to consumers (Buckwell & Nadeu, 2016). Interviewee 12 looks to the environmental conscious consumer as the market. ‘You are ending up with people who think “oh this is nice, I am going to fertilize my plants with struvite from urine”. One person will buy just a cheap bag of fertilizer and another person will look where it comes from, the more environmental conscious consumer’.

Price/performance is not mentioned specifically as a barrier in the interviews. Although the comment of the interviewees can be linked to price/performance ratio, it cannot be extracted whether the price/performance of struvite is good or bad.

For that reason, the barrier is unknown for struvite.

Ash

Data on the price/performance of products from the ash route is not available as the technologies are still under development. As such, this barrier is unknown as well.

Barrier 12: Financial resources for consumer are lacking

A lack of financial resources is interpreted as having not enough money to buy a certain product, with the assumption the consumer wants to buy the product.

When following this interpretation of the barrier, there is no indication of a lack of financial resources for Dutch consumers. No conclusion can be made for international consumers.

Therefore, the barrier is rated as low for the Dutch market.

Barrier 13: Price of raw material is lower than recycled products

A low price of mineral phosphate makes it difficult for recycled phosphate to compete on the market. Secondly, if the price of recycled products would be high, this could increase phosphorus recycling initiatives.

Interviewee 6 says the current price of (mineral) phosphate is too low and this makes many recovery processes less interesting. Increasing the price would boost the recovery (I6, 2016). Interviewee 8 says the price is a powerful tool and he mentions the phosphate from Morocco as an example ‘Morocco can just lower their prices and that makes it difficult to compete. With the price you can do a lot, if prices are low, companies will choose the low price’. So on the hand does the low price of mineral phosphates makes it difficult for recycled phosphates to compete and at the same time it keeps the market price of recycled phosphates low. ICL can use struvite as input for fertilizer production, but as Interviewee 7 says, it must be economically attractive. ‘What is hindering for this type of applications, is that we do not have a cost price which is the same as the market price. Our cost price is lower than the market price, so for us the price should be better than the price of our own phosphate’. One of the consequences of the low price of recycled phosphates is a reduced revenue of struvite recovery. However, the interviewees have said that installing struvite recovery is mostly driven by reduced maintenance costs and not by selling the struvite (I11, 2016; I12, 2016; STOWA, 2013).

The discussions at the EU workshop led to the conclusion that implementation support is essential for nutrient recycling, because the price of mineral fertilizers is relatively low compared to technology and logistics costs of recycling nutrients (European Commission, 2015b)

The low price of phosphate rock was mentioned by several interviewees. The low price reduces the urgency to recover phosphorus and secondly, it makes it difficult for recycled materials to compete. The low price of phosphate rock affects both recycling value chains and applies to EU level.

Based on the above, the barrier is rated as a strong barrier towards the growth of phosphorus recycling for both routes.

Barrier 14: Externalities are not reflected in the price

Externalities are positive or negative influences that have not been included in the price. For example, environmental costs of mining are not in the price of mineral fertilizers.

Externalities have not been a subject in the interviews. However, Buckwell and Nadeu (2016) state there is ‘widespread market failure due to a lack of internalising environmental impacts’. Collective action is needed but it is not clear what kind of collective action must be taken (Buckwell & Nadeu, 2016). If externalities could be internalized, the price of mineral fertilizers would increase. This would have a direct effect on the previous barrier and on barrier 11 as it would increase the competitiveness of recycled phosphates. But the strength of the effect of internalizing the externalities on the price is not known.

Hence this barrier is regarded as having medium strength for both routes.

Conclusion financial barriers

Table 4. Conclusion of financial barriers

Financial	1: Low amount of competitors and new companies in the field	2: Low investment in research	3: Negative landscape developments	4: Financial support for linear or incumbent systems	5: Not enough financial resources available	6: Investment calculations often based on one lifecycle	7: Labour is taxed instead of materials	8: High amount of investment costs	9: Long payback period	10: Application is too narrow	11: Price/performance is bad	12: Financial resources for consumer are lacking	13: Price of raw material is lower than recycled products	14: Externalities not in price
Struvite	-	-	+-	+-	-	?	?	-	-	+	?	-	+	+-
Ash	-	-	-	+-	+-	?	?	+-	+-	-	?	-	+	+-

6.3.5. Infrastructural barriers (If)

Barrier 1: Complementary services & products are lacking

This barrier can be applied from a technology perspective and from a product or user perspective.

Struvite

From a technology perspective, additional treatment is needed for the struvite slurries to clean the slurries. There is no indication that these technologies are lacking. Interviewee 6 indicated in his interview that farmers want grains which are compatible with their existing machinery. The Pearl technology provides such a grain, but struvite slurries from other technologies need treatment steps to create usable products. The struvite slurries can still be used in fertilizer production.

Because the producer wants to sell their struvite, the producer has the need to make a product which is compatible with the market. The consumer, in this case, is not in the need of complementary services or products.

To conclude, because most of the struvite slurries need additional steps to make the struvite usable in current applications, the barrier is regarded medium for struvite producers and low for consumers.

Ash

The interviewees did not mention the lack of complementary services or products. The phosphorus is turned into fertilizers, which can be applied by current machinery.
For those reasons, this barrier is rated weak for further phosphorus recycling from ash, for both producer and consumer.

Barrier 2: Scale of supply is too small

A small scale can hinder the development of the supply chain. For example, Buckwell and Nadeu (2016) state the issue of market imperfection, in which a new smaller scale fertilizer product needs to compete with the established fertilizer sector. The scale of supply refers to the produced amount of struvite or phosphorus from ash production.

Struvite

The scale of supply is mentioned as one of the barriers in the interviews. As Interviewee 2 states: ‘Often a water board is too small to market an idea, because a bigger volume is needed. But you see that now more water boards are recovering struvite, the government starts to think along and that is the power of the collective’. Later on in the interview he states that more parties are getting interested because of the bigger scale of struvite recovery. But the amount of locations where struvite recovery can take place is limited for various reasons, see Subsection 4.4.1, and the produced amount of struvite with certification is even lower. One of the reasons for that is the complexity of getting and EoW status and the costs related to obtaining a REACH declaration.

One interviewee, who is involved in struvite marketing, mentioned the scale of supply as a barrier. The small supply of certified struvite hinders the valorisation of struvite to its full potential as a direct fertilizer, but does not hinder the use of struvite as input for fertilizer production.

Because the barrier is mentioned as a problem for the direct use of struvite, but not for the struvite to be used in further processing, the barrier is expected to be of medium strength.

Ash

The recovery of phosphorus works at larger scale. With the RecoPhos project, ICL is able to cover the whole German sewage sludge ash market, which is 350,000 tons of ash, according to Interviewee 7 (I7, 2016). For Interviewee 7 the scale is important. 'We choose for this consciously, because the market first needs a bulk solution and next to that, it is nice if you can develop some niches. But first take care that at any time your bulk is functioning well'. Furthermore not only sewage sludge ash, but other resources such as ash from slaughter waste are possible to use in the technologies. As a consequence the scale in which phosphorus is produced is expected to be higher.

The interviewees do not mention the current scale as a problem. The expectancy is that this barrier is weak for the phosphorus produced from ash.

Barrier 3: Low alignment with incumbent infrastructure

Incumbent infrastructure refers to the current system and current technologies in place.

Struvite

Interviewee 12 praises the easy implementation of their Airprex struvite reactor as it is in-line with their treatment system. However, the space they have at their MWWTP in Amsterdam is really limited. He wonders whether an installation such as the Pearl installation would fit at their location and he expects it wouldn't. His comments show the incumbent infrastructure can influence the decision for installing struvite installations.

Other comments suggesting that the struvite technologies have problems with fitting in the current infrastructure have not been found. Because there are various types of struvite reactors available, needing different amounts of space, this barrier is expected to be weak.

Ash

For good ash quality mono-incinerators are desired. De Ruijter et al. (2016) notes that current mono-incinerators of SNB and HVC are aimed at dewatered sludge. Other input requires another type of oven. This means that existing mono-incinerators cannot straight away process current co-incinerated inputs. For an increase of sewage sludge ash for phosphorus recycling this can be a problem. The integration of recycled phosphates in the process of ICL led to technical problems as described in Subsection 4.4.2. A new system is engineered which is expected to solve the problems. For the RecoPhos and for the EcoPhos technologies new plants will be built or are being built.

The problems with low alignment have not been specifically mentioned as hindering the use of ash technologies. But due to the above information from De Ruijter et al. (2016), this barrier is rated as medium strength as it could hinder the further development of using sewage sludge ash as input for phosphorus recycling.

Barrier 4: Incomplete production chain for technology or product

There are no indications found in the desktop study or interviews that the production chain is incomplete for the technology or the product for any of the routes. The barrier is therefore labelled weak for both.

Barrier 5: Companies are relying on external providers to adopt CE principles

External providers are for example suppliers. If companies want to adapt CE principles or improve sustainability, they are often relying on their suppliers to green their supply chain.

For the struvite route it is unclear to what extent this barrier plays a role. The role of suppliers was not discussed in the interviews and the desktop study did not provide any indication for this barrier. For that reason, the strength of the barrier is unknown.

The ash processors are more clearly relying on external providers, because they are depending on the ash producers for bringing a certain quality of ash to them. In the case of phosphorus, this 'barrier' can also be seen the other way around as the 'providers', in this case SNB and HVC, are depending on other parties such as EcoPhos and ICL to be able to adopt CE principles such as recovering phosphorus from ash. However, the collected data did not provide enough inside to identify to what extent this barrier play a role in phosphorus recycling and therefore the barrier strength is unknown.

Conclusion infrastructural barriers

Table 5. Conclusion of infrastructural barriers

Infrastructural	1: complementary service & products are lacking a. Producer b. Consumer		2: Scale of supply is too small	3: Low alignment with incumbent industry	4: Incomplete production chain for technology or product	5: Companies are relying on external providers to adopt Ce principles
Struvite	a. +-	b. -	+-	-	-	?
Ash	a. -	b. -	-	+-	-	?

6.3.6. Knowledge barriers (K)

Barrier 1: Lack of knowledge dissemination

Knowledge dissemination is important because it enhances innovation. Conferences, platforms and research collaborations can contribute to knowledge dissemination.

The case study shows knowledge dissemination takes places through European projects such as P-Rex, through platforms such as Nutrientplatform and ESPP or through events such as the ARREAU Learning Alliance and the STOWA symposium at Opening Omzetpunt Amersfoort. Knowledge dissemination goals are often explicitly formulated such as in the Green Deal and the SRRLA (UvW et al, 2014; Kabbe, 2016b). In the interview ICL values the existence of Nutrientplatform as 'it is a crucial aspect for innovation to sit with officials around the table'. He sees it also as an important instrument to meet people from the value chain (I7, 2016).

The interviewees did not mention knowledge development or cooperation as a problem. The amount of events, collaborations and platforms suggests knowledge dissemination takes place in different forms and actors from both struvite and ash route are involved in these networks. This leads to the conclusion the barrier is of weak strength for both routes.

Barrier 2: Low amount of R&D and pilot projects

Positive outcomes of R&D projects and pilots have positive effect on the belief in potential of technology or product according to the theory of FIS. It can reduce uncertainty or risks related to the technology or product.

Struvite

The data shows several pilots have been done and full-scale projects are already implemented. Subsection 4.5.1 shows many research projects have taken place, nevertheless there is still always a need for more research, like on the agricultural value, on the safety aspects around pathogens and on data for benchmarking. Interviewee 8 explains the Green Deal with Waternet and French companies is also a learning project: 'the aim of the Green Deal is to learn. Let's try it, which obstacles are we encountering, do things have to change. This is the way they do it in France and we do it this way, how can we solve that'. Interviewee 6's opinion is that research is not the problem. He mentions Germany, where the research is much more academic, but he sees it a less effective approach as 'the key does not lay in research, not anymore'.

The interviewees did not indicate that the amount of R&D and pilot projects is hindering the growth. As the social barrier 'no believe in potential' is also low, it can be concluded that this barrier is weak too.

Ash

Several the technologies are still under development or full-scale plants are currently build. The interviewees did not mention a lack of research for this type of technology. For the technologies in this case study, the research take place within companies and not much data could be found on specific studies. The new plants could serve as a proof-of-principle, stimulating the recovery of phosphorus from ash.

The interviewees did not explicitly mention the lack of pilots and because for ash the social barrier 'no belief in the technology' is also weak, this barrier is estimated to be of weak strength for further growth of phosphorus recycling from ash.

Barrier 3: Lack of human capital

For innovation specialised knowledge is needed. If there is a lack of skilled people, educational programs could contribute to overcoming a shortage of skilled employees.

From the data there seems to be no indication that there is a lack of professionals, see also knowledge barrier 7. As a consequence this barrier is of weak strength for both routes.

Barrier 4: Gap between research and practical needed knowledge

A gap between research and practice can lead to unused research and to innovations that cannot be implemented or lead to problems with implementation. On the other hand it can lead to practical problems which are not solved.

According to Interviewee 6 'The key to success is not found in research or not anymore. On lab scale there are fantastic processes but if you are going to implement those, the phosphorus is 20 times more expensive as mineral phosphate rock and that is not going to work'. Thereby he referred to Germany where a lot of research takes place.
In the Netherlands the STOWA is doing research based on questions of the water boards, which improves the practicality of the research. For the ash route, the technologies are further developed by companies for installation. That research is assumed to have practical added value.

The interviews did not show signals of gap between research and practice for the struvite nor the ash route and this barrier as such is expected to be weak for both cases.

Barrier 5: Low cooperation between firms

Low cooperation between firms can hinder technological development, for example it can lead to a lack of complementary services or products. Furthermore cooperation can help to overcome lack of materials or financial resources. This barrier can be influenced by the social barrier 'low trust between companies'.

Cooperation between firms is done in consortia or in EU projects. Often these collaborations include knowledge institutes, companies and sometimes government representatives as can be seen in Subsection 4.5.2. Interviewee 5 explains that projects of the EU and projects part of the Dutch TKI program need to work according 'the golden triangle' which means knowledge institutes, companies and government should be involved in the project. The pilot of Waternet and ICL is a good example of collaboration as it led to the final installation of a struvite reactor. Interviewee 2 gives the example of Aquaminerals that markets the struvite of several water boards and uses cooperation with companies as a strategy to create products which are directly applicable. Another example of cooperation is the water board of Rijn and IJssel who cooperates with Aviko to produce their struvite (Nutrientplatform, 2016e). Interviewee 5 names the pilot of Schiphol with Evides Industrial Water and Vewin to produce struvite as example (KWRwater, 2016; Evides, 2016). A last point that implies collaboration is the comment of Interviewee 12: 'we are fairly working together', followed by saying that several water boards have asked Aquaminerals and EFGF to look for sales channels. In the ash route the contract of HVC and SNB with EcoPhos is a good example of collaboration. And also the agreement of HVC with their shareholding water boards on struvite recovery shows cooperation is taking place.

To conclude, none of the interviewees specifically said there is low cooperation between firms. The case study shows a couple of examples of collaboration within the field and there is willingness to take action together. This leads to conclude the barrier is weak for struvite and low for ash.

Barrier 6: Lack of awareness by intermediaries on developments

If intermediaries, parties or actors who are acting between supply and demand such as consultants or retailers, are not aware of developments, the connection between supply and demand will not be soon established.

Technologies concerning struvite are known by installing companies like Grontmij, Eliquo and consultancy companies like Tauw, as these companies have been found in the case studies to play a role in the installations of the current struvite reactors. In this research no contact with retailers has been made, except for the company Aquaminerals who serves as a marketing channel for the produced struvite. No general statements can be made on the awareness of retailers on recycled fertilizers. But the Dutch fertilizer sector organisation Meststoffen NL, who has retailers as member, is part of the Nutrientplatform and can follow the developments.

As the ash technologies in the Dutch case are implemented by companies who are already part of the fertilizer industry, the connection with the demand side seems not to be a problem.

This barrier has not been elaborated in the interviews and not enough other data was found to give a clear conclusion on this barrier and therefore the barrier strength is concluded to be unknown for both routes.

Barrier 7: Lack of knowledge required to develop, produce and control technology

A lack of knowledge inhibits the development, improvement, installation and optimal performance of a technology.

Struvite

Lack of knowledge to develop, produce or control the struvite technology does not seem to be a bottle neck. These factors were not mentioned in the interviews and could not be derived from the analysed events. Therefore this barrier is weak.

Ash

Interviewee 7 gives an example of how ICL outsourced the new design of their current installation to adapt it to the use of recycled phosphates in their process, see Subsection 5.4.2. Furthermore he tells they have composed a group of consultants to work on the further development of the RecoPhos technology. This leads to the conclusion the knowledge to develop the technology was not completely in-house but ICL seems to manage this problem by hiring the right people. For that reason, the barrier is considered low.

Barrier 8: Lack of data on material flows

Data on flows can show where valuable resources go and where these are lost (Aldersgate Group, 2012). Data or knowledge can support governments in taking action, to direct resources and to make choices on direction or creating visions. In general it can support guidance of the search.

At European level the need for data is expressed. At the ESPP 2015 conference data monitoring of phosphorus flows was mentioned as a need and the need to use LCA to provide data to support policies (ESPP, 2015b). Another type of data that is needed is information on the costs and necessary infrastructure to do benchmarking in the sector. Because of the lack of data there is little insight in what type of infrastructure is needed for new fertilizer products and what the costs are (Buckwell & Nadeu, 2016). For the Dutch communal wastewater chain, data on the phosphorus flows are known. STOWA published a report on the potential of struvite and phosphorus from ash in the communal water chain (STOWA, 2013).

The interviews did not indicate that this barrier is important for the Dutch situation and because the P flows in the communal wastewater chain have been researched, this barrier is weak for both routes.

Barrier 9: Lack of knowledge on roles of companies in circular economy

Within a CE the role of companies can shift as waste turns into products and new business models based on services instead of product selling are put are into practice. This changing system can lead to uncertainty for companies.

Struvite

As waste processors are turning into resource providers, vagueness can arise, especially legislative, on the role of a company in a CE. An example found in the case study is the role of the water boards. As explained in Section 2.3 the water boards are a public authority who are not allowed to make profit. A discussion arose on whether they were allowed to sell struvite as fertilizer and to what extent this conflicts with their original role as a public body. The juridical guidebook of Slooter and Klootwijk (2014) provided clarity for the water boards on this subject.

To conclude, the barrier was not mentioned by any of the interviewees. The data seems to indicate there was uncertainty, but the involved actors have done research to create clarity. Based on the above, the barrier is expected to be low.

Ash

Interviewee 7 gives the example on how ICL Amsterdam, part of ICL Fertilizers and the incumbent fertilizer industry, is trying to shift their focus towards a CE. He explains that it took a while before they were able to convince their management of this new approach. He said ‘I can garantuee you that for somebody who is not confronted with recycling or phosphate surpluses, this is an odd story’, referring to using other types of phosphate sources while the company has their own phosphate mines.

The comments of Interviewee 7 indicate there are some struggles within the incumbent industry to transform, but the barrier seems to be of low importance for the further growth of phosphorus recycling by ash.

Barrier 10: Lack of knowledge or awareness of CE by producers and consumers

A lack of knowledge and awareness of the CE principles can lead to not seeing CE opportunities from a producer’s perspective. It can also hinder demand creation for CE products. This barrier is related to the social barrier ‘lack of a sense of urgency’.

The actors currently involved in phosphorus recovery are aware of the CE principles, because often one of the incentives is closing the phosphorus loop. To what extent consumers are aware of CE principles cannot be easily retrieved from the data.

Interviewee 1 named communication to the market an issue, because struvite was largely an unknown product. They tried to create awareness of phosphate recycling by organising events, see also social barrier 4 ‘sense of urgency’. Interestingly, Interviewee 7 told in his interview that not all their consumers know there is recycled phosphate in their products. According to him, the recycled phosphates are not yet a wish of the clients. In theory such practices could lead to a barrier for consumers who are searching for recycled phosphates as input.

From the data it cannot be concluded whether there is a lack of knowledge on CE principles for consumers nor whether it is an obstacle. For that reason the barrier is rated as unknown.

Barrier 11: Lack of skills or knowledge to apply or deal with product

The lack of knowledge on possible uses can hinder a broad use of the product and if the consumer does not known how to apply the product, the willingness to buy the product will be low.

Struvite

At the moment the only known application for struvite is as fertilizer or as input for fertilizer production. Because struvite has a specific composition and the plants have specific fertilizer requirements, it is possible that not all the potential consumers know the product could be useful for their plants. To overcome this, research was done by STOWA on the use of struvite in agriculture (STOWA, 2016a). Recent research on other applications of struvite was not found. Furthermore, Interviewee 6 said in his interview that farmers want a product that is good and usable with their existing machines. ‘People sometimes make sludge or a powder, but that is not good. It should be grains and it should be cheaper’.

There is no indication the consumer lacks the skills or knowledge to use struvite or phosphorus. If the product meets the criteria of farmers and can be used by the current machines used in agriculture, there is no problem. However, from the data it cannot be concluded whether this barrier is active. Therefore this barrier is rated as unknown.

Ash

Pure phosphorus has several known applications if the same purity of phosphorus from phosphate rock can be achieved. As the ash route would produce a product that is already known by the market, no problems are expected.

This barrier is expected to be low for the ash route.

Conclusion knowledge barriers

Table 6. Conclusion of knowledge barriers

Knowledge	1: Lack of knowledge dissemination	2: Low amount of R&D and pilot projects	3: Lack of human capital	4: Gap between research and practical needed knowledge	5: Low cooperation between firms	6: Lack of awareness by intermediaries on developments	7: Lack of knowledge required to develop, produce and control technology	8: Lack of data on material flows	9: Lack of clarity on roles of companies in CE	10: Lack of knowledge and awareness of CE at producers and consumers	11: Lack of skills or knowledge to apply or deal with product
Struvite	-	-	-	-	-	?	-	-	-	?	?
Ash	-	-	-	-	-	?	-	-	-	?	-

6.3.7. Social barriers (S)

Barrier 1: No belief in potential of the technology

Interviewee 8 is in general positive about the technologies. He says: 'Technically there is a lot possible, that won't be the problem'.

Struvite

The data and interviews do not show signs of unbelief on the working of the technology. It was not mentioned as a barrier in the interviews and pilots and full-scale plants have demonstrated the possibilities. However, there seems to be a lack of growth potential. When talking about the focus of this research, Interviewee 3 said 'there are not much new things to be found with the water boards, this (struvite recovery) is already settled'. Interviewee 12 is expecting that some installations will still be build, but that most of the water boards will use the ash route for phosphorus recycling. Interviewee 6 is a bit critical about using the struvite route for phosphorus recycling. He states that struvite reactors 'do lead to reduced costs and sludge volume, but to say this is the end of the development and we have saved the world, that would be exaggerating'. He sees that the scale of struvite recovery will stay smalle and phosphorus from ash can work on a bigger scale.

This barrier has not been explicitly mentioned in the interviews. It seems that there is belief in the potential of the technology with regard to the technical possibilities but there is no a shared belief the technology will help phosphorus recycling on a larger scale.
For these reasons the barrier is rated at medium impact.

Ash

At the moment the technologies are still further being developed, but no clear signs of disbelief in the potential were identified. The involved actors HVC, SNB and ICL inherently show belief in the potential by committing themselves to these projects. Other interviewees who mention or spoke about the ash route, like Interviewee 6, Interviewee 8 and Interviewee 11 did not give any sign of disbelief.

To conclude, this barrier is regarded low for ash.

Barrier 2: No belief in the potential of the product[17]

If users do not believe in the potential of the product, consumers are less likely to buy those products.

Struvite

When talking about the users, different types of users of struvite can be distinguished: The direct marketing of struvite as product to farmers, struvite sold to fertilizer mixers and struvite sold to actors such as ICL as input in their fertilizer production process. Interviewee 2 stated that more parties are getting interested in struvite. ‘You really see that in the past only 1 party was interested to receive struvite, now also a lot of manure processors are saying “this is an interesting product and I can add that to my manure product to increase the phosphate concentration in order to make it more attractive to transport the product over longer distances” ‘.

For direct marketing Interviewee 1 saw that struvite was a relatively unknown product. ‘Using struvite itself as a product, that was not known. So we did a trial with Lumbericus to show the agricultural added value of struvite (see STOWA, 2016a). And we can use that on the market side, this is the product and you can use it for that’. Although Interviewee 1 does not say there is no belief in the product, his words imply the consumer need to be convinced about the added value of the product, by first making the consumer aware of the product, see also knowledge barrier 6.

The lack of belief in the potential of the product was not clearly mentioned by the interviewees, although Interviewee 1 indicated that the consumer needs to see the added value. However, he seems to think that awareness is the problem. At the same time, Interviewee 2 experiences an increased interest for struvite, which indicates other actors see potential in the product.

Based on the above, the barrier is rated as weak.

Ash

The interviewees did not mention the belief in the potential of the product. There is no indication the involved actors do not believe in the potential of the product. Using the ash in fertilizer production is expected to deliver a product with the same characteristics as the products from phosphate rock and other types of ash. But this hypothesis can only be validated when the full-scale technologies are installed and running.

Therefore the barrier is unknown.

---

[17] The interpretation of the barrier is: looking at the potential of the product to be used in the foreseen application from a user perspective. Another interpretation, the potential of the product to fulfil the goal of the recycling such as preventing phosphorus scarcity, is elaborated upon in the Discussion, Chapter 7.

Barrier 3: No clear vision

A clear vision can stimulate assigning resources, create awareness and guide developments.

Although nutrient recovery and closing the loop are subjects that can rely on support from the government and society, no clear vision could be found on how phosphorus recovery should be implemented in the Netherlands. Several parties are doing it and there are different options for recycling, but there is no overall guidance. The interviewees think the government can play a role in this. Interviewee 1 thinks the government could stand up and take on a more guiding role in the developments (I1, 2016). Interviewee 11 does not recognize such a national approach. He adds to that ‘of course the UvW made national agreements, but at the moment is every water board figuring out for themselves what are opportunities and handy ways for them and I think this will come together again’.

When asking Interviewee 8 about the existence of a vision on phosphorus recycling he says ‘yes, but not in the sense of a quantitative goal. We had discussions on that, but it is very difficult to say for example in 2020 we want 80% of the phosphate recovered. It is very difficult to set those targets and determine whether you have achieved them. That is why we formulate targets more as actions like “we are going to do this now” ’. According to Interviewee 8 ‘the most important thing is that you move in the same direction with a big group of parties and that is already happening quite successful. There are actors in the platform that are in there to cooperate and not only for their personal gains’. The Nutrientplatform is actively bringing actors together and published an ambition plan for 2018, as a kind of follow-up for the Ketenakkoord Fosfaatkringloop.

To conclude, the actors do not mention the lack of vision as a barrier, but do see room for improvement and suggest a more guiding role of the government. However, struvite recovery can impact ash recovery and therefore the lack of a vision can hinder the phosphorus recycling from ash in the current situation. Because of those reasons, the barriers is weak for struvite and medium for ash.

Barrier 4: Negative landscape developments

The landscape is a stable external structure which includes cultural norms, political coalitions but also external factors such as war, the economic situation and environmental problems that are present (Geels, 2011). Landscape developments such as war, climate change and an economic crisis can impact the transition towards phosphate recovery. In financial barrier 3, in Subsection 6.3.4, the landscape from a financial perspective was described.

The awareness of Europe on problems such as climate change, food security and the attention for sustainability can enhance the support for phosphorus recycling. A more local landscape element is the political situation. At the moment the Dutch government is in the formation phase of a new Cabinet and as a consequence, the new political direction of the Netherlands is not clear yet.

Section 6.2 identified various drivers in the landscape and so the barrier is rated low for both routes.

Barrier 5: Sense of urgency is missing by producers or consumers

This barrier directly influences actions of actors, government and public. If the sense of urgency rises, this could have a positive effect on the speed of changing regulation and behaviour in production and acquisition behaviour. Interviewee 6 implies the urgency at the government is not high. ‘It is on the political agenda just like another ten things so it can take ten years before somebody steps up. I have been busy for years with lobbying but there was nobody who said “you are great and here is some money” or “we are going to change the regulation to make phosphorus recycling obligatory”. There are many regulations and actions to recycle glass, plastic and a lot more but according to what I know the glass will not be depleted in a short time'. He also points out that if the price of fertilizer rises, the developing countries will be the first to experience the problems so in the end the phosphorus recycling is in the interest of everybody. Subsection 4.6.1 went into the problem perception of phosphorus shortage which can influence the sense of urgency.

The awareness of the urgency at the supply side is diverse. Water boards are very well aware of the potential phosphate problems and use this as an argument to recover struvite. But there seems to be no urgency among fertilizer companies, except for exemptions like ICL. This can be partially explained by the interests of incumbent fertilizer companies, as most fertilizer companies have their own mines. The Dutch sludge processors, which threat most of the sewage sludge, stimulate P-recovery. This barrier is weak from a producer perspective for both routes, because looking at the Dutch communal water chain, there are many initiatives for phosphorus recycling for both routes.

From the user perspective, the sense of urgency missing at the general public and consumers. Mostly, awareness of the problem is missing and several interviewees have stated the general public should be involved. Interviewee 3 says 'more could be done on the awareness side'. Interviewee 6 adds that farmers are not really interested in recycled materials. 'They have so much to explain to their customers, they are getting crazy from what everybody is expecting from them and then say to them that they should work with recycled phosphates?!' (I6, 2016). In other words, their preoccupation already includes proving to their customers their compliance with many other regulations, so they have no bandwidth to consider the use of recycled phosphates. The words of Interviewee 6 imply he does not expect that asking farmers to use recycled phosphates has big effects. From a consumer perspective, this barrier is regarded as highly relevant for both struvite and phosphorus from ash.

In conclusion, although the sense of urgency is expressed by the producers, from an overall perspective the sense of urgency seems to be lacking. As this influences the whole value chain, the barrier is rated as strong.

Barrier 6: Shareholders have short-term thinking (with focus on benefits)

Shareholders have influence on the strategy of companies. If they focus on short term profit they will feel less attracted to get involved in new long term uncertain projects.

Struvite

The water boards are public bodies and do not have shareholders. SNB and HVC have public bodies as shareholders. Water boards should not pursue profit as described in Section 2.3.

For that reason, this barrier does not seem to be an issue for the further struvite recovery in the municipal water chain and is regarded low.

Ash

The ash route involves commercial companies. Interviewee 7 said ICL Amsterdam had to convince quite some people from within the company to proceed with their recovered phosphate plans as the ideas of ICL Amsterdam seem to conflict with the actions of ICL worldwide. Interviewee 8 sees 'companies are sometimes more progressive than the ministry of EA. Also from their own interest, because they think they can earn money and in the world of economics, money is important on the short term. But a lot of bigger companies see also that in 20 years they still want to exist and therefore they have to look further and then sustainability plays a role'.

Although the interviews give some indications, there is no clear indication to what extent this barrier plays a role for phosphorus recycling from ash. Therefore this barrier is unknown.

Barrier 7: Waste management is focused on discarding waste with minimal societal damage instead of focused on recycling

If waste management is focused on discarding waste, opportunities for a useful purpose for the waste can be easier overlooked.

The difficulties with the standard waste status for sewage sludge products are an example of how waste management is focused on minimal societal damage. Some changes in attitude can be found, like the proposal of Mulder that was accepted by the Dutch House of Representatives. This proposal asks for a focus on quality of the material instead of origin of the material when the material is reviewed (Mulder, 2015). Interviewee 8 from the government says ‘first, we looked mostly at environmental quality, but now we are looking more at lifecycles, waste materials, and circular economy. That does not mean we lose sight of the first thing’.

Struvite

Interviewee 2 explains a change of attitude is needed to increase the quality of recycled. ‘The wastewater treatment system is built for treatment and now they suddenly are trying to make products from it’. Interviewee 11 gives an indication is his interview that this barrier does play a role. He says the water board looks at their decisions from a risk perspective and not from an opportunity perspective (I11, 2016).

Although the barrier was not mentioned in the interviews, the interviews led to the interpretation this barrier does play a role. The perspective on waste management influences waste policies that hinder easy recycling. Therefore it is estimated to be a medium barrier.

Ash

In the case of ash the treatment (burning) of waste (sludge) contributes to the recycling of phosphorus. Ash processors use the waste as a product and are not part of the waste treatment. The interviews did not provide any other indication and therefore this barrier is rated low for ash.

Barrier 8: Incumbent companies not willing to cooperate and resist changing status quo

Unwilling companies decrease the amount of collaborations and resist information exchange thereby inhibiting a faster technology development. It also lowers the possibility to use existing infrastructure and will make the lobby for changes more difficult.

Incumbent fertilizer producers are still holding back in actively getting involved in secondary phosphate resources, except for the fertilizer company ICL. But also ICL experienced resistance from within the company as explained in Subsection 5.6.1. Interviewee 9 explained that the chemical (incumbent) industry is lobbying to prevent lowering the allowed cadmium concentration in phosphate rock (I9, 2016). As described in Subsection 5.1.1 the adjustment in cadmium concentration could act as a driver for phosphate recovery from other sources. Also Interviewee 6 says that ‘some part of the fertilizer industry is really not interested. Some of those companies see phosphorus recycling as a threat. They say at conferences that phosphorus recycling is bullshit, that phosphate resources are not finite and that they are sustainable themselves’. Interviewee 8 points out that e.g. Morocco can simply lower their phosphate prices thus making it difficult to compete with recycled phosphates.

The interviews provided different examples on how the incumbent industry is resisting change and how this effects the whole phosphorus market. But as the barrier itself was not mentioned as a big problem, the barrier is regarded of medium strength for both routes.

Barrier 9: GDP[18] is not a good measure of welfare

GDP is used as an indicator to calculate the welfare of countries. Kok et al. (2013) say a reorientation is needed, from the production of goods, as happens in GDP, to other measures of well-being. Prosperity and material consumption should be decoupled.

This research could not relate the use of GDP to phosphate recycling and as a consequence this barrier is unknown.

Barrier 10: Lack of trust between companies

Trust is needed for collaboration between companies. A lack of trust can therefore be a barrier towards sharing information and collaboration and thereby hindering further innovation.

Lack of trust between companies was not discussed in the interviews, nor was specific data on this barrier found. However, trust can influence cooperation between firms and thereby knowledge barrier 5. Because knowledge barrier 5 is rated as low, this barrier is regarded low as well for both cases.

Barrier 11: Acceptance of service products instead of ownership of products

In Circular Economy new business models are developed in which services, like renting washing machines or jeans, are provided instead of selling a product to a consumer. If consumers are reluctant to use service products, these innovations have difficulties in entering the market.

There are no service models yet for fertilizer or phosphate products, therefore the barrier is unknown.

Barrier 12: Consumers interest in sustainability is not reflected in buying behaviour

The inconsistency between buying behaviour and consumer’s attitude towards sustainability will make it difficult to find buyers for sustainable products and will keep unsustainable products in the market.

The interview with Interviewee 8 gives an example of how this barrier plays a role in the government. He talked about the guidelines for sustainable buying of the government. ‘This is important, but very difficult to get it started. We think about it, but at the end of the day, we are the government and we have to look at the costs and we take the cheapest option. That is a consideration, together with other types of considerations, but often it turns out that sustainable is not the cheapest’. Buckwell and Nadeu (2016) underline that ‘businesses and citizens are reluctant to accept the higher costs of behaving in a more responsible and sustainable way. Converting societal or collective acceptance (as expressed by willingness to pass laws) into individual acceptance (as expressed by individual action) is the real challenge’ and they see information and awareness as an important step to improve this.

As seen in barrier 4, there seems to be no call from farmers for recycled phosphates, but from the case study it seems the hesitation to buy the product is primarily related to the specific characteristics of the product or to the risk associations. On the other hand show the comments of

[18] GDP stands for Gross Domestic Product. GDP is ‘the expenditure on final goods and services minus imports: final consumption expenditures, gross capital formation and exports less imports (OECD, https://data.oecd.org/gdp/gross-domestic-product-gdp.htm). In easier words: GDP is the market value of all final goods and services produced in a certain period (https://en.wikipedia.org/wiki/Gross_domestic_product, May 29, 2017).

Interviewee 8 show this barrier can still hinder the demand for recycled phosphorus if the other barriers are resolved. Therefore this barrier is rated medium in the current situation.

Conclusion social barriers

Table 7. Conclusion of social barriers

Social	1: No belief in potential of the technology	2: No belief in potential of product	3: No clear vision	4: (Negative) landscape developments	5: Sense of urgency is missing a. Producer b. Consumer	6: Shareholders have short-term thinking (with focus on benefits)	7: Waste management is focused on discarding waste with minimal societal damage	8: Incumbent companies not willing to cooperate and resist changing status quo	9: GDP is not a good measure of welfare	10: Lack of trust between companies	11: Acceptance of service products instead of	12: Consumers interest in sustainability is not reflected in buying behaviour
Struvite	+-	-	-	-	a. - b. +	-	+-	+-	?	-	?	+-
Ash	-	?	+-	-	a. - b. +	-	-	+-	?	-	?	+-

6.3.8. Functioning of the subsystems

A well-developed substructure contains a sufficient number of actors, institutions and artefacts that contribute to the diffusion and use of technology. The definition of a well-developed subsystem was altered to 'a sufficient number of actors, institutions and artefacts that contribute to the diffusion and use of the recycled product', see Subsection 3.2.2.

Functioning of the supply side

As a recap, the supply-side encompasses all actors involved in the production of recycled phosphates and institutions such as quality standards and a shared vision on the market.

There are 6 struvite installations installed at MWWTP. Of these installations the Pearl technology installation in Amersfoort produces an EG- certified struvite and the Airprex in Amsterdam produces REACH certified struvite. The struvite of NuReSys installation in Apeldoorn is sold commercially and has almost completed the REACH procedure (Peters, 2017). At least one new location, Den Helder, is considered for struvite recovery in the near future. For recycling of phosphorus from ash the two sludge processors SNB and HVC made a contract to deliver the ash from their mono-incinerators to EcoPhos. ICL Amsterdam is developing the RecoPhos technology to be able to process ashes. But because SNB and HVC have a contract with EcoPhos, ICL will probably process other type of ashes instead of the Dutch sewage sludge ash. Institutions stimulating the supply side are almost absent. But one of the main hurdles to put a good product on the market is the lack of clear quality standards for the recycled phosphates, except when the product meets the definition of EG-certified fertilizers.

About the supply side, Interviewee 3 said 'on one the hand you have the waste streams, from where you can recover products and on the other side you have the buyers. The initiatives all come from the supply side. The consumers are not the problem owners'. Interviewee 8 sees no barriers for the supply side as he says 'the supply will come, only the question is whether you are able to sell it. The technology is coming, not only in the Netherlands. The challenge is how to connect the two sides and ensure the phosphate gets from places where there is too much to places where it is needed'.

From the interviews there is no indication the supply side is regarded as under developed. The data shows there are several installations for struvite and the delivery of ash for phosphorus recycling is expected to start in 2018. The amount of installations is quite small, but this research could not indicate for how many other locations struvite recycling would be viable in the current situation. There are no institutions stimulating phosphorus recovery except the water quality standards which serve as a driver to remove phosphorus from the effluent in MWWTPs.

Based on the conclusion that there are several installations, although the quality varies and that the interviewees do not indicate a problem with the supply side, but also seeing there is room for improvement, the supply side of struvite regarded as medium developed. For phosphorus recycling from ash the supply side is underdeveloped, based on the fact that there is currently no production yet.

Functioning of the demand side

Demand-side covers all actors that use recycled phosphates and for example institutions that stimulate the demand for a certain product. Actors can include intermediary consumers such as retailers and consumers such as farmers and industry.

The demand side is mentioned by many interviewees as a problem. Interviewee 3 says that the market is an obstacle. 'The problem is that the market is unknown or there is no contact with it'. Interviewee 1 said an exploration of the market was done but that he did not believe that all the potential consumers are identified. Interviewee 8 states 'the problem lies for the biggest part at the demand-side. The question is can you sell it? That is the most important question. And this has two sides, can you sell it because there are other countries where there is a shortage of phosphate and you want to bring it to there, but also what kind of products are you making from it'. His answer explains that the demand-side in the Netherlands is hindered by the phosphate surplus but that also the characteristics of the product influence the demand. One of the aims of the Ketenakkoord Fosfaatkringloop was to create a market for recovered phosphate. Interviewee 8 says to this 'creating a market, when has that been done? For example, we made several steps, that is what you can say, but the market is not there yet, let alone the European Market'. He specifically states the market is not developed yet.

Interviewee 1 sees that the Netherlands is a phosphate saturated market and if you come with a phosphate product on the market, the farmer will first get rid of his manure before he is going to put phosphate on his land. Interviewee 3 explains steps are taken to look for a European market, because East and South Europe have regions with shortages. But they are not really enthusiastic for recycled products from North West Europe. Interviewee 6 sees problems with the characteristics of struvite in the demand development. 'Struvite is not really the product that somebody wants, it can be allowed but that is different than that somebody really wants the product on large scale'.

Interviewee 7 looks positively to the future, he expects the discussion on CE is going to play in the USA and Asia, thereby creating opportunities. Thereby he seems to refer to business opportunities for selling the technology and not the recovered phosphorus itself. He expects the phosphate demand to increase by 2% worldwide, but that West-Europe stays stable and for East-Europe a small increase can be expected. And Interviewee 8 says, as an answer to whether we can reduce phosphate import, that the development will take time and that it will be 2030 before we can substantially play a role in this field.

To conclude, the identification of the consumer is difficult. There are not many consumers in the Netherlands, especially not for the direct use of struvite. The demand for phosphorus from ash is not known yet. There are no institutions support demand development and actually is the low alignment with current legislation acting as a barrier.

For those reasons the demand-side is regarded underdeveloped for both ways of recycling phosphorus.

Functioning of the supportive substructure

The supportive subsystem encompasses government agencies, ministries, investors and other types of organisations that support phosphorus recycling. It includes laws and policies from the government. The supportive substructure can be viewed from a financial perspective and from a government perspective.

The case study revealed not many external investors. Most of the investments are made by the actors themselves such as the water boards and ICL. It deemed that the amount of subsidies for struvite and ash technologies was low, see also 6.3.4. The interviewees mention the missing subsidies for pilots and implementation. It seems not to be a very important barrier for struvite recovery, but the current ash technologies have higher investments costs and the speed of development could be improved if investments were raised.

The study of Buckwell and Nadeu (2016) calls the substantial set of legislation on nutrient management in Europe reassuring and alarming. To their opinion does the amount of legislation means Europe is looking into nutrient management but also that the problems are not resolved yet. This could be due to wrong regulation, gaps in regulation or poor implementation.

On the role of the government, the interviewees have different opinions. Interviewee 8 of the ministry of Infrastructure & Environment says he thinks it is important to work together with society, with actors that want to do something and therefore the ministry is an active member of the Nutrientplatform. On the question whether the ministry of I&E has a vision, he answers 'yes, but at the moment not in the sense of a quantitative goal. We had some discussions about that, but it is very difficult to say for example we want to recover 80% of the phosphate in 2000. It is very difficult to set such goals, to determine whether a goals is achieved and to determine whether the goal is feasible'. The current objectives are formulated as actions to be taken (I8, 2016). Interviewee 3 feels the actions of the government show the government is taking a facilitating role and they do not imposing anything[19]. The Dutch mind-set is that the government wants to facilitate initiatives and that market parties should take things up instead of obligations coming from the government (I3, 2016). The words of Interviewee 8 are in line with this: 'but we also let things happen. That is the energetic society, we, as the government, are not going to do everything. Companies also come with ideas'. The perception of Interviewee 2 is that the government is risk avoiding and thereby inhibiting innovation. Sometimes there is opposing legislation and he calls for the government to think along with innovation instead against it (I2, 2016). Interviewee 1 thinks the government could stand up and act as an actor that can guide the developments. On the other hand he sees that there is quite good communication with the government if you look at the agreements such as the Green Deals. 'Then it is a shared interest' which makes it easier to work on the goals. He sees it is important to have the decision makers on your side to start the projects (I1, 2016). Interviewee 7 is quite positive about the role of the Dutch government as they are helping his company a lot more than the government in Germany and especially Arnoud Passenier from the ministry of Infrastructure & Environment and of ESPP helped to create possibilities. The biggest fear of him is therefore that the financial cuts at the ministries will endanger the delegation of the ministries in the Nutrientplatform, while it is a crucial aspect for innovation to sit with officials around the table (I7, 2016). But Interviewee 7 also thinks more could be done by the government. The government has a lot of information on who is doing what. If they are more active in using this information, they

[19] The interviews took place before the publication of the CE program. It is not known if the CE program altered the interviewees opinions.

could create clusters or shared initiatives. But the mind-set of the officials is not in this direction (I7, 2016).

But the regulations of the EU also impact the phosphorus recycling in the Netherlands. And Interviewee 8 points out that the relevant regulations do not all fall under the same person. For example, the Fertilizer Directive falls within Enterprise, because it is a trade product and therefore does not fall within Agriculture. ’And that is difficult in Brussels[20], those pillars’.

To conclude, the financial support seems underdeveloped, which can be a threat especially for the further development of phosphorus from ash recycling. The government is trying to support the developments, by being active in the Nutrientplatform and by creating Green Deals to support innovation, but on the other hand is the legislative field and the time it takes to change things slowing down the development. Both routes experience legislative obstacles. For those reasons the supportive substructure is regarded as medium developed for both pathways.

Functioning of the intermediary substructure

The intermediary substructure encompasses actors that improve relations between all subsystems with a specific focus on linking supply and demand. These can be retailers, consultants and other type of actors. Policy programs aimed at collaboration are part of this substructure as well.

The Nutrientplatform is playing a crucial role in the intermediary substructure. It connects the supportive subsystem (ministries), the knowledge substructure (KWR) and the supply-side (ICL, UvW) with the demand-side (Aquaminerals, ICL). Interviewee 8 says ‘the Nutrientplatform as organisation is actually more important than the agreements that were made’. According to Interviewee 3 there is a ‘ons-kent-ons’ network with people working on phosphorus recycling, which means everybody knows who is working on phosphorus recycling, partly due to the small but active group of actors. Interviewee 7 also acknowledges the importance of the Nutrientplatform by saying it functions as an important tool to meet people from the value chain. But the demand-side is still underrepresented in this platform. The Nutrientplatform functions also as a link to the European playing field. The Nutrientplatform functions both as a learning and a political network. Such a network is important as it can influence future expectations, share a set of beliefs and can influence the political agenda. And this again is important to gain access to resources and change the institutional environment (Vasseur et al., 2013).

Besides Nutrientplatform, are companies such as Grontmij and Tauw, who connect water boards with technology providers, and the organisation Aquaminerals, who connects supplier (water board) with consumers (ICL and others) functioning as intermediary actor. Rules such as working according ‘the golden triangle’ in EU or Dutch TKI projects, which means knowledge institutes, companies and government should be involved, are stimulating collaboration, see Subsection 6.3.6. Retailers, who can be the link between supplier and final consumer or companies that can blend fertilizers are still lacking in the intermediary substructure.

Barriers that can be linked to intermediary functions, like lack of knowledge dissemination (K1), gap between practice and research (K4), lack of awareness of intermediaries on developments (K6), lack of trust between companies (S9) and cartel regulations hinder collaboration (I7), are rated as low or unknown. On the other hand, the intermediary substructure in the form of a platform can contribute to creating legitimacy by influencing the institutional context. And currently, low alignment with policy is a strong barrier.

[20] With Brussels he refers to the European Institutions because Brussels hosts European institutions such as the European Commission, Council of European Union and the second seat of the European Parliament.

To conclude, the intermediary substructure shows a strong connector in the shape of the Nutrientplatform. However, the link between supply and demand is still weak. For that reason the intermediary subsystem is rated medium developed.

Functioning of the knowledge substructure

The knowledge substructure encompasses actors involved in knowledge development, assessment and dissemination, such as public and private research institutes and educational programs.

In the case of struvite, various studies took place, see Section 4.5 but there is still need for new research. The knowledge sector functions quite well with pilots and full-scale plants that are being developed and information is shared between parties on national and international level. STOWA plays an important role in the knowledge creation and dissemination in the Netherlands. Of the technologies that are implemented in the Netherland, have Airprex and Pearl participated in the P-REX project of the EU, sharing information on their technologies and allowing a LCA.

The situation for ash is different. According to Interviewee 7 the technology (RecoPhos) is not yet matured. ICL has set-up a team to work on the further development of the technology and these people are contracted for the duration of the project (I7, 2016). In the case of ash, information on knowledge development was less easy to find, except some information of the consortium working on RecoPhos. My interpretation is that this is because the ash-technologies are in the hands of commercial companies while the research on struvite is done by public bodies. To what extent knowledge dissemination takes places on larger scale is also unclear.

To conclude, because of the amount of research that has taken place, both in the Netherlands and at EU level, the knowledge subsystem seems to be well-developed for struvite. The current practices do not seem to hinder the further development of struvite recovery. Because the knowledge development and dissemination is less obvious for the phosphorus from ash, it is more difficult to assess the development of this subsystem. It is concluded that because of the lack of clear R&D and mostly the lack of large scale pilots, which hinders the belief in the potential of the route, the knowledge subsystem is regarded as under developed.

Conclusion functioning of substructures

Table 8. Conclusion of the functioning of substructures

Subsystem	Supply	Demand	Supportive	Intermediary	Knowledge
Struvite	+-	-	+-	+-	+
Ash	-	-	+-	+-	-

6.4. Conclusion of barrier analysis & validation

The previous Section identified which barriers of the barrier list were experienced in the case study. In this Section, the barriers, which were rated as medium and strong, are summarised for both routes. The barriers rated as strong are considered the most important. The results of the analysis are checked by a small validation step.

After the analysis, six of the interviewees were asked to rate the barrier list in order to have a quick validation step. Three interviewees were able to deliver the results in time, which are used to reflect on the outcomes. The participants were asked to rate the barriers on a scale from 0 to 2 for both struvite and ash. The three respondents were Interviewee 6, 7 and 8. The barrier list that was send to the interviewees can be found in Appendix B.

Validation approach

The outcome of the barrier analysis was considered of a higher value than the individual opinions of the respondents, so if only one of the respondents had a different opinion, the outcome of the barrier analysis was leading. If two respondents have a different opinion, the outcome is reconsidered. If three respondents disagree, the rating is changed.

For the conclusion, only the strong barriers are important. A barrier is rated strong when:

- The barrier was rated strong in the analysis and was also mentioned by at least one respondent as being strong.
- The barrier was rated low or medium in the analysis, but at least two of the three respondents experience it as strong.

6.4.1. Conclusion on important barriers for struvite route

Figure 18 presents the outcome of the analysis for struvite. Most barriers are related to institutional, financial and social aspects.

I3 Absence of regulatory pressures
I4 Regulations change slowly
I6 Recycling rates focus on quantity and not on quality
F3 Negative financial landscape developments
F4 Financial support for incumbent industry or absence of tax system supporting sustainable product
F14 Externalities are not taken expressed in the price
If2 The scale of supply is too small
K10 Lack of knowledge and awareness of CE principles
S1 No belief in the potential of the technology
S6 Waste management is focussed on discarding waste with minimal societal damage
S7 Incumbent companies are not willing to cooperate
S12 Consumers interest is not reflected in sustainable buying behaviour

I1 Low alignment with current legislation
I9 Lack of CE standards for recycled products
T2 Risk associated with the product
T6 Limited quality of the product
F10 Application is too narrow
F13 Price of raw materials is lower than recycled products
S5b Lack of a sense of urgency by consumers

Figure 18. Analysis: medium and strong barriers for struvite

Validation

The three respondents gave different answers, but all of the barriers identified as strong in the analysis, were mentioned at least by one of respondents. The low alignment with current policy (I1), the lack of CE standards (I9) and the narrow application of the product were mentioned once (F10), while the risk associated with the product (T2) and the low price of raw materials (F13) were named by two persons. Also the lack of a sense of urgency (S5b) was labelled by two respondents as a strong barrier. However, barrier T6 was mentioned by one respondent as weak to strong with the comment this was of course depending on the producer. The two other respondents regarded T6 as low and medium.

In addition other barriers were rated as strong by the respondents. The vagueness around using the waste hierarchy (I5) was mentioned by 2 respondents and the following barriers were rated as important by one of the respondents: lack of regulatory pressures (I3), the low quality of the product (T3), financial support for the incumbent industry or lack of support for sustainable systems (F4), the low price/quality ratio (F11), the lack of data on phosphorus flows (K9), the feeling the incumbent industry is not willing to cooperate (S8) and the fact that consumers interest in sustainability is not translated in the buying behaviour (S12).

Including the validation step, I1, I9, T2, F10, F13, S5b and I5 are rated as important barriers for struvite. Based on the validation, it was decided that T6 was not strong enough to be regarded as strong, see Figure 19.

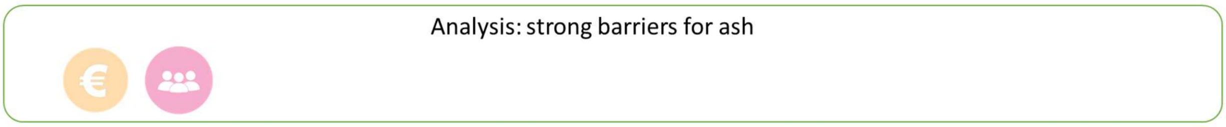
I1 Low alignment with current legislation
I5 Lack of clarity on how to use waste hierarchy
I9 Lack of CE standards for recycled products
F10 Application is too narrow
F13 Price of raw materials is lower than recycled products
S5b Lack of a sense of urgency by consumers
T2 Risks associated with product

Figure 19. Conclusion strong barriers for struvite

6.4.2. Conclusion on important barriers for ash route

Figure 20 presents the outcome of the analysis and shows the medium and strong barriers of the ash route. The analysis shows that less barriers are regarded strong for the ash route than for struvite.

I1 Low alignment with current legislation
I3 Absence of regulatory pressures
I4 Regulations change slowly
T2 Risks associated with product
F4 Financial support for incumbent industry or absence of tax system supporting sustainable product
F8 High investment costs
F9 Long payback period
F9 Long payback period
F5 Not enough financial resources for producer
F14 Externalities are not expressed in the price
If3 Low alignment with incumbent infrastructure
S8 Incumbent companies are not willing to cooperate
S11 Consumers interest in sustainability is not reflected in buying behaviour .



F13 Price of raw materials is lower than recycled products
S5b Lack of a sense of urgency by consumers

Figure 20. Analysis: medium and strong barriers for ash

Validation

The answers of the respondents gave a different view on the situation. Interviewee 7 and Interviewee 6 are involved with the ash route, which makes their answers on the ash route more interesting.

The missing sense of urgency by consumers (S5b) and the low price of raw material (F13) were confirmed by two of the respondents as a strong barrier. In addition, six other barriers were regarded as strong by two of the respondents: The low alignment with the current legislation (I1), the lack of regulatory pressures (I3), the high investments costs (F8), the related long payback period (F9), the limited application of the product (F10) and the bad price/quality ratio (F11).

According to Interviewee 7 there are also barriers from a knowledge perspective as he rates the lack of R&D projects (K2), lack of knowledge on how to use the product (K11) and the lack of knowledge on CE principles (K10) as having strong impact. From the social barriers, he beliefs that the lack of belief in the potential of technology (S1) and the lack of sustainable consumer behaviour (S12) are hindering more phosphorus recycling from ash. Furthermore, he experiences the slow changing policies (I4) as a strong barrier. Interviewee 6 beliefs the financial support for the incumbent system (F4) and the unwillingness of incumbent companies to cooperate (S8) are a barrier for this route.

To conclude, the quick validation step led to more insights in the barriers experienced in the ash route. Including the validation step: barrier I1, I3, F8, F9, F10, F11, F13 and S5b are regarded as strong barriers, see Figure 21.

I1	Low alignment with current legislation
I3	Absence of regulatory pressures
F8	High investment costs
F9	Long payback period
F13	Price of raw materials is lower than recycled products
S5b	Lack of a sense of urgency by consumers

Figure 21. Conclusion strong barriers for ash

6.4.3. Conclusion on functioning of substructures

According to the analysis, the demand-side is for both routes underdeveloped. Furthermore, both the supply side and the knowledge substructure are underdeveloped. This means also the current state of these two substructures are hindering the growth of phosphorus recycling from ash. The validation step with the interviewees showed a different view on the substructures, see Table 9.

Table 9. Validation step substructures

Substructures	Struvite		Ash	
	Analysis	Interviews	Analysis	Interviews
Supply	+-	+- / +- / +-	-	- / + / +-
Demand	-	+- / - / -	-	- / - / -
Supportive	+-	+- / +- / +-	+-	- / +- / +-
Intermediary	+-	- / - / +-	+-	- / - / +-
Knowledge	+	+ / + / +-	-	+- / + / +-

The validation step shows that most of the respondents experience the demand-side as underdeveloped for both routes, which is in line with the outcomes of the analysis. The same holds for the answers of the respondents on the supportive substructure, as most of them rate the supportive substructure as medium.

The interviewees are more negative about the state of the intermediary substructure. In the validation however, the barriers, that were expected to contribute to the development of the intermediary substructure, were rated as low. In the attachment that was sent to the interviewees, the intermediary substructure was explained as including actors and regulations connecting the supply and demand side. This description can explain the different outcomes with the rating of the author in the analysis, because the author used the broader definition of the intermediary subsystem in which intermediaries contribute to improving relations between all subsystems. For that reason, the overall intermediary substructure is stated to be medium developed.

The interviewees show different opinions on the development of the supply-side of ash, from underdeveloped to good developed, while the supply-side was rated as underdeveloped by the analysis of the author. However, the expectancy is that within two years the first phosphorus can be produced. Therefore, the outcome of the analysis is adapted to medium, which was the average outcome of the validation step. The knowledge substructure of ash is rated moderate to good developed, while the author's analysis expected the current state of the knowledge substructure is hindering the development.

The knowledge subsystem for struvite is rated medium to good, quite well in line with the analysis. The opinions on the supply-side of struvite are also in line with the analysis.

To conclude, the validation step shows that the demand substructure and the link between supply and demand need more attention. The input of the validation led to adjusting the rating of the knowledge and supply substructure of ash to medium developed. See Figure 22 for the conclusion.

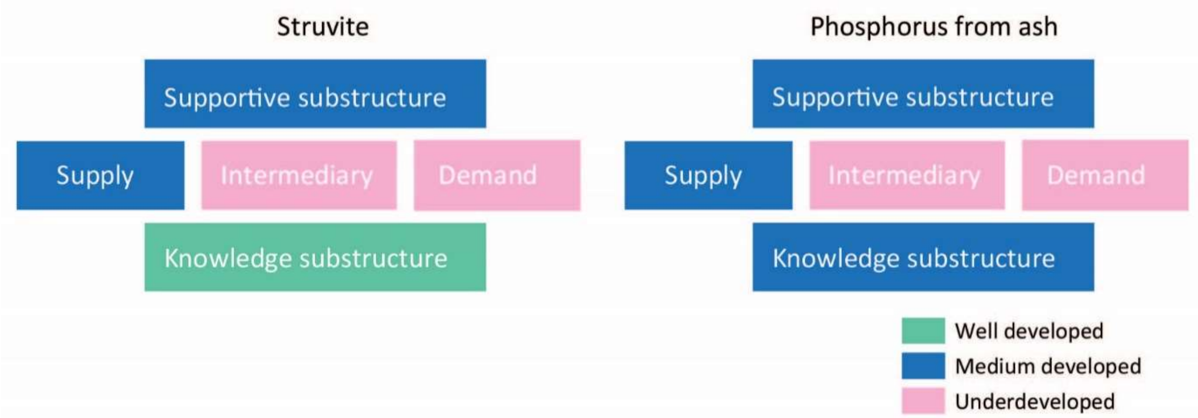


Figure 22. Conclusion on development of substructures for ash and struvite

6.5. Conclusion on functioning of the system

The demand and intermediary substructure need to be further developed. The barrier identification has shown that the demand for struvite is hindered by risk association, the low price of raw material and lack of a sense of urgency. For ash, the lack of a sense of urgency, the low price of raw material, but also the low alignment with current legislation, the limited application of the product and the bad price/quality are hindering the demand-side development. For the supply-side of ash the high investment and long payback period are as barriers. The improvement of the supportive substructure can be expected if the low alignment with policy and slowly changing policies are addressed. The intermediary substructure needs to be more developed, to improve the link between supply and demand. That said, the analysis shows that the Nutrientplatform is an important actor in the intermediary substructure and provides the opportunity to further link supply and demand by bringing actors together.

Section 6.2 showed there are drivers on both international and national level that stimulate phosphorus recycling in general. These driving forces are the stimulation of Circular Economy, reducing the independency of phosphorus import and reducing the environmental impact. For the Dutch context the phosphate surplus and the opportunities that companies see for contributing to Circular Economy are drivers for phosphorus recycling. These aspects support phosphorus recycling in general and not specifically phosphorus recycling via the communal wastewater chain. More specific for the communal wastewater chain the discharge requirements for wastewater, the Ketenakkoord Fosfaatkringloop and Green Deals are drivers. The actors of the supply-side show the most incentives to be active, which explains the current supply driven situation. Actors active in phosphorus recovery are driven by cost reduction, business opportunities and are motivated for recycling by their sustainability perspectives or the wish to serve as a role model.

Struvite recycling is in a further stage of development when looking at the amount and type of technologies installed at the Dutch MWWTPs. Recovering phosphorus from ash is still an earlier phase of development but carries the promise of high recycling potential. However, as can be seen from Figure 16 in Subsection 4.4.1, the recovery of struvite has influence on the P-content, and in that way on the feasibility of phosphorus recovery from ash. Not only ash, but the struvite can also be used as input for fertilizer production. This makes a clear separation of the two routes impossible. The fact that both routes are complementary and competing has been pointed out by the involved actors as well. This point will be further elaborated in the discussion.

7 Discussion

In this chapter the results of the analysis are discussed. The barrier analysis has delivered insights on the barriers experienced in the two routes for phosphorus recycling. This chapter will go into the linkage between the two routes, the problems that occur because of this relation and on how the barriers itself are interlinked.

7.1. Interrelation of the two recycling routes

The two routes, struvite and ash are interlinked. As explained in Subsection 5.4.2 the recovery of struvite from wastewater influences the amount of phosphorus in the sludge and thereby the economic feasibility of recovering phosphorus from sludge. The two routes, struvite and ash, are partly conflicting, but not interchangeable. The routes deliver different type of products and work on a different scale. The ash route can recover phosphorus on a larger scale than struvite and the technologies can process ash from different sources. However, recovering struvite at the MWWTP has advantages on financial grounds and has environmental benefits.

The data indicates there is small friction between the two routes. As Interviewee 1 says: 'There is some competition on whether you do recovery at the treatment plant or through EcoPhos' (I1, 2016). Interviewee 3 said that according to the sludge processors struvite has only a marginal contribution to the phosphate problem (I3, 2016). Interviewee 7's sayings support this opinion as he said that the yearly struvite production in the Netherlands is on average the amount of material that his factory processes within two days. Interviewee 6 even states that the focus of the water boards on struvite recycling prevents getting the phosphorus recycling towards a higher level (I6, 2016). But the water boards have their own incentives and opinions on recovering struvite in their MWWTP.

In the ambition plan of the Nutrientplatform the conflict clearly comes forward. HVC stressed the importance of making decisions together as the sludge processor states they can have problems with phosphorus recovery from ash if the water boards are recovering struvite and reducing the concentration of P in the sludge. Therefore, the shareholders of HVC have agreed upon not recovering struvite, but if they have to, due to problems in the water treatment, HVC will receive the struvite to be able to keep the P-concentration in ash high enough to sell the ash to EcoPhos (Nutrientplatform, 2016c). Another example of the importance to work together are the words of Henry van Veldhuizen of the EFGF in an article: 'It is fine if companies want to treat their wastewater themselves and want to recover nutrients, but that is not convenient if the water board has just invested in a central installation to treat their wastewater. Those high costs will not be recovered' (Hooimeijer, 2014).

The growth of the two routes independently can lead to suboptimal use of resources and possibly to a situation in which optimal phosphorus recycling does not take place. These two routes cannot be assessed separately, but must be seen as one system. For that reason an idea on how these two routes should develop in the future is desired.

7.2. Towards a future state of phosphorus recycling in the communal wastewater chain

As described in the previous Section, the two routes of phosphorus recovery are complementary and partly competing. If both routes are stimulated to grow, the effectiveness of investments can be reduced and conflicts can occur as recovering phosphorus earlier in the value chain reduces the recovery potential downstream the value chain. To optimize phosphorus recycling a system approach should be used and a good integration of both routes is needed. In this Section a vision on how this future state looks like and which extra barriers occur towards reaching this future state will be elaborated.

7.2.1. Creation of a future state

The data showed there is no clear vision on how phosphorus recycling in the Dutch communal water chain should take place. In order to move to a desired future state, the determination of such a state is needed.

To create an optimal situation, the drivers behind phosphorus recycling can act as starting points. As stated in the introduction the phosphorus recycling is driven by three main goals: prevent scarcity, reduce dependence on other countries and reduce environmental impact. This means phosphorus recycling needs to meet the following criteria:

- High amount of recovered phosphorus, to reduce phosphorus scarcity
- Produces a phosphorus product that is usable, to reduce the dependency of import
- Phosphorus is recovered by a sustainable process, to reduce environmental impact

The following conditions are desired as they can lead to a faster growth of phosphorus recycling:

- Fast implementation process
- Compatible with current infrastructure
- Collaboration and shared goal with a big group of actors

Meeting the criteria

The two methods are rated to what extend they meet the criteria. A rate between - - to ++ is given by the author, in which - - means 'not meeting the criteria at all' and ++ means 'meeting the criteria to a large extent'.

Table 10. Meeting criteria for future state development

	Struvite	**Ash**
Criteria		
Potential amount of recycled phosphorus	+- (maximum of 40% input MWWTP)	++ (90-95% from ash)
Usable product	+- Only one type of technology produces a ready product, which can applied for niche applications. The other struvite can be used as input for fertilizer production.	++ The product can be used as input for fertilizer production and in the chemical industry
Sustainability	++ The installation of a struvite reactor reduces maintenance needs at the MWWTP. The LCA shows struvite is more sustainable than mineral fertilizers and	+ The sustainability differs per process, but LCA indicates the use of ash recycled phosphorus is more

	more sustainable than the current ash technologies[21].	sustainable than mineral fertilizer production.
Preferred conditions		
Fast implementation process	+ Technology can be implemented at biological WWTP	+- A new production facility needs to be build
Compatible with current infrastructure	+ technology fits in current biological treatment plants, some struvite product need further treatment to be used	+- New production facility is needed, produced phosphorus can be used directly

Preferred future state

The advantages of the struvite recovery are a lower environmental impact and the easy implementation in the current system. The advantages of the ash route are a high phosphorus recovery rate, a large scale potential and diverse application possibilities of the product.

To be able to use the advantages of both routes, I think a combination of the two routes is desired, as this leads to:

- A balance between sustainability and maximum phosphorus recovery.
- The biggest potential for collaboration and a combined vision of the stakeholders.

The preferred future state is therefore:

Recovery of struvite where possible, to reduce the environmental impact of wastewater treatment, without compromising the ability to recover phosphorus from sludge ash.

In practice this means a minimal level of phosphorus needs to stay in the sludge to be able to keep phosphorus recycling from ash feasible. This could be done by bringing the struvite back in the sludge in order to keep the minimal phosphorus limit. This future state is in line with the conclusion of STOWA (2016b, page V): STOWA states that struvite recovery should happen where possible and the sludge of those MWWTPs should go to other sludge applications than mono-incineration. Sludge from MWTTPs without struvite recovery should be burned in mono-incinerators to recover phosphorus from sludge ash. Further, STOWA states that a sustainable roadmap should be developed for the phosphorus recycling in the communal water chain (STOWA, 2016b). Such a roadmap can guide decisions within the communal wastewater chain and can prevent ineffective investments due to conflicting projects.

7.2.2. Barriers towards a combined future state

The preferred future state is a combination of both routes and this state is only reached when actors in the value chains cooperate. Looking with this perspective to the barrier list, some of the barriers in the barrier list become more profound. These are the barriers related to collaboration.

From the barrier list, the main barrier is expected to be:

[21] This LCA is based on the use of struvite as a direct fertilizer. To what extend the LCA outcome changes if struvite is used as input for fertilizer production is not known.

- No clear vision on how phosphorus recycling should take place

Although it seems quite logic that the lack of a vision can hinder reaching a desired future state, it is important to see what this actually mean in practice. Most probably the main reason for not having a clear vision on phosphorus recycling, is that there are very different perspectives on what should be the optimal route for phosphorus recycling in the communal wastewater chain. Getting the actors aligned in their visions can be a real challenge. The interviews indicated already there are different perspectives, for example on the contribution of struvite to phosphorus recycling. At the moment the actors are not indicating the lack of a vision is a barrier. They work together on issues that they can tackle together. However, creating a vision is not only important for the discussion between struvite and ash, but also to discuss further development of the value chain and the impact of future innovations.

The following barriers can hinder the process of vision generation or hinder reaching a created vision:

- Incumbent industry is not willing to cooperate

The incumbent industry are mostly the actors themselves. The technologies are developed by new actors but the actors installing the struvite and ash technology are part of the incumbent industry. The willingness to cooperate and to let go of traditional visions can hinder the creation of a shared vision. Interviewee 6 is very outspoken and he sees the attitude of the water boards as a potential barrier towards a shared vision, because the water boards show a profound belief in the importance of struvite recycling to contribute to the phosphorus challenge, while Interviewee 6 thinks the contribution of struvite is only marginal when looking at a larger scale. He thinks more attention could be paid to how the water boards contribute to phosphorus recycling in the ash route. Furthermore collaboration of agriculture, more fertilizer companies and the chemical indstruy is needed.

- Cartel formulation legislation maybe hinder collaboration

At the moment this is not a problem, but if collaboration increases between actors in the value chain regulation on cartel formulation could lead to barriers to cooperation.

- Lack of trust between firms

Lack of trust between firms can reduce the willingness or effectiveness of collaboration between firms. It can also lower the chances of realising a shared vision.

- Responsibilities at different governmental departments

A barrier that was not on the list, but which came up Subsection 4.1.1., is the fact that the responsibility on nutrient problems is spread over different departments within the government. This issue was also pointed out by Hoppe et al. (2016). To address a future state or reached a shared vision, the government should increase collaboration between their departments. In this phosphorus case these are the ministry of Infrastructure & Environment and the ministry of Economic Affairs.

- Conflicting views on sustainability

This barrier came up during the reflection and therefore can be found in Section 9.1.2.

7.3. System approach to barriers

Whether or not a shared approach towards phosphorus recycling is taken, the barriers that were found in the barrier analysis are still in place.

These barriers are often interrelated and the presence of one barrier enforces the other barrier. Kuokkanen et al. (2015) stated in their research: "As many of the failures are actually inter-related and coevolutionary, an unequivocal disentangling is neither possible in a straight forward way, nor desired". In other words, the barriers cannot be seen separately and should be addressed as a cluster. The use of substructures is one way to address the barriers as a cluster. The analysis showed the demand development was underdeveloped and by the analysis of the intermediary substructure, the link between supply and demand was identified as weak. The identified barriers of the barrier list have been grouped by the author into several issues and related to the substructures. First demand development as general barrier is described, followed by aspects influencing the demand development.

Demand development

Struvite has been developed with a supply push. The consequence of this development is an underdeveloped demand side. One of the measures to stimulate the development of the demand side, is to introduce regulatory pressures. Regulatory pressures, such as a minimum amount of recycled phosphorus in products, will only be accepted if the product itself is accepted. The social acceptance and the consumer acceptance are preferred pre-conditions to be able to implement legislative pressures. One could understand that a government will not implement regulations or will experience great resistance if the product is regarded as dirty or unsafe. Addressing the farmers alone to stimulate the use of recycled phosphorus will not work out well if retailers or other buyers of their products are resisting the use of products with recycled phosphorus. Therefore, not only research is needed to find out what the demands of the consumers are, but also in what way the consumers are experiencing barriers towards buying the recycled phosphorus. The collected data in this research was not sufficient enough to research more in-depth potential barriers of the farmers or chemical industry.

Two barriers of struvite that enforce each other are the niche application and economy of scale. A bigger supply is mentioned as a solution to get more companies interested, but on the other hand is the niche application of struvite mentioned as a barrier. An increase of supply will make struvite probably more interesting as input for fertilizer production, but if the struvite producers want to stimulate the direct use of struvite, other markets outside the Netherlands must be found.

When the full-scale plants of EcoPhos and RecoPhos have been installed and are running, the phosphorus recovery from ash can further develop. The possibility to use recycled phosphorus in the industry will hopefully attract sustainable companies who want to exchange their mineral phosphates into more sustainable alternatives. The use of recycled phosphorus by companies can create a positive feedback loop, because these companies often communicate their sustainable steps to a broad audience. Frontrunners are therefore able to reach general public and other companies in their field.

For the further demand development four main issues were defined and discussed hereunuder.

Risks and public acceptance

One of the problems with the product acceptance of struvite are the risks related to the use of the products. Several interviewees have mentioned the problem of pathogens and drug residues in the struvite. For ash, the heavy metal content can become a problem, but as the product is still under development, the discussion on risks is still small.

To address this issue, actions are needed on knowledge level, on social level and on legislative level. Knowledge is needed to develop methods to measure pathogens and drug residues in the recycled phosphates. Second, criteria for recycled products must be established to make certification and alignment with legislation possible. A critical review of current legislation on heavy metals in fertilizers is also needed. Third, process development can take place to improve the quality of the produced materials and last, social acceptance must be addressed. Research to understand the risk perception and factors influencing the acceptance must first be researched in order to address the social acceptance.

Price

The high price of recycled phosphates compared to mineral phosphates reduces the demand for the more sustainable alternatives. Opportunities to reduce the price barrier are financial measures, such as tax systems favouring recycled phosphates. Other possibilities include improving the technology and reduce production costs of the recycled phosphorus. For struvite another approach would be the further processing of struvite into higher valued products, which makes the struvite compete in a different market.

Low alignment with institutions

Low alignment with institutions is a great barrier towards the use and valorisation of recycled phosphates. Especially the EoW status, EU Fertilizer Directive and REACH certification play a crucial role in the whole recycling process. This barrier can be addressed by: (1) finding coalition partners and increase lobbying, (2) strengthen the scientific background to serve as a basis for changing the legislation and (3) to aim for legislative experiments whereby legislation is less stringent under specific conditions.

Sense of urgency

The lack of a sense of urgency from the consumers is experienced as a strong barrier. A standard approach is information sharing with the general public and potential consumers in order to increase awareness and explain the urgency of contributing to the phosphorus challenge. This has a knowledge and social perspective as in includes information sharing, but also changing the perception of people on how important issues such as phosphorus security and reducing environmental impacts are. The sense of urgency can also rise when formal institutions stimulate the use of recycled phosphorus.

Linking supply and demand

Organisations such as Nutrientplatform and Aquaminerals play an important role in linking supply and demand.The analysis of the intermediary substructure and validation indicate the connection between supply and demand can be improved and supply could be better adjusted to the consumer demand. As Interviewee 3 said about struvite: ‘The product has been developed because “it is possible” but not with the idea to think of who can use the product’. Therefore there is a strong need to involve possible users. Retailers, manure processors, fertilizer blenders could be involved to adapt the struvite to consumer demand.

For phosphorus from ash, it is expected that the produced phosphorus is used straight away in fertilizer production or other existing applications, which means the product is already tailored to the current demand. Still there is improvement possible in linking the supply and demand side to support recycled P-producers to find companies willing to buy sustainable phosphorus.

8 Conclusion

In the previous chapters the results of the data gathering and the analysis of the data have been presented, complemented with a discussion on the results. The aim of this research is to provide the reader with an understanding of the current state of phosphorus recovery in the communal wastewater chain and to identify barriers that are preventing the growth of phosphorus recycling. To be able to reach this goal, three sub-questions were formulated to guide the research. Here the answers to these sub-questions and the main research question are presented.

8.1. Answers to the sub-questions

To answer the main research question, first the sub-questions are answered.

Sub-question 1: What is the current state of phosphorus recycling in the Dutch communal wastewater chain?

In the Netherlands two methods are practised to recover phosphorus from the communal water chain: through phosphate recovery at the sewage treatment plants and by phosphorus recovery from sewage sludge ash after the sewage sludge is burned. There are two main types of municipal wastewater treatment installations: biological and chemical treatment. In the Netherlands phosphate is recovered at municipal wastewater treatment plants (MWWTP) with biological treatment.

For phosphate recovery at the MWWTP there are several technologies available and the technologies currently applied in the Netherlands are based on rejection water or crystallisation in digested sludge. There are currently 6 struvite installations running at municipal wastewater treatment plants in the Netherlands. STOWA (2013) calculated the potential amounts of struvite and P-recovery from ash. It showed that 2.7 kt P is possible through struvite recovery and up to 9.1 kt P from sludge ash.

For phosphorus recovery from ash the two Dutch sludge processors HVC and SNB are working with the Belgian company EcoPhos to recover phosphorus from their sludge ash, while the fertilizer company ICL has acquired the RecoPhos technology to be able to recover phosphorus from ash.

Sub-question 2: What types of barriers towards phosphorus recycling are described in literature?

The literature did not provide a clear framework to identify barriers in nutrient recovery cases. Therefore, it was chosen to create a barrier list from several theories. Recycling of nutrients involves recovery and reuse of the nutrients, which meant the theories should focus both on technology implementation for recovery and on market aspects that hinder reuse of the recycled phosphorus. The combination of the Functions of Innovation System theory and Circular Economy literature was used to create a barrier list based on six types of barriers. These types are institutional, technological, financial, infrastructural, knowledge and social barriers. Using the system perspective of Innovation Theories, the framework was completed by adding five concluding barriers, focused on the functioning of five subsystems: The supply-side, demand-side, supportive subsystem, intermediary subsystem and the knowledge subsystem. The complete list of specific barriers can be found in Section 3.5.

Sub-question 3: Which barriers are experienced in the recycling of phosphorus through the Dutch communal wastewater chain?

The barriers that were found to be strong in the analysis are presented here as answer to sub-question 3, see Figure 23. The rating of other barriers can be found in Section 6.3 and the concluding Section 6.4. The most important barriers relate to institutional and financial aspects. The barriers differ for struvite and ash due to the different characteristics of the products, the different scale and the stage of development.

The main barriers found for both routes in the system are:

- The low alignment with the current policy, the narrow application of the products, the low price of raw materials and the lack of a sense of urgency on the phosphorus problem by consumers.

The additional barriers for phosphorus recycling through struvite are:

- The lack of Circular Economy standards for products, the lack of clarity about the use of the waste hierarchy and the risks associated with the product.

The additional barriers for phosphorus recycling through ash are:

- The high investment costs, the related long payback period, a bad price/quality performance and the lack of regulatory pressures.

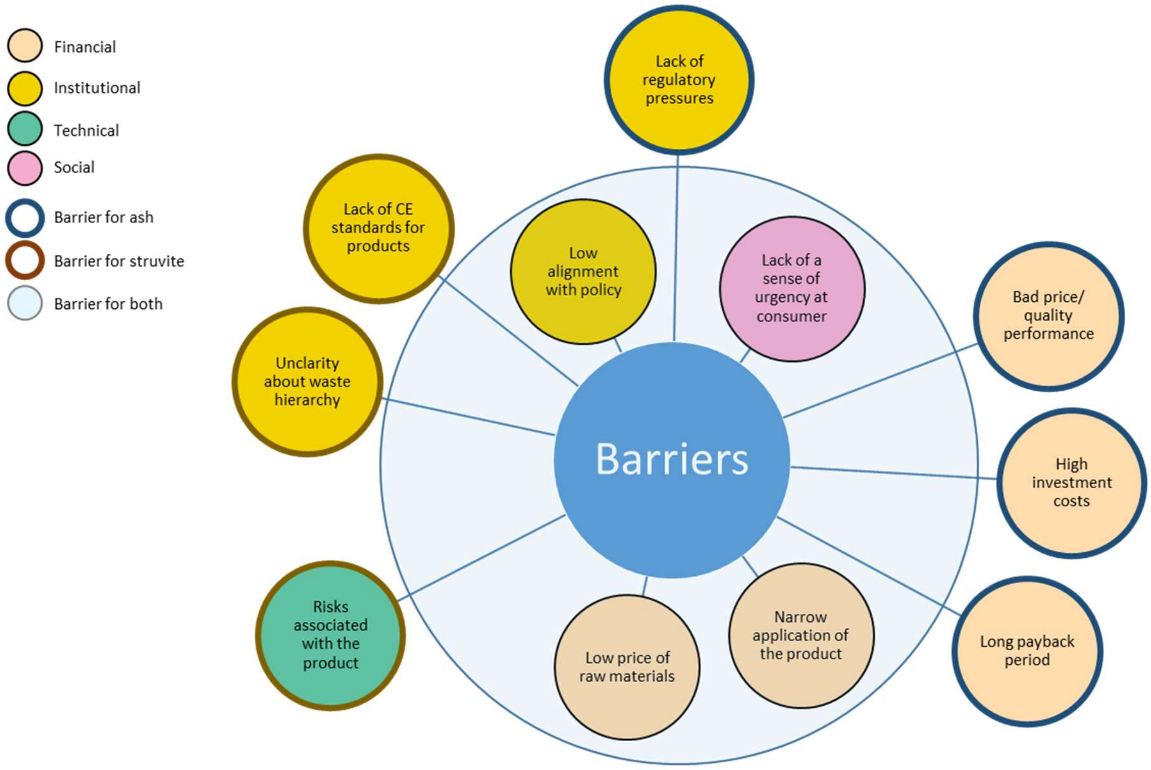


Figure 23. Most important barriers from barrier list

8.2. Answer to the main research question

The main research question of this research is:

Which barriers need to be addressed in the current situation to increase phosphorus recycling in the communal wastewater chain in the Netherlands?

The sub-questions have led to the identification of two routes for phosphorus recycling in the Dutch communal wastewater chain. These are struvite recovery at the municipal wastewater treatment plant and phosphorus recovery from sewage sludge ash.

The case study showed several positive points in the current situation, which stimulate phosphorus recycling. Stimulants are the Ketenakkoord Fosfaatkringloop, the Dutch ambition to strive for Circular Economy and the set-up of a Green Deal to stimulate phosphorus recycling in the communal wastewater chain. When looking at the actor field, the Nutrientplatform is a valuable organisation in the stimulation of phosphorus recycling. It is a small but active network containing the most active organisations that are advocating phosphorus recycling. The platform brings actors from the value chain together and tries to reduce barriers in collaboration with the government. The water boards are motivated to bring their recovered struvite to the market, which is expressed by the multiple studies on struvite and cooperation between Aquaminerals and EFGF to improve the valorisation of struvite. ICL Amsterdam is a frontrunner in the field of phosphorus recycling from secondary sources and is an example of how the current industry can contribute to more sustainable phosphorus use.

Despite these positive developments, the third sub-question led to the identification of barriers, hindering the growth of these two routes. As elaborated upon in the Discussion, the individual barriers should be approached from a system perspective and can be linked to the development of the subsystems.

From that perspective, the lack of demand development and the underdeveloped link between supply and demand are seen as the most important barriers towards recycling and should be addressed. There are different reasons causing the underdevelopment of the demand. For both routes, the lack of a sense of urgency by consumers and the low price of raw materials are hindering recycling. In addition for struvite, the risks associated with the product, which is linked to consumer acceptance, act as a barrier towards demand development. Thereby, the lack of criteria for the recycled products hinders reducing the risk association. In addition for ash, the bad price/quality is hindering demand. The lack of regulatory pressures, which was identified as a strong barrier for ash, hinders both demand and supply development. Next to demand development, the link between supply and demand must be improved, which could be done by better adaption of the recycled products to the needs of the consumer or by searching external markets.

The Discussion also pointed out that the two methods for phosphorus recycling are interrelated. For both routes steps can be advised to stimulate the development of phosphorus recycling, however a coordinated approach is needed. Without a clear vision on how phosphorus recycling in the communal water chain takes place, there is the risk of conflicting actions leading to suboptimal situations. This means cooperation between actors is needed to guide the developments and to prevent ineffective investments in the value chain.

9 Reflection

Reflecting on research gives the opportunity to look critical at the used methodology, the validity and the usefulness of this research. First is reflected on the used theory, secondly on the methodology and thirdly an Industrial Ecology perspective on the case study is described. The last part of this chapter includes a reflection of the author on this research.

9.1. Reflection on theory

To analyse the barriers for phosphorus recovery a theoretical framework was composed in Chapter 3. The framework generated a list of potential barriers, see Section 3.5, which was compared with the data found in this research. In this chapter the usability of the used framework will be discussed.

9.1.1. The used framework

The framework was based on the theory of Innovation Systems, Functions of Innovation Systems and on Circular Economy theory. Barriers from these three fields created a list of potential barriers in phosphorus recycling. The problem that arose by combining these three theories was the fact that they provided different types of barriers. First the usability of the three different theories will be described, followed by my experience of combining these.

Innovation Systems

The innovation system consists of actors, institutions and technology factors. Between these three structural elements, relations exist or emerge and form networks. The Innovation System was divided into five subsystems by Suurs (2009): Supply, Demand, Intermediary, Government and the Knowledge structure. In the beginning of this research it was chosen to transform the Government structure into the Supportive structure to be able to include investors in the Supportive structure. In the end I think this was not really necessary because the investors could also be included in one of the other substructures, depending in what type of investments are done.

One of the difficulties in using the substructures for my analysis was the definition of what beholds the supply side and what or who is part of the demand side. If the focus was on the use of the technology than the supply side consisted of technology providers and the demand-side included the water boards and waste stream owners. If the focus was on the production of recycled phosphates, the water boards would be regarded as the supply-side. If struvite produced at the MWWTPs was an end-product, the consumers or demand-side could be farmers, garden centres or other types of direct consumers. If the struvite from the water boards was sold as a resource for fertilizer production, the consumers were companies like ICL or industry. But these companies would in turn sell the products to the final consumer and could therefore also be seen as being part of the supply side. As the focus was on the whole supply chain instead on just the technology, it made the categorisation of the actors and institutions difficult. And some elements, especially institutions, are contributing to different subsystems. For example a tax law stimulating the demand is part of the demand-side and part of the supportive structure.

It was chosen to alter the definition of what a well-developed subsystem was, by focussing on the recycled product instead of the technology. This makes quite a difference because the innovation theory is normally used for technology development while now the focus was put on the end-product. Still, the analysis of the subsystems with this perspective was useful for the author. The barriers could be linked to the functioning of the different subsystems and it made it clearer that most of the problems were related to the demand-side and the link between supply and demand.

In the beginning of this research it was chosen to look more in-depth into Technological Innovation Systems instead of Sectoral Innovation Systems as a basis for the theoretical framework. The TIS seemed more suitable to specifically focus on the technologies. It turned out it was not possible to see them as separate routes for phosphorus recycling. From that perspective it could have been useful to use SIS instead. According to Bergek et al. (2015) sectors tend to exhibit high degrees of institutionalization with a stable network between supply-side actors. There should be sector-specific regulations, clear user practices and buyer-supplier preferences. The phosphorus recovery from ash could well fit into the fertilizer sector. Struvite on the other hand is experiencing more problems to integrate into the fertilizer sector. This is also because struvite is mostly recovered for maintenance purposes. To my opinion the use of TIS was still the better option to use in this case. If the aim would have been to improve fertilizer production, the SIS could be used for a broader scope.

Functions of Innovation Systems

The Functions of Innovation System theory identifies seven functions that contribute to the development of a technology. It is often used to study renewable energy systems. In the literature some critics on the theory can be found. Markard et al. (2015) reviewed six main criticisms and three of them are shortly discussed here as they were experienced in this research as well.

The first criticism is that the impact of the context could be better incorporated in the theory. Ghe context in which the technological development and dissemination takes place does not only influence the innovation system, but is in turn itself also affected by the developments in the system. The second criticism relates to the incorporation of politics in the framework. Beliefs, strategies and the roles of the various actors could be incorporated better in the analysis. This case study showed also that it is important to study the motivations and strategies of actors to understand their choices. One of the indicators of Market formation is ‘price/performance is bad’ but if consumers value the story behind a product, their willingness to pay more can go up. Such effects could be in cooperated in a more obvious way. The third criticism is that FIS does not provide a critical note on desirability of the chosen technology as part of the analysis. The FIS analysis can be used to stimulate the development and implementation of phosphorus recovery technologies, but as the Chapter Discussion showed, it is important to take a greater perspective and discuss whether or why the studied technology is the most beneficial to society.

The FIS theory is focused on the implementation of the technology but I used the barriers of FIS to look also at the use of the products coming from using the technology. FIS is used often for renewable energy technologies, but energy from renewable sources is for the user not different than electricity produced from fossil fuels. However, not all recovered phosphorus is a direct substitute for an existing product, especially in the case of struvite. Struvite has a specific composition of phosphorus, nitrogen and magnesium and is therefore not a direct substitute for other types of P-fertilizers. And sludge ash as input for fertilizer production requires a different technology than mineral rock phosphate.

Although there are some differences between studying a technology and studying a technology in combination with a product, I do think FIS is useful to study the latter.

Circular Economy

Circular Economy is a broad concept and based on several theories. Although a lot has been written about CE and about case studies on implementing CE principles, no framework or scientific based theories on Circular Economy barriers were found. For that reason, general CE barriers were mostly extracted from non-scientific sources.

This resulted in the fact that not all the CE barriers were applicable to the case study. On the other hand important barriers for nutrient recycling were difficult to extract. The worries about pathogens or pollution by using recycled materials is one of the issues that was not found in the sources used for the barrier list. Also, the social impact of recycled products was not addressed as much as the technological challenges in recycling were. The CE theory should include more social aspects such as consumer acceptance, beliefs and values that influence people's decision, because this type of barrier is underexposed in my opinion.

The combination of the theories

Each theories gave a list of barriers, but combining these gave difficulties. The barriers were partly overlapping, partly applicable on different levels and focused on different aspects. This resulted in a big list which was not easy in use. Furthermore the barriers influenced each other, which made it difficult to indicate which factor is actually the barrier. The barrier 'low cooperation between firms' could be caused by 'cartel formulation legislation', 'low trust between firms', 'low amount of new companies' or because there is a 'low amount of collaborative R&D projects' related to 'lack of financial resources'. The Function of Innovation Systems incorporates these feedback effects in the analysis of technology developments, but because specific barriers were extracted from this theory, the added value of this aspect disappeared in using just the list of barriers.

The barriers were divided in 6 categories, of which Institutional, Technological, Financial, Infrastructural and Social were taken from CE literature and I added Knowledge as the sixth. It was sometimes difficult to indicate what exactly falls within this category. For example 'lack of knowledge on roles of companies in CE', is that a knowledge, social or institutional thing? But this question I asked myself often during the analysis. Although knowledge could for example be incorporated in Technological, I do think it was useful to add the sixth category as it provided the opportunity to look closely at the research and development that takes place and how this could inhibit the further spread of the innovation.

The positive aspect of combining these theories lies in the analysis of the subsystems in combination with the barrier list and the six perspectives. In this research a subsystem was well-developed if 'it contains a sufficient number of actors, institutions and artefacts that contribute to the diffusion and use of the recycled product'. This was a rather vague and broad definition to work with. But by using the six perspectives and the barrier list, the substructure could be analysed in a more structured way. For example, the demand-side did not have a sufficient numbers of actors and no institutions that stimulate the use of the product. By looking at the demand-side from the six perspectives and by using the barrier list, it became clearer why this demand-side was underdeveloped. The fact that there is no regulation to stimulate the demand-side is maybe based on a social aspect, namely the Dutch culture. But this barrier is not explicit in the barrier list and this makes a good bridge to the following Subsection where additional barriers are mentioned that were found in the case study.

9.1.2. Additional barriers from the case study

Although the barrier list provided many barriers, some aspects that act as barriers were underexposed in the used framework. To make these issues more concrete, they are described here below.

- Consumer acceptance

Consumer acceptance is very important as recycling includes recovery and reuse. In the used CE literature consumer acceptance is shortly mentioned in combination with service models. However, for nutrient recycling the difficulties are not related to service models but to the characteristics of the recycled products. The following types of acceptance can play a hindering role in recycling cases.

- Acceptance of waste products

Products from waste are in general perceived as being of less quality and in the case study there were additional concerns on the safety of recycled products. Because most phosphate is used in food production, the consumer perception is even more important than if the product would have been used for non-food applications. As Interviewee 7 said 'In Germany there is a nasty slogan which is "Kein brot aus kot", or no bread from shit. That is where the mind-set starts'. Consumers are getting more critical towards food production, whereby local, pure and organic seem to be words that appeal to the critical consumer. So how waste related products are perceived by the consumer needs to be further researched.

- The Not-In-My-Backyard (NIMBY) effect

The NIMBY effect was mentioned by one of the actorss. This is a special type of acceptance as in this case the product or technology itself is not rejected, but it is rejected on basis of local impact of the technology. The reasons behind this NIMBY effect can be diverse. For ICL it was not clear for what reason the local officer in Germany delayed the building process of a new industrial plant and Interviewee 7 felt the local officer did not want the new plant to build. In the rest of the case study the NIMBY effect did not play an important role, but for other cases this barrier must be kept in mind.

- Religion based consumer acceptance

Another type consumer acceptance is related to religion. Religions have often specific standards for food consumption and production. At first sight there seems to be no problem with using struvite or phosphorus from ash in the food production chain. However, I can image that the use of ash from sewage sludge or slaughter waste could raises questions by certain religious people, although I am do not known if there are any religious beliefs against the use of recycled products from human waste. Because the diversity of religions in the Netherlands increases, this barrier should not be overlooked to prevent unexpected problems.

- The culture of a country

An item that was found when looking from a social perspective to the case study, was that the culture of a country influences barriers. The fact that there are no obligations (yet) for obligatory recovery or for the use of recycled phosphates is influenced by the Dutch mentality. The Dutch culture is focused on market mechanisms. The governments leaves initiatives to the market and tries to support companies by playing a facilitating role. The current trend of the government is deregulation and reducing the complexity of the legislative field. But this also means the government hesitates to adopt new legislation. And to tackle big issues such as the phosphorus problem, the European Union comes into sight as the party that is able to develop supporting legislation while on the other hand The Netherlands wants less interference of the EU. Other countries such as Germany and Swiss have decided to make phosphorus recovery obligatory for the communal wastewater chain but till now The Netherlands refrains from such actions. This shows that the culture of a country can explain why certain actions are not taking place.

- Conflicting ideas about sustainability

Conflicting ideas on the importance of different sustainability aspects such as nutrient recovery, CO_2 reduction and energy efficiency can be an important barrier in moving towards a more sustainable society. Legislation on CO_2 reduction can prevent installations aimed at nutrient recovery, if these technologies lead to increased CO_2 emissions. Even if the installation and production would lead to an overall global CO_2 reduction by preventing CO_2 emissions in other processes. In the Netherlands energy is an important topic which is reflected in subsidies for promoting sustainable energy. Also CO_2 reduction is important due to international agreements, such as the Paris climate agreement (European Commission, 2017). Although actors are very involved with sustainability, these conflicting ideas can lead to misunderstanding and act as a barrier.

- Conflicting routes for reaching the same goal

In the theoretical framework attention is paid to competing technologies. However, the case of struvite and recovery from ash is a special case, because the technologies are both competing for the same source and on the other hand complementing and aiming for the same goal. Secondly, within these routes there is an overlap in actors. Some water boards are active in struvite recovery and at the same time through their shareholder role active in ash recovery. As an example, water board Aa en Maas is shareholder of SNB, but installed a struvite reactor in the MWWTP in Land van Cuijk. This example shows that by focussing on closing the loop, more attention should be paid to the value chain and the availability of the material that is recovered. The same principles apply to energy cascading. Coordination in the value chain will become more important to improve the alignment and expediency in investments. Another example from the case study that shows the importance of this statement comes from HVC. HVC states in their annual report of 2015 that optimisation of energy recovery at MWWTPs leads to reduced supply for the sludge treatment installation, which lowers energy production in the sludge incinerator. HVC calls for more direction in the complete waste chain, to align investments and increase their effectiveness (HVC, 2015, p31).

9.1.3. Theoretical contribution

As stated in Subsection 9.1.1 difficulties were experienced with the barrier list that was created by combining theories. The previous Subsection 9.1.2 showed some aspects are little exposed. The use of a list of barriers can help to make barriers more concrete, but I advise a different list of barriers is set-up or a different type of framework is created to address Circular Economy or nutrient recycling cases.

The phosphorus recycling case is characterised by a multi-disciplinary and multi-sector character. The use of the six perspectives was found to be useful in this case, because a diverse set of barriers was identified. Not only technical challenges hinder a system transition, but social and economic aspects need to be addressed as well in order to let phosphorus recycling succeed. Second, the value chain approach that was adapted in this research served as a basis to find the barriers in specific parts of the value chain.

The author has the following suggestions for analysing a CE case or for building a CE framework for the analysis:

- The framework should stimulate to start with the whole value chain to identify the different steps in the recycling process, from development of the technology to consumer adaption.
- The framework should support taking different viewpoints on the case study: institutional, technological, financial, infrastructural, knowledge and social perspectives. The use of six sub-questions could guide the analysis.
    - The institutional perspective looks at (inter)national legislation and regulation and give insight in how sector regulations or standardisation procedures influence the recycling possibilities.
    - The technical perspective looks at both technology and product characteristics and to what extent these characteristics influence technology installation or product adaption.

  - The financial perspective looks at the financial resources available for R&D, installation, production and marketing. It looks at costs, financial feasibility and to financial systems that are in place which can hinder or support the recycling case. In addition, the potential market and profit can be analysed in this perspective.
  - With an infrastructural perspective the integration of the technologies in the current infrastructure can be analysed. This includes the technology installation, logistical challenges and the available complementary technologies, which support the technology or the use of the product. This perspective can be used to look at the total supply and scale on which the technology and product can be implemented and produced.
  - The knowledge perspective looks at knowledge development and dissemination. Knowledge does not only include technical knowledge from R&D and pilot testing but also knowledge on legislation, knowledge of consumers and producers to work with the technology and product and skills such as marketing skills. Studying knowledge dissemination can give insights in how organisations work together and how communication takes place. Therefore it is advised to use a broader definition of knowledge dissemination in which different types of knowledge are exchanged.
  - The social perspective gives the possibility to look at norms, values, opinions and incentives that lead to actions or hinder the recycling initiatives. Public perception, consumer acceptance, visions on the system, conflicting perceptions of sustainability and willingness of the incumbent industry to cooperate should be part of this perspective, thereby opening a different perspective on what hinders development. This perspective gives clearly attention to social factors which play a role in the adoption of technology and recycled products, an aspect that is to my opinion less outspoken in innovation theories or the barriers extracted from CE literature.
- The framework should take a holistic approach and look at the connection and reciprocity of the barriers of the six perspectives. It should use these connections to identify the biggest barriers. An example from the case would be product adoption by consumers. Consumers do not trust the product because of risk perception (social). This has to do with the product quality (technical) and therefore there is a call for more research on the product quality and risk of the product (knowledge). For that, clear product standards are needed (institutional). Insights from Function of Innovation Theories can help to make these connections more concrete.
- In addition, it is advised to use a framework that should lead to a manageable amount of barriers to make the framework easier in use.

Furthermore, I advise to include a reflection step to identify whether the product or technology contributes to more sustainability in a broader perspective. This provides the opportunity to look at the desirability of the technology or product and to discuss different sustainability views which can hinder the development of the technology or product.

The guidelines can be seen in Figure 24.

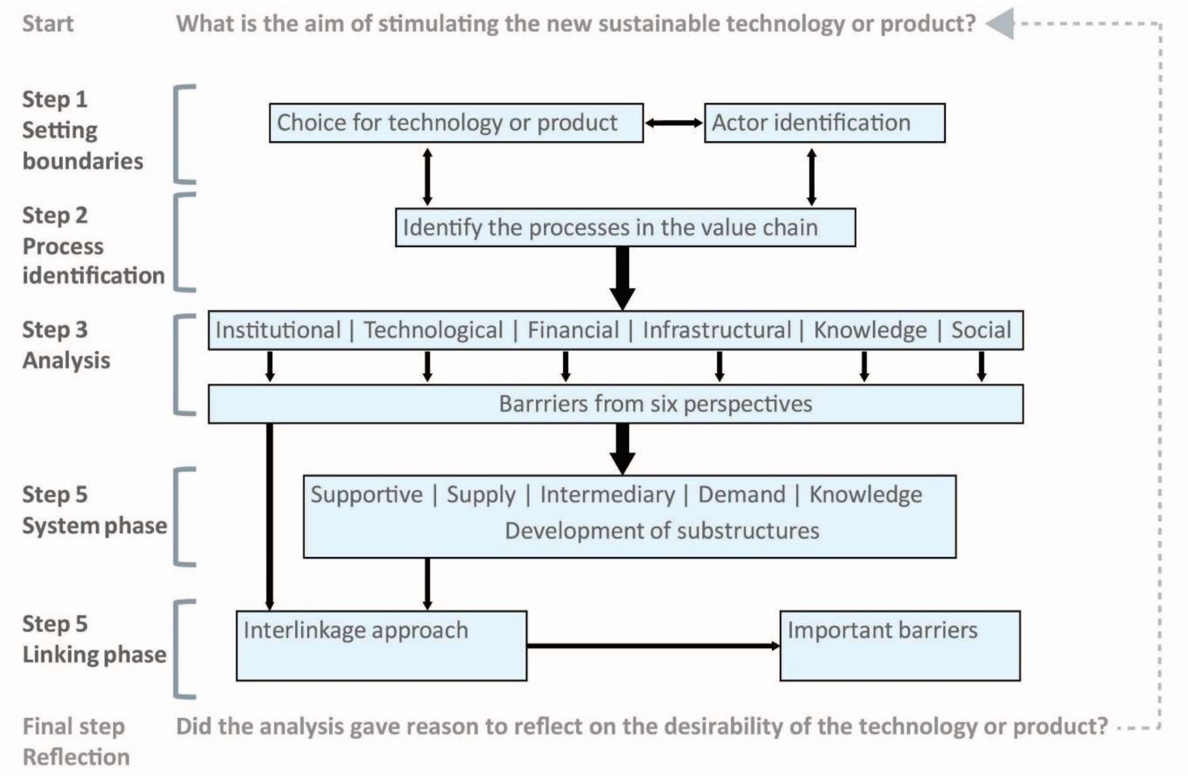


Figure 24. Guidelines for a systematic barrier analysis for CE cases

9.2. Reflection on research methodology

A research always has limitations and is important to be aware of these limitations. Limitations can arise from trade-offs due to time or data access, while other limitations are inherent to the used method. This Section describes these limitations and a reflection on the methodology.

9.2.1. Limitations related to data gathering and scope

The collected information is restricted because of limitations in collecting the data. It is possible that not all information was publicly available and during interviews the researcher was depending on the information the interviewees wanted to give. There was also a time constraint for this thesis and therefore the researcher had to set boundaries on data gathering and the amount of interviews. The information in this research includes literature and empirical data that was collected between March and December 2016.
The limitations experienced in this research and the scope setting had the following consequences:

- Some actor groups were left out of this research

Twelve interviews with people from several actors groups have been conducted, but the not all the important stakeholders were interviewed in this research. SNB, HVC and EcoPhos have not been interviewed which means the barriers found in the ash recycling route are mostly based on desktop study and the interview with ICL. Representatives from agriculture, horticulture and chemical industry have not been interviewed. Interviewing these groups could give better insight in what the barriers for potential consumers are.

- Other technologies were left out of the scope

This research focused on technologies that were already linked to the Dutch communal wastewater chain. This means that technologies usable in chemical WWTPs or other type of ash recovery technologies were not further studied. It could be possible that these technologies provide an added value for the Dutch communal wastewater chain by providing the opportunity to recover phosphorus from more MWWTPs or they may have other benefits compared to the technologies current in use. Further research is needed to see whether this is true.

In addition, other developments such as decentral sanitation and critical gasification of sludge (STOWA, 2016c) have been left out while these developments can influence the current wastewater chain and can impact the current phosphorus recycling routes or provide alternative routes for phosphorus recycling.

- Other phosphorus sources

Manure is left out of the scope while it has a big potential for phosphorus recovery. During this research it became evident that animal manure is a worthy source of phosphate and there is a manure surplus in the Netherlands. Recovering and reusing phosphate from manure will have different barriers for marketing than struvite. For example an end-of-waste status for animal waste is not yet possible (OmzetpuntAmersfooI2, 2016b). Also economic and infrastructural barriers exist due to the costs of transporting animal manure. To be able to improve the phosphate recycling in the Netherlands the potential of phosphate recycling from manure must be researched more in-depth. Nutrient recovery from manure could conflict with other types of manure processing such as energy recovery. If this is the case, legislation stimulating sustainable energy production or nutrient recovery could guide the manure owners into a preferred direction.

9.2.2. Reflection on methodology

The use of events for data collection

This research started with an event analysis. With the aid of internet multiple articles, press releases, websites and research reports were found which led to an overview of what happened the last six years on phosphorus recovery in the communal wastewater chain. The event analysis is a good tool to see the developments over time. However, the events are mostly facts and consists of information that parties want to share with others. Informal communication, internal decisions and motivations are not easily found through an event analysis. To be able to understand why certain steps are taken, communication with the actors themselves is needed. An event analysis should therefore preferably be supported by interviews with involved actors. With interviews and internal documents the communication and collaboration can be understood more in-depth. I started with presenting the data as an event analysis in a historical time line, but eventually this was not the most appropriate way to present the data in this report. Although it was of help in seeing the different steps taken over time to understand barriers, the aim of this research was to define the barriers and not to explain the developments over time. It was also difficult to include information of the interviews in the timeline as the interviews present the opinions at that time and not necessarily the opinions of a couple of years ago. Therefore the historical timeline was abonded, the data was categorised in six perspectives and only a short historical summary was given in Chapter 2.

The interviews

The first six interviews were done to get an overview of what was going on in the field and to get some ideas for a research direction. For this reason, the interviews had an open and broad setup. During the interviews it turned out that getting a good overview of the barriers in the field was a research on its own and the open interviews became part of the data analysis. Due to the broad set-up it was possible to be very flexible in the interviews and that resulted in a lot of information. The consequence was that the interviews were not comparable and the interviews did not cover the same subjects. In addition, the input of previous interviews was used in the following interviews to ask about specific points. By using this method, it is possible the interviewer created a bias towards these subjects. To overcome this in future research, it is advised to use more semi-structured interviews, especially in the second round of interviews. Semi-structured interviews give the possibility to ask standard questions which lead to comparable answers, but on the other hand leaves room to further examine specific topics that come up during the interviews. This could also overcome a second barrier experienced by the author, namely the interpretation of the data by the researcher. Some comments in the interviews suggest a certain viewpoint, but these viewpoints were not always made explicit. This leads to interpretation by the author which can be biased.

Next to alter the structure of interviews, I advise to do more interviews. Some important actors were not interviewed such as SNB and HVC. Secondly, the interviews reflect the opinions of the interviewees themselves and did not necessarily reflect the general opinion of the company or institute. The interviewees were all active with phosphorus recycling in their organisations. This can create a more positive vision on phosphorus recycling than what the actual situation is. A broader range of interviewees with actors which are less involved could create other insights and bring up other types of barriers.

The validation step

At the end of this research, the interviewees were asked by email to fill in the barrier list as a validation step. There was little time and only three interviewees responded, which makes the validation step less valid. Two of the respondents are involved with the ash route, which makes them on the one hand more knowledgeable about that part and on the other hand potentially more subjective. The interviewees experienced that the barriers in the list were interpretable in multiple ways and the information in the document was a bit abstract, making it hard for the interviewees to fill in the list. Furthermore, the author discovered later on that one barrier was missing from the barrier list (no belief in potential of the product). The validation was used to estimate whether the barrier analysis was valid. To my opinion I could not clearly validate the results, but the answers led to reconsider the strength of some barriers. I decided to create a validation rating, but if another rating method was used, the outcome would have been different. In Appendix D the result of a different validation rating is shown. It is advised to validate the results with more actors and not only with the interviewees. Because the author played an important role in the interpretation of the interviews, it is advised to let external people help with analysing the interviews and judge the interpretation steps that were, sometimes unconsciously, made.

The barrier list

The amount of barriers per category was not equally divided. Institutional, financial, knowledge and social barriers were overrepresented in the barrier list compared to the potential technical and infrastructural barriers. Furthermore, some of those barriers were comparable or interrelated. For example the high investment costs often lead to a long payback period, but because this is not always the case, the barriers were used separately. The conclusion can state that the found barriers are important but it could be a bit biased to say that most of the barriers are institutional, financial and social related, because of the unequal barrier list.

9.3. An Industrial Ecology perspective

The recycling of phosphorus in the communal wastewater chain cannot be decoupled from the bigger context. As Interviewee 6 nicely stated in the interview ‘the problem is that the system is damn complicated. Phosphorus is in people, in waste, in slaughter waste, in sewage water, so you cannot say “here is a container and put your phosphate in it”, that makes it all very complicated’ (I6, 2016). Therefore this chapter looks at the system from a broader perspective, at the concept of sustainability and to the relevance for Industrial Ecology.

9.3.1. System thinking

Especially in the Netherlands it is important to look at the complete Dutch phosphorus picture. One of the barriers and at the same time driver for phosphorus recycling is the manure surplus which leads to a phosphate surplus. Several interviewees have mentioned the agricultural sector and the manure surplus as something that influences phosphorus recycling. As Interviewee 1 said: 'the agricultural sector is very determinative in the reuse of phosphorus. When there is a phosphate surplus in the Netherlands, it becomes more expensive to transport it to outside the country. If you are able to use the manure locally, then it would be a lot cheaper because you have less transport. In that way the sector has definitely influence'. He also says he sees opportunities for the sector to remove the phosphate from the manure. But according to him it is a difficult sector to collaborate with and the financial driver is missing, because transporting the manure is still cheaper than processing.

Looking from a complex system perspective to the Dutch case can help to identify other developments that can form a threat to the current developments in the communal wastewater chain:

- Lock-in of the system

High investments in the current system can lead to a lock-in of the technologies and will make the system less flexible and adaptive to new developments. Interviewee 8 mentioned phosphate recovery from wastewater with algae as one of the new developments and Interviewee 10 sees developments in other types of sludge valorisation. For example, Interviewee 10 says that at the moment fermented sludge is just waste which goes to the sludge incinerator. He hopes this will change, because 'actually you don't want to burn things, you want to valorise sludge. This is difficult because of heavy metals in the sludge but that is a development we are working on. You talk about 10 years, it goes really slowly but there are several small scale experiments for research' (I10, 2016). Such changes in valorisation or change in perspective can lead to a reduced sludge flow and thereby impact the phosphorus recycling in the routes which have been described in this case study. And as Buckwell and Nadeu (2016) stated, waste stream policies focussing on reducing waste, may reduce waste flow from current levels.

And again, therefore it is important to collaborate within the value chain. On the one hand collaboration is needed to make effective investments for the long term and on the other hand the system needs to stay flexible to be able to adjust to new developments. These developments can include decentral sanitation, phosphorus recovery at company level and valorisation of sludge in other ways, but developments such as supercritical gasification could also lead to new routes for phosphorus recycling. As stated before, having a sustainable roadmap for phosphorus recycling can take such developments into account and guide decisions.

- Collaboration and integrated approach

The interrelation of the two phosphorus recycling routes and the influence of other sustainability initiatives on phosphorus recycling, call for collaboration within the value chain and outside the value chain across various sectors. Not only a roadmap for phosphorus recycling is necessary, but an integrated approach towards nutrient recycling as a whole. This will require extensive collaboration, which will be a challenge as Hoppe et al. (2016) nicely stated: *'mostly inter-sectoral communication and collaboration, and the general absence of a nexus approach in managing deeply-rooted contradictions between economic and environmental goals that appear to be challenges that make developments leading to the framing of an integrated sustainable nutrients policy framework troublesome'.*

9.3.2. Reflection on sustainability

Recycling phosphorus is seen as a sustainable alternative to phosphorus mining. But recycling systems can have unexpected side effects which could influence the total sustainability of such projects. For example, if current sludge ash is used in the cement industry but will be used to recover phosphate, the question comes up what will happen with the cement industry. Is the ash still usable for the cement industry after the phosphorus is recovered from the ash? And if not, what will be the alternative for this industry? Maybe the alternative material for the cement industry is more environmental unfriendly than the used sludge ash. Interestingly, some articles promote the use of sewage sludge ash in construction an example of Circular Economy (Smol et al, 2015). This indicates opinions on sustainability vary and depends on the perspective that is taken.

The interviewees have mentioned the difficulty of stating what sustainability is. As Interviewee 6 said 'Everyone has their own definition of sustainability. But what is sustainable? What is the most important? You cannot say the one thing is more sustainable than the other, you can only say "we think that phosphorus is very important and we can use more energy for that". People also look the way which suits them the most' (I6, 2016). And in the interview with Interviewee 11 it comes up as a question on the ambition of the water boards. He says 'the question is "what is our ambition?" how much CO_2 do we want to reduce and is that the way we want to go or do we want to look at reducing our energy use?' (I11, 2016). And also Interviewee 4 says 'maybe people understand different things when they talk about sustainability. What do we mean when we say sustainable, that is not really concrete yet' (I4, 2016). Not only the concept of sustainability is vague, the application of the concept Circular Economy has also different outcomes. As Interviewee 8 says in the interview 'one of the boundary conditions for CE is at least conservation of the natural capital. And from the ministry of I&E this is a point which needs to be guarded because from the perspective of the ministry of EA the concept Circular Economy is also a lot of economy' (I8, 2016). And Interviewee 8 mentions another important point when he says 'CE can also be greenwashing, we do something nice and we call it CE. You should be aware of that'.

Life Cycle Assessments (LCA) are tools to make the concept of sustainability more concrete. Making a good LCA is very difficult and to be able to compare different LCA's the choices made by the researcher must be clear. STOWA published a report with two LCA's on EcoPhos and the Pearl technology. The LCA for struvite recovery is positive but it compares the produced struvite with direct fertilizers, while currently it is used as input for fertilizer production and not as a direct substitute. Using struvite as input for fertilizer production, could make the outcome of the LCA less positive. The P-REX LCAs suggest sludge leaching technology as a third recycling option, but this is currently not practised in the Netherland. These technologies have a higher energy demand and chemical impact, but in combination with co-incineration the energy demand could be offset. The advantage of sludge leaching compared to struvite production is the higher P-recovery efficiency, but the ash coming from incineration would not be suitable for P-recovery anymore (P-REX, 2015a). Still, the use of LCA includes certain assumptions on which indicators are deemed most important and this makes a shared idea on what sustainable is, a must.

Recycling waste is seen as a sustainable strategy but it can bring other problems such as pollution risk. Closing the loop by only focussing on recycling rates will bring micro pollutants back in product cycles (Lee et al, 2014). This is also a concern for using recycled phosphorus. Therefore more research is needed to understand the long-term impact of using recycled phosphorus and In comparison with using mineral rock phosphate with decreasing quality.

In conclusion, the concept sustainability is difficult to grasp and has multiple interpretations. The use of LCA can give provide data on the sustainability of products and technologies but the interpretation is also depending on which factors are experienced as most important. But recovery of phosphorus is not the only way to a more sustainable phosphorus loop. Nutrient recovery is driven by the possible ending reserve of phosphate and by pollution of soils due to low quality phosphates. One of the challenges in closing the loop is the low efficiency of nutrient use. “Nutrient recovery and reuse per se cannot change farmers’ decisions about fertilizer use and feeding of livestock, neither can it influence citizens’ decisions about their dietary balance. Whilst it can provide an important contribution to more sustainable nutrient management, it is not the solution” (Buckwell & Nadeu, 2016). In other words, if we want to become more sustainable, we should not only recover nutrients but also change our system at the front side.

The different perspectives on sustainability are also reflected in the schools of thought and thereby in the approaches to Circular Economy. Some people believe that everything should be made biodegradable while others focus on easy recycling or durability. These beliefs have a very different outcome when desiging a system. Is the focus on reusing waste or desiging out waste? There is not one clear answer to that. What is sustainable depends to different contexts and sustainability is not a determined end-state. Sustainability itself is an innovation, that we need to keep on further developing.

9.3.3. Relevance for IE and society

Industrial Ecology

Industrial Ecology (IE) is aiming at creating synergies between environment and technical systems. Natural processes serve as inspiration for technical systems. IE takes a holistic approach to sustainable development in which environmental, social and economic aspects are important. The three pillars of sustainability, People, Planet and Profit, are at the base of solving complex sustainability issues. The phosphate cycle is a natural cycle which is distorted by human involvement. To close the loop again, new technical systems and changed behaviour are needed. The recovery and reuse of phosphate is part of a sustainable transition towards a more efficient use of nutrients. Instead of just mining phosphate rock, the focus lies on using waste as resource for raw materials. Not only the ecological impact of mining is a driver for this recovery but also the social and economic effects of reduced accessibility to phosphate are driving forces for closing the loop. Effects of reduced accessibility can include price inflations of fertilizers and consequently impacting food security and potential famine, due to a decrease in food production. Political aspects also play a role in the EU as the EU is dependent on the import of phosphate rock from outside Europe.

Closing the phosphorus cycle is a typical Industrial Ecology challenge. Working on phosphorus recycling involves system thinking as the value chain of struvite includes sectors such as the water sector and agriculture. It beholds different types of actors including technology producers, consumers, legislative bodies who all have different motivations to be involved. Second, the barrier analysis shows barriers are definitely not only found in technology aspects but also in legislative and social aspects. And third, the system perspective is needed, because an optimal solution for one party or one part of the value chain does not mean it is the best solution for the Netherlands or for Europe. Although there can be a common goal, the lack of agreements on how to reach this goal can lead to suboptimal use of resources. In order to make agreements, it is helpful to be aware of the different motivations of actors and to have clear what their perception of sustainability is.

This research tried to apply Innovation System theories to a nutrient recycling case to close a material loop. To my opinion this approach showed the use of Innovation System theories is not sufficient to identify all the barriers in such a recycling case. It was also concluded that the literature of CE did not provide a good theoretical barrier approach and a framework for analysing recycling cases is missing. This research gave a first step for setting criteria for such a framework. Creating a framework could support Industrial Ecologists in analysing more recycling cases for Circular

Economy. This research also recommends the 6 perspectives approach. It provides a structured approach towards the analysis of the value chain, thereby the related stakeholder and legislation analysis.

At last, this research reflected on the concept of sustainability and showed that interpretation of the concept sustainability plays a crucial role in decisions. An Industrial Ecologist is very well aware of the different visions on sustainability and should this take as an advantage to get these assumptions out in the open, thereby enabling a discussion on what the aims of sustainability strategies are and discussing the advantages and disadvantages of 'sustainable' choices.

Contribution to society

The contribution of this thesis is twofold. On the one hand this thesis can help stakeholders in the field of phosphate recovery and reuse to understand the different hurdles that are preventing the growth of the phosphorus recycling in the communal water chain. In addition actors can learn from these barriers and use this case study as an example for other types of resource recycling from communal wastewater.

Secondly, this research points out that there not only barriers in the current system. There are actually several strong points found in the case study, which can also serve as learning points. The Nutrientplatform is an example of how a platform can play an important role in bringing actors together and to stimulate cooperation to take up shared challenges. Also the experiments with Green Deals can serve as an example to work on solutions together, on national and international level.

9.4. Reflection of the author

This research has started with the interest in what is happening in the field of resource recovery from wastewater in the Netherlands. As the scope was very broad, I decided to narrow the scope by looking at phosphorus, an element of which I didn't know before that it was mined and is used almost solely for food production. The energy and the dedication of the actors to be involved in phosphorus recycling was striking. A big group of motivated people, connected in a unique platform where actors are trying to find shared interests and work together. Such a group, a diverse group, is really important I think to address the phosphorus recycling. They managed to get attention for it in the Netherlands and they even took it to European level. It is nice to see that although the involved actors have different opinions on their roles within phosphorus recycling, they are able to work together on shared goals such as creating a market for recycled phosphates. Their willingness to collaborate, to innovate and contribute to a more sustainable Netherlands should be stimulated and cherished.

But the case study did also show the difficulties in taking up a challenge like the phosphorus challenge. The field is broad and you need many fields of expertise to understand the complex situation. Knowledge on legislation for market entry, on consumer interests, on sustainability and life cycle analysis, supply chain functioning, wastewater treatment and issues that play when you get involved in the food industry, for example by providing fertilizers for food production. There are many things that play a role in finding solutions to tackle the phosphorus problem. And that is exactly the reason why taking steps in the right direction is difficult. And the reason why one person, one organisation or one country cannot address the challenges alone. The whole phosphorus system is very complex.

During the research I found out that the barriers were already known by the involved actors. The problems with market entry for struvite producers or the lack of sense of urgency of consumers, these problems were known across the actor field. So why aren't they resolved yet? I think that there are multiple reasons for this.

First, some things just take long. The revision of the EU Fertilizer Directive is a good example of this. It takes lobbying, it takes research, and it takes time to adjust regulation. And sometimes that is good, legislation is in place for a good reason, but experiments with legislation and initiatives such as (international) Green Deals can really help in taking steps forward.

Second, there is no guiding actor in the field. The government stimulates, or facilitates, initiatives that are sustainable and have market potential. But there is no clear vision on how ideally the phosphorus flows in the Netherlands would look like. There is no one responsible for this question. Phosphorus is kind of a common good and the problems resulting of misuse is a problem of the commons. In the end we will all feel the effects of shortage of phosphorus. The fact that there is no one responsible makes it difficult to take action. Although actors are willing to take action, no one wants be responsible by own choice and this has to do with costs. The Fertilizer industry is willing to remove cadmium from phosphate rock, if everybody else has to do that as well. Of course farmers don't mind to use recycled phosphates, if it is save and obligatory for everyone to use. But who has the power and the will to make these choices and start a discussion on how we, as the Netherlands, can address phosphorus problems and guide the developments in the Netherlands?

That links to the third point, the urgency. The recycling of phosphorus is aimed at preventing phosphorus scarcity and the related problems such as a price increase. But at the moment there is no phosphorus scarcity. The opposite is true, the Netherlands is experiencing a problem with phosphate surplus due to the intensive livestock farming and manure surplus. The demand for fertilizers is not found in the Netherlands but abroad. But reaching the ones that are affected by phosphorus scarcity involves costs. Taking it a bit further; these costs will only be made if the costs for not bringing phosphorus to these people will become higher or in other words, when our food prices will be affected. Then it becomes an ethical question. Another way to increase the urgency in Europe is to lower the cadmium standards for phosphate rock. This will raise the price for high quality phosphate rock and increase dependency of Russia, two undesired consequences but which could stimulate phosphorus recycling in Europe.

The Netherlands is a country that sees opportunities. We are a country of trade. And this mentality has been mentioned by the interviewees. The Dutch people see chances, Dutch companies are good willing, the companies are sometimes more progressive than the government. But on the other hand this market approach has a negative side. The government facilitates but tries to refrain from setting rules. I think the market is good for new initiatives, seeing chances, for innovation but I believe the market alone is not able solve the difficult challenges of our time and there is a need for guidance. Guidance to take the sustainable road, to stimulate initiatives where it is needed and to discuss with all of us on how this sustainable future could look like.

I praise the water boards for their innovative attitude and their enthusiasm to create valuable products from their wastewater and I see different projects are being started, not only on phosphorus but the water boards are looking also at synergies with manure treatment or making clothes from cellulose from their wastewater treatment plants. The idea of the MWWTP as an energy and resource factory is something that appeals and I think it is a valuable starting point. But I think there is one aspect that could be improved. More attention can be paid to their role in the different supply chains. For energy, for phosphorus, for other elements, it can be very valuable to look where in the supply chain the most benefits can be realised. Not only economic, but also environmental and societal. A systematic approach to a value chain. This requires a critical attitude towards the role of an organisation in a supply chain. This attitude has led to the vision that was described in the Discussion. Struvite is good to recover, but it should not lead to problems in phosphorus recovery from ash. Because if that happens, less phosphorus is recovered in the end.

This point is not only valid for water boards, but for companies and organisations in general. It means a far bigger view on the system is needed to make sustainable choices. The phosphorus case is a good example because there are different places where phosphorus can be recovered and the these options have different impacts. The same applies to energy as energy can only be recovered once. And the combination is valid too. Which waste streams can be used for phosphorus recycling and how does this influence the energy production in the system? As described in 9.3.2 the use of sewage sludge ash in construction is from a phosphorus perspective a loss of valuable resources while from another point of view it could be a sustainable alternative. This examples shows again how decisions with regard to sustainability cannot be made from just one perspective. I must admit that keep broadening your scope can result in not taking any steps, so zooming out must be accompanied with zooming in, to prevent getting stuck in the bigger picture. But zooming out is needed for a critical reflection on the desirability of the technology and whether the technology should be implemented at all. So it cannot do any harm to keep the following in mind when taking decisions:

Look at the decision from a bigger perspective and from a societal perspective. And if you were in someone else's position, then what would you do?

So how do we move forward?

I think the actors have the answers. During the interviews they gave suggestions such as setting a minimum of recycled phosphates in fertilizers, to look for labelling possibilities, to improve awareness at the general public, to involve the industry and the agricultural sector more, to think critically on the role of the current stakeholders, to involve the government more and create the link with energy, to research the safety of the products and last but not least, involve the end users. Ideas enough. So, the following is needed to take that next step and bring the phosphorus recycling in the communal wastewater chain and phosphorus recycling in general to a higher level:

- Keep the dialogue. Keep talking about how the communal water chain should like look. What will be the role of decentral sanitation be, how will the sludge system transforms but also keep the eyes open for landscape developments that can change the incentives of actors and change relations between actors. Talk about the consequences of higher phosphates prices and the expectations that an actor may have with a changing context.
- Involve other actors. The end-user, the farmer, retailers, agricultural sector, the chemical industry. Talk about possibilities, about chances, involve them and create a vision with them on how phosphorus could be recycled.
- Keep the Nutrient- Energy- Water (NEW) perspective when dealing with questions on how to transform the system and thereby taking a system perspective.
- Look out for and keep an open mind to new innovations and new insights from other sectors to transform the system bit by bit to a sustainable future.
- Look further than the communal water chain and look at wastewater from companies and to manure.
- Keep the function of the Nutrientplatform, keep working together and let the Nutrientplatform be an example for addressing complex issues and bringing actors together.
- Learn from phosphorus recycling and use the lessons to develop other valorisation opportunities.

10 Recommendations

From the conclusion, the discussion and the reflection on the theory and research, the following recommendations are formulated. The recommendations are categorised into recommendations for the main system, for struvite, for ash and for future research.

10.1. Practical recommendations

The practical recommendations are divided into recommendations for the system as a whole and recommendations to overcome specific barriers found in the struvite case and ash route. The recommendations are based on the barriers identified In Section 6.4.

10.1.1. Phosphorus recycling in the main system

- Vision creation

To optimize the phosphorus recycling from the Dutch communal water chain, a vision or roadmap for the whole value chain is advised. Such a roadmap vision could improve cooperation and allocation of resources in an optimal way and lead to an integrated approach towards phosphorus recycling. Although several actors are working to overcome barriers such as creating a recycled phosphorus market, there is no clear vision to what extent phosphorus recovery must take place and by which means. New developments that influence the communal water chain such as decentral sanitation and other types of sludge valorisation should be incorporated in this vision. Especially decentral sanitation on a larger scale could impact the composition of incoming water at the MWWTP and thereby influence the possibilities and business cases of further P-recycling at the MWWTP and from sludge. In the creation process of a vision, external influences such as the increasing prices of phosphate should be considered to create a resilient roadmap. This vision must be created by the actors involved in the supply chain, by actors affected by the choices made in the roadmap and by the government. The latter is especially of great importance, as governmental decisions can greatly influence the direction of the system. For example, regulatory pressures such as using a minimum amount of recycled phosphates for the industry or legislation making the recycling of phosphorus from sludge obligatory will impact the system. The biggest challenges are to involve all parties and to define the vision in which parties see benefits in reaching this goal together. In order to create such a vision, the costs and benefits of different scenarios should be clear, meaning that environmental and social benefits should be mapped. Mapping these effects will also help to identify how the benefits are distributed, which actors bear the costs and in what way the benefits and costs could be more fairly distributed. The Nutrientplatform and the government should take the lead to bring actors together and discuss the role of the communal water chain in phosphorus recycling in general. In order to broaden the perspective on phosphorus recycling, actors from agriculture, retailers, more fertilizer producers and industrial consumers of phosphorus should also be consulted.

- Decrease the price gap between primary and recycled materials

The low price of primary materials is experienced as a problem. A higher price of phosphorus would stimulate the recovery of phosphorus and it would make recycled phosphates more competitive. To reduce the price difference between primary and recycled materials, a technological and governmental approach can be used. A technological approach is the development of phosphorus technologies that are able to produce cheaper phosphorus. Examples of a governmental (economic) approach are taxes on imported mineral phosphorus or subsidies for recycled phosphorus. The governmental approach beholds a political choice. It is advised to think about these choices and to what extent the government thinks the recycling of phosphorus from the communal water chain or phosphorus in general is important. It can be expected that these choices should not only be made on a national level but taken broader and discussed at the EU level. The Nutrientplatform and the ESPP are good organisations to start these discussions in the political system.

- Focus policies not only on energy production but also on nutrient recycling

At the moment sustainable energy is one of the main focus points of the government, but also water and nutrients are important for life. Therefore, the government is advised to focus not only on energy as the narrow focus on sustainable energy production neglects other sustainability issues.

- Research the risk of reusing recycled phosphorus

More research is needed to understand the long-term impact of using recycled phosphorus compared to the scenarios of using mineral rock phosphate with decreasing quality. It is recommended to monitor the application of recycled phosphates, for example the soil in which the recycled fertilizers are used. The reuse of recycled materials holds a risk on bringing micro-pollutants or heavy metals back into the system. Therefore research is recommended to research whether an undesired build-up of risk materials in the applications takes place.

- Work on social acceptance

Two challenges for social acceptance can be distilled: changing the perception of using waste and improving the public outreach in order to bring awareness and a sense of urgency on the phosphorus problem. Phosphorus scarcity is not a commonly known problem. Sharing success stories and telling about the practical steps taken forward will open up the dialogue on whether products from wastewater are desirable and what the role of consumers can be in the phosphorus recycling. The story of phosphorus recycling can be combined with other theme's that currently play a role in society such as independence of foreign countries, the demand for local products and exploitation of natural resources. An increased sense of urgency can stimulate consumers to reflect their interests in their buying behaviour. Public outreach should be done by all actors to be able to present the phosphate challenges from different perspectives.

- Keep up the good work of the Nutrientplatform

The Nutrientplatform is a valuable platform and a good medium to work together with various actors. The strength of the platform lies in bringing together actors from multiple sectors and to keep them talking with each other. This collaboration platform should be valued, strengthened and broadened to include more actors from other sectors to work on P-recycling: the end-user, the farmer, retailers, agricultural sector and the chemical industry and facilitate the dialogue between their members and external parties. It is important to keep the main goal clear: to contribute to a sustainable use of phosphorus. The Nutrientplatform is stimulated to keep on working on institutional alignment by setting the phosphorus challenge on the political agenda.

- Share (un)successful stories

For the internal network, it is important to share not only success stories but also the 'unsuccessful' stories. Knowledge on failures, whether it was a negative business case, a technology not working properly or problems with legislation, will help with to overcome these challenges and learn from the projects. The ARREAU Learning Alliance is a good initiative in this case.

10.1.2. Struvite recycling

The barriers for struvite recycling are the lack of Circular Economy standards for products, the risks associated with the product, the low quality of the product and the narrow application. The following recommendations are given for the struvite route.

- Create standards for CE products

The lack of criteria for recycled phosphorus hinders product development, as it is not clear how recycled materials can fulfil the end-of-waste status and it creates uncertainty about the safety of the products. The creation of standards can lead to the development of methods for analysing the products and reducing the risk perception of recycled products. STOWA and RIVM are stimulated to work on creating standards for CE products for the communal wastewater chain.The experience gained in the collaboration can be used to address similar barriers for other products recovered from wastewater.

- Invest in product quality

The current struvite technologies for struvite production can be further developed to produce clean, high quality products, such as the Pearl technology produces. The technology developers are challenged to improve the technologies with a focus on product development and not only on wastewater treatment. Furthermore can the collaboration between Aquaminerals and EFGF provide opportunities to look at additional central or decentral struvite processing, thereby creating a more uniform product.

- Investigate demand requirements

Struvite can be used as a direct fertilizer or as input for fertilizer production. By widening the scope of struvite uses, struvite can be used to enrich other types of fertilizers or manure and thereby increase the potential recycled amount of struvite. To be able to sell struvite directly to consumers, it must be clear what the demands of the farmers or other consumers are and what their trade-offs in use of recovered phosphates are. For example, the use of granulates or slurry or the ease of mixing the product with other fertilizers. Setting criteria with consumers can be a supporting step in the reuse of phosphate. If other countries are the main target, research on the demands of these consumer groups must be done. It is advised to work with Aquaminerals or retailers in order to improve the compatibility of struvite with the demands of the end-users.

- Explore external markets and use CSR as a strategy

To improve the market potential, it is advised to research external markets. The international Green Deal is one of the initiatives that should be further stimulated. An interesting case worth mentioning is the initiative of the Chocolatemakers in cooperation with Waternet[22]. The ambition of this Dutch chocolate company is to close the phosphorus loop by bringing phosphate back to the country they are getting their resources from. This idea could directly address the problems related to phosphorus shortage: namely a shortage of phosphorus in developing countries due to the high fertilizer prices. Aquaminerals, who does the valorisation of struvite for several water boards, could take up this challenge and research whether such initiatives are viable and sustainable. Other options would be to set-up local projects with for example allotment gardens or school gardens. Such projects can be combined with an educational aspect on phosphorus and phosphorus related problems. These projects can be taken up by the water boards in their function as a public body.

[22] Chocolademakers. 2016. https://www.chocolatemakers.nl/chocolatemakers/ooit-van-struviet-gehoord/

10.1.3. P-recycling from ash

Apart from the main barriers towards phosphorus recycling in the communal water chain, the phosphorus recycling from ash is characterised by high investment costs, an early stage of implementation and the lack of knowledge and belief in potential. The following recommendations are given for the ash route.

- Governmental support for high investments

The high investments in phosphorus from ash recycling are experienced as a barrier. If the government wants to stimulate and speed up Dutch initiatives in this field, it could act as an investor by providing loans in order to reduce the financial risks for the companies involved.

- Stimulate pilot projects

As the ash technologies are still in the development phases, more pilot projects are needed. These projects are needed to stimulate learning and improvement of the technologies. Furthermore it can increase the belief in the technology. For the internal network, it is important to share not only success stories but also the ‘unsuccessful’ stories. Knowledge on failures, whether it was a negative business case, a technology not working properly or problems with legislation will help with overcoming these problems and learning from the projects.

- Experiment with different types of legislation

Slow changing policies are experienced as a barrier. To enable a faster implementation of CE, the government should experiment with different types of legislation. Working on a more individual case approach whereby legislation is loosened by giving benefit of the doubt under strict conditions. An open attitude of the government, such as happens in Green Deals, can serve as an example.

10.2. Recommendations for scientific research

The following recommendations for future research are given.

- Theoretical framework for nutrient recycling and Circular Economy cases

It is recommended to do more case studies using the six perspectives and value chain approach to to research whether it provides a good basis to create a framework for CE or recycling cases. In general more case studies should be done to create insight in the experienced barriers in such cases. Inspiration for a barrier framework can possibly be found in literature on recycling of gold, paper and other recycling processes.

- Responsibility in Circular Economy cases

During the research, questions around responsibilities came up. Sustainability challenges often deal with responsibility that is shared by numerous actors. Phosphorus shortage would be a problem for poor countries and, if price drastically increases, also for farmers in the EU. The pollution in water areas by phosphate is experienced as a problem by the water boards and Dutch Government. This means that problems are experienced by other parties than the actors who are able to make a difference. Often actors are willing to take action but taking responsibility is a step too far. The case study provided an example of companies who are wondering to what extent they should take financial risks to set up a business case that contributes to addressing the general phosphate challenge. Responsibility came also back as a driver: some of the actors felt it was their responsibility to serve as a role model and take steps in the right direction. Research on the role of responsibility in such complex cases could provide interesting insights in how actors experience responsibility and how this perception influences decisions.

- Creation of methodology to compare different P-recycling routes

There is no most appropriate technology for P-recovery, as local conditions determine the optimal choice. For several technologies, both struvite and ash the technical feasibility has been shown and implementation costs are known. However, technologies have been investigated without a standard methodology and therefore an appropriate methodology is needed to be able to make an objective, integrated and comparative assessment between the different technologies to produce fertilizers from phosphorus sources.

- Modelling external influences on the system

In this research the author often looked at the bigger context and questions arose on how external developments influence the phosphorus recycling in the communal wastewater chain. This includes drastic phosphate price changes, but also the effect of regulatory pressures. For example to what extent do regulatory or financial measures lead to the desired effect and what are the side effects. In addition to that it would be interesting to model the behaviour of actors to these stimuli. What if the phosphate price would increase by 20%, how will the costs and benefits shift and in what way will the actors react. Such research can also be used in setting up regulatory pressures or make agreements on how to act when changes in the system occur.

References

Scientific articles

Alkemade, F., Kleinschmidt, C. and Hekkert, M.P., 2007. Analysing emerging Innovation Systems: A Functions Approach to foresight, *International Journal of Foresight and Innovation Policy,* 3(2): 139-168.

Berg, K.T. 2009. Finding connections between lobbying, Public relations and advocacy, *Public Relations Journal*, 3(3)

Bergek, A. Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B. 2015. Technological innovation systems in contexts- Conceptualizing contextual structures and interaction dynamics, *Environmental Innovation and Societal Transitions*, 16, 51-64

Bergek, A., Hekkert, M., Jacobsson, S., 2008. Functions in innovation systems: a framework for analysing energy system dynamics and identifying system building activities by entrepreneurs and policy makers. In: Foxon, T., Killhler, J., Oughton, C. (Eds.), Innovations in Low-carbon Economy. Edward Elgar, pp. 79e111.

Coe, F.L., Joan, M.D., Parks, J.H., Asplin, J.R. 1992. The pathogenesis and treatment of kidney stones, *The New England Journal of medicine*, 327(16), 1141-1152

Cordell, D., Drangert, J. White, S. 2009. The story of phosphorus: Global food security and food for thought, *Global Environmental Change*, 19, 292-305.

Cordell, D., White, S. 2011. Peak Phosphorus: Clarifying the Key issues of a vigorous debate about long-term phosphorus security, *Sustainability*, 3, 2027-2049.

Cordell, D., Rosemarin, A, Schröder, J.J., Smit, A.L. 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options, *Chemosphere*, 84, 747-758

Cordell, D. Turner, A., Chong, J. 2015. The hidden cost of phosphate fertilizers: mapping multi-stakeholder supply chain risks and impacts from mine to fork, *Global Change, Peace & Security*, 27:3, 323-343

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.

Geels, F.W. 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms, *Environmental Innovation and Societal Transitions*, 1, 24-40

Ghisselini, P., Cialini, C., Ulgiati, S. 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, *Journal of Cleaner Production,* 11, 11-32.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R. E. H. M. 2007. Functions of innovation systems: A new approach for analysing technological change, *Technological Forecasting & Social Change,* 74, 413–432

Hoppe, T. Kuokkanen, A., Mikkilä, M., Kahiuoto, H., Kuisma, M., Arentsen, M., Linnanen, L. 2016. System merits or failures? Policies for transition to sustainable P and N systems in the Netherlands and Finland. *Sustainability*, 8, 463: doi: 10.3390/su8050463

Kamp, L.M., Smits, R.E.H.M., Andriesse, C.D. 2004. Notions on learning applied to wind turbine development in the Netherlands and Denmark, *Energy Policy*, 32, 1625-1637

Kuokkanen, A., Mikkilä, M., Kahiuoto, H., Kuisma, M., Linnanen, L. 2015. Not only peasants'issue: stakeholders'perceptions of failures inhibiting system innovation in nutrient economy, *Environmental Innovation and Societal Transitions*, http://dx.doi.org/10.1016/j.eist.2015.11.001

Lee, J., Pedersen, A.B., Thomsen, M. 2014. Are the resource strategies for sustainable development sustainable? Downside of a zero waste society with circular resource flows, *Environmental Technology & Innovation*, 1(2), 46-54

Lommen, J. 2010. Kringen rondom fosfaat. MSc thesis, Wageningen University and Research Centre.

Malerba, F. 2002. Sectoral systems of innovation and production. *Research Policy*, 31(2), 247-264

Markard, J., Raven, R., Truffer, B. 2012. Sustainability Transition: An emerging field of research and its prospects, *Research Policy*, 41, 955-967

Markard, J., Truffer, B. 2008. Technological innovation systems and the multi-level perspective: towards an integrated framework, *Research Policy*, 37(4), 596-615

Schipper, M., 2014. The Phosphorus cycle of Berlin-Brandenburg, Msc thesis Delft University of Technology/ Leiden University. TU Delft Repository

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., Wzorek, Z. 2015. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy, *Journal of Cleaner Production*, 95, 45-54

Suurs, R.A.A. 2009. Motors of Sustainable Innovation, Utrecht. Phd thesis ISBN 978-90-6266-264-7.

Van Alphen, K., Hekkert, M.P. and Van Sark, W.G.J.H.M., 2008. Renewable Energy Technologies in the Maldives – Realizing the potential, *Renewable and Sustainable Energy Review, 12(1): 162-180.*

Vaneeckhaute, C., Lebut, V., Michels, E., Belia, E., Vanrolleghem, P.A., Tack, F.M.G., Meers, E. 2016. Nutrient recovery from digestate - systematic technology review and product classification, *Waste Biomass Valor*, doi 10.1007/s12649-016-9642-x

Vasseur, V. Kamp, L.M., Negro, S.O. 2013. A comparative analysis of Photovoltaic Technological Innovation Systems including international dimensions: the cases of Japan and The Netherlands, *Journal of Cleaner Production*, 48, 200-210

Watkins, A. Papaioannou, T., Mugwagwa, J., Kate, D. 2015. National innovation systems and the intermediary role of industry associations in building institutional capacities for innovation in developing countries: A critical review of the literature*, Research policy*, 44(8), 1407-1418

Institutional reports and government data

Aldersgate Group. 2012. Resilience in the Round- seizing the growth opportunities for a circular economy. Retrieved from http://www.aldersgategroup.org.uk/asset/download/242/Report%20-%20Resilience%20in%20the%20Round.pdf

Buckwell, A. Nadeu, E. 2016. Nutrient Recovery and Reuse (NRR) in European agriculture. A review of the issues, opportunities, and actions. RISE Foundation, Brussels.

Bosma, B. 2014. Ontketen de fosfaatketen. Internship report for Nutrientenplatform, Wageningen University.

Carabain, c., Boonstoppel, E., Hulsen, M., Van Douwen, N. 2016. Nederlanders & de wereld, Kaleidos Research: Amsterdam. ISBN: 978-90-74612-74-6

CBS. 2016a. Zuivering van stedelijk afvalwater; technische kenmerken installaties. Retrieved May 29, 2017 from StatLine: Zuivering van stedelijk afvalwater; technische kenmerken installaties.

CBS. 2016b. Statline: zuivering van stedelijk afvalwater; afzet zuiveringsslib, regio, CBS Den Haag/Heerlen. Retrieved 29 May, 2017 from http://statline.cbs.nl/Statweb/publication/?VW=T&DM=SLNL&PA=83434NED&D1=a&D2=a&D3=0&D4=0-2,7,12,17,22-27&HD=170501-1116&HDR=G3&STB=G2,T,G1

CLO. 2016. Afzet van zuiveringsslib naar bestemming, 1981-2014. Retrieved May 1, 2016 from http://www.clo.nl/indicatoren/nl0154-afzet-van-zuiveringsslib-naar-bestemming.

Council of the European Union. 2016. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009. File 2016/0084 (COD), 111848/1/16 REV 1. Retrieved May 29, 2017 from http://eur-lex.europa.eu/search.html?qid=1496056711237&text=cadmium&scope=EURLEX&type=quick&lang=en&DD_YEAR=2016

Croezen, H.J., Bijleveld, M.M., Mulder, M. 2012. GER-waardes van teruggewonnen fosfor, CE Delft publication number 12.26763.54, September 2012.

De Ruijter, F.J., Van Dijk, W., Van Middelkoop, J.C., Van Reuler, H. 2016. Phosphorus recycling from the waste sector. Wageningen, the foundation Stichting Dienst Landbouwkundig Onderzoek. Plant Research International, Wageningen UR (University & Research centre), PRI report 641.

Dijksma, S.A.M. 2014. Besluit van 15 december 2014, houdende wijziging van het Uitvoeringsbesluit Meststoffenwet ter uitvoering van het vijfde Actieprogramma Nitraatrichtlijn en in verband met herwonnen fosfaten en strorijke mest, *Staatsblad van het Koninkrijk der Nederlanden*, Jaargang 2014, nr 543.

Dijksma, S.A.M., Kamp, H.G.J. 2016. Nederland Circulair in 2050, Rijksbreed programma Circulaire Economie, september 2016. Retrieved from www.rijksoverheid.nl/circulaire-economie

Dijkstra, R. Mulder, A. 2015. Groene economisch groei in Nederland (Green Deal), proposed on 17 December 2015, Tweede Kamer, vergaderjaar 2015–2016, 33 043, nr. 49

EGTOP. 2016. Final report on organic fertilizers and soil conditioners (II). Retrieved February 20, 2016 from https://ec.europa.eu/agriculture/organic/sites/orgfarming/files/docs/body/final-report-egtop-on-fertilizers-2_en.pdf

EMF. 2013. Towards the Circular Economy - Economic and Business rationale for an accelerated transition, Vol.1. The Ellen MacArthur Foundation

EMF. 2014. Towards the Circular Economy, Vol.3. The Ellen MacArthur Foundation

EU. 2016. Factsheet The EU Emission Trading System. ISBN 978-92-79-62369-7

EU. 2014. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions, *On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative*, COM(2014) 0297 final. Retrieved March 10, 2016 from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0297

European Commission. 2014. Report on Critical Raw Materials for the EU. May 2014.

European Commission. 2015a. Closing the loop- An EU action plan for the Circular Economy, Brussels 2.12.2015 COM(2015) 614 final.

European Commission. 2015b. Circular approaches to phosphorus: from research to deployment, ISBN 978-92-79-46827-8. doi: 10.2777/17832

European Commission. 2015c. Communication from the European Commission to European Sustainable Phosphorus platform on 7 December 2017, *subject: Registration of struvite-response to e-mail of 12 December 2013*, GROW/DI/EGJ/ds Ares(2015)6112781. Retrieved from Aalke Lida de Jong of Aquaminerals.

European Commission. 2017. Paris Agreement. Retrieved April 30, 2017 from https://ec.europa.eu/clima/policies/international/negotiations/paris_en.

Feijen, C., Mesman, W., Strijker, A., Wennekers, C. 2014. Assessing the sustainability of phosphate recovery in the Dutch wastewater sector. IPG Group of the master Industrial Ecology, Delft University of Technology & Leiden University.

Gaalen, F van., Tiktak, A., Franken, R. 2015. Waterkwaliteit nu en in de toekomst, tussentijdse rapportage ex ante evaluatie van de Nederlandse plannen voor de Kaderrichtlijn Water. PBL-publicatienummer 1765. Den Haag: PBL

Graaff, L. de, Naber, N. 2016. Potentie struviet in de Nederlandse landbouw, CE Delft report 16.2H98.50.

Hari, L. Riiko, K. 2016. Twists in Nutrient Recycling in the EU, English summary of BASG report of the Järki Lannoite project, April 2016. Retrieved from http://www.jarki.fi/sites/default/files/dokumentit/bsag-report_twists_in_nutrient_recycling_in_the_eu_summary.pdf

Het Groene Brein. 2015. Knowledge Map Circular Economy. Retrieved August 8, 2016 from https://kenniskaarten.hetgroenebrein.nl/en/kenniskaart/circular-economy/

Jasinski, S.M. 2016. U.S. Geological Survey, Mineral Commodity Summaries, January 2016. Retrieved from http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/ dd 24/03/2016.

Ketenakkoord Fosfaatkringloop. 2011. Ketenakkoord fosfaatkringloop 4 Oktober 2011, Retrieved March 10, 2016 from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2011/10/04/ketenakkoord-fosfaatkringloop/ketenakkoord-fosfaatkringloop-011011.pdf

Kok, L., Wurpel, G. & Ten Wolde, A. 2013. Unleashing the Power of the Circular Economy. Report by IMSA Amsterdam for Circle Economy, April 2, 2013. Retrieved from http://mvonederland.nl/system/files/media/unleashing_the_power_of_the_circular_economy-circle_economy.pdf

Korse, M. 2015. A Business Case Model to make sustainable investment decisions – adding Circular Economy to Asset Management. Msc thesis. University of Twente. Retrieved from https://blog.mauritskorse.nl/en/2015/05/thesis-circular-economy/

KWRwater. 2016. Project: Sustainable airport cities. Retrieved March 30, 2016 from https://www.kwrwater.nl/en/projecten/sustainable-airport-cities/

Mansveld, W.J. 2013. Communication to the Kabinet on VANG, letter IenM/BSK-2013/104405

Mansveld, W.J. 2014. Van Afval naar Grondstof- Uitwerking van 8 operationele doelstellingen, Januari 2014. Bijlage 1 bij kamerbrief Invulling van programma van Afval naar Grondstof. Retrieved from https://www.rijksoverheid.nl/onderwerpen/afval/documenten/rapporten/2014/01/28/van-afval-naar-grondstof-uitwerking-van-acht-operationele-doelstellingen

Mansveld, W.J. 2015a. Voortgang ketenakkoord fosfaatkringloop, letter to the Dutch Kabinet 2 July 2015. Reference IENM/BSK-2015/118238.

Mansveld, W.J. 2015b. Voortangsrapportage Van Afval Naar Grondstof, letter to the Dutch Kabinet 15 April 2015. Reference IENM/BSK-2015/68748

Mentink, B. 2014. Circular Business Model Innovation – a process framework and a tool for business model innovation in a circular economy. Msc thesis Industrial Ecology. Retrieved from TU Delft repository.

Mostert, E. 2015. Dictaat Waterrecht en –organisatie, module CIE 5500. Retrieved March 4, 2016 from TU Delft blackboard

Mulder, A. 2015. Groene economisch groei in Nederland (Green Deal), proposed on 17 December 2015, Tweede Kamer, vergaderjaar 2015–2016, 33 043, nr. 52

P-REX. 2014. Deliverable 5.1. Description of sludge related processes. Retrieved from http://www.p-rex.eu/fileadmin/P-REX-Reserach/Downloads/P-REX_D_5_online.pdf

P-REX. 2015a. Deliverable D9.2. Lice Cycle assessment of selected processes for P recovery from sewage sludge, sludge liquor or ash. Retrieved from http://p-rex.eu/uploads/media/P-REX_D9_2_Environmental_Impact_Assessment_LCA_Remy_2015.pdf

Ridder, M. de., Jong, S. de., Plochar, J., Lingemann, S. 2012. Risks and Opportunities in the global phosphate rock market, The Hague Centre for Strategic Studies, Report 17/12/12 ISBN/EAN: 9789491040696

Rizos, V., Behrens, A., Kafyeke, T., Hirschnitz-Garbers, M., Ioannou, A. 2015. The Circular Economy: Barriers and Opportunities for SMEs, ISBN: 978-94-6138-479-9.

Sloover, I., Klootwijk, K. 2014. Juridische handreiking duurzame energie en grondstoffen waterschappen, rapport 2014-40. ISBN: 978.90.5773.670.4

STOWA. 2010. NEWs: The Dutch roadmap for the WWTP of 2030, rapport 2010-24. ISBN 978.90.5773.484.7

STOWA. 2011. Fosfaatterugwinning in communale afvalwaterzuiveringsinstallaties, rapport 2011-24. ISBN: 978.90.5773.539.4

STOWA. 2012. Innovatie en Duurzaamheid: valorisatie van afvalwater, rapport 2012-47. ISBN 978.90.5773.596.7

STOWA. 2013. Fosfoshoudende producten uit de communale afvalwaterketen, rapport 2013-32. ISBN: 978.90.5773.629.2

STOWA. 2014. Strategienota 2014-2018, report 2014-01, ISBN 978.90.5773.623.0

STOWA. 2015. Verkenning van de kwaliteit van struviet uit de communale afvalwaterketen, rapport 2015-34. ISBN: 978.90.5773.71.4

STOWA. 2016a. Marktverkenning en gewasonderzoek struviet en struviethoudende producten uit communale afvalwater, rapport 2016-12. ISBN: 978.90.5773.731.2.

STOWA. 2016b. Levenscyclus van grondstoffen uit rioolwater, rapport 2016-22. ISBN: 978.90.5773.713.8

STOWA.2016c. Experimenteeel onderzoek superkritisch vergassen van zuiveringsslib, rapport 2016-16. ISBN: 978.90.5773.717.6

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizetti, B., de Vries, W…. Zhang, F.S. 2013. Our Nutrient World, the challenge to produce more food and energy with less pollution, Edinburg, NERC//Centre for Ecology & Hydrology. ISBN: 978-1-906698-40-9.

Thalen, M., de Weerd, E., Rienitz, A., van Engelen, G., Kan, D. 2015. An explanatory research on the environmental impact of phosphate recovery from wastewater sludge incineration, IPG report of the Master Industrial Ecology, Leiden University.

UvW. 2011. Green Deal GD057. Retrieved from http://www.greendeals.nl/wp-content/uploads/2015/06/GD057-Unie-van-Waterschappen1.pdf

UvW. 2013. Routekaart Afvalwaterketen 2030, visiebrochure. Retrieved from https://www.uvw.nl/publicatie/visiedocument-afvalwaterketen-2030/

UvW, STOWA, Rijksoverheid. 2014. Green Deal Grondstoffen C-174. Retrieved March 4, 2016 from http://www.greendeals.nl/wp-content/uploads/2015/06/GD174-Grondstoffen-UvW-Rijk.pdf

Van Kauwenbergh, S.J. 2010. IFDC: World Phosphate Rock Reserves and Resources. ISBN: 978-9-88999-167-3

World Bank. 2017. Global Economic Monitor (GEM) Commodities. Retrieved April 30, 2017 from http://databank.worldbank.org/data/reports.aspx?source=global-economic-monitor-(gem)-commodities

News articles, presentations and company information

Aquaminerals. 2014. Fosfaat uit Amsterdams rioolwater, *Stof tot Nadenken*, najaar 2014, 21.

Aquaminerals. 2015. ReststoffenUnie brengt struviet van waterschap op markt, *Stof tot Nadenken*, najaar 2015, 23.

Aquaminerals. 2016. Annual Report 2015 ReststoffenUnie

BN DeStem. 2012. *Waterschap dupe van faillissement Thermphos*, 20 November 2012. Retrieved from http://www.bndestem.nl/moerdijk/waterschap-dupe-van-faillissement-thermphos~ad38144d/

Boerenbusiness. 2016. *Fosfaatmeststof beschikbaar voor derogatie bedrijven*, 16 March 2016. Retrieved from http://www.boerenbusiness.nl/melk-voer/artikel/10868744/fosfaatmeststof-beschikbaar-voor-derogatie-bedrijven

Boon, L. 2012. *Fosforfabriek Thermphos definitief failliet- 450 mensen verliezen baan*, NRC 21 November 2012. Retrieved from https://www.nrc.nl/nieuws/2012/11/21/fosforfabriek-thermphos-definitief-failliet-450-mensen-verliezen-baan-a1439795

Collins, S. 2017. Could fertilizer prices go even higher due to new EU rules, April 21, 2017. Retrieved from http://www.independent.ie/business/farming/eu/could-fertilizer-prices-go-even-higher-due-to-new-eu-rules-35629800.html

Colsen. 2014. *Flyer Anphos.* Retrieved December 12, 2016 from http://www.colsen.nl/products

Das Mooi. 2013. Ministeries op werkbezoek bij Groen Fosfaatfabriek in Echten [press release]. Retrieved October 11, 2016 from http://www.dasmooi.nl/nieuws/21218/ministeries-op-werkbezoek-bij-groen-fosfaatfabriek-in-echten/

DBC. 2016. *Watervalorisatie binnen de biobased industrie* [presentation], Watervisie February 18, 2016. Retrieved from Annita Westenbroek, director DBC.

De Jong, A. 2016. Presentation Omzetpunt Amersfoort 17 June 2016, personal notes

De Jonge, A., Weijers, S., van Veldhoven, J. 2015. Local initiatives as stepping stone towards sustainable sanitation, IWARR 2015 [presentation].

Deloitte. 2012. The Chemical Industry in the Netherlands: World leading today and in 2030-2050

Dutchwatersector. 2015. *Water board Vallei-Veluwe opens state-of-the-art recovery facilities at MWWTP Apeldoorn, the Netherlands*, 8 July 2015. Retrieved from http://www.dutchwatersector.com/news-events/news/14777-water-board-vallei-veluwe-opens-state-of-the-art-recovery-facilities-at-MWWTP.html

Dutchwatersector. 2016. *Next-step sludge treatment integrates three advanced technologies at MWWTP Amersfoort, the Netherlands*, 20 June 2016 [press release]. Retrieved from http://www.dutchwatersector.com/news-events/news/19835-next-step-sludge-treatment-integrates-three-advanced-technologies-at-MWWTP-amersfoort-the-netherlands.html

EFGF. 2015. Hoe zit het met.. struviet en de wet? Juridische factsheet struviet, version 2, 18 December 2015. Retrieved October 17, 2016 from http://www.efgf.nl/uploads/editor/20151218_Struviet_en_de_wet_2.pdf

EFGF. 2015b. Annual report 2015, 'Winnen wat van waarde is'.

Ellenbroek, H. 2008. Van rioolslib tot biogranulaat- 20 jaar slibverwerking in Tiel en Zutphen. Meerpaal Grafmedia, Tiel

EMF. 2016a. Schools of thought, EMF website. Retrieved April 8, 2016 from https://www.ellenmacarthurfoundation.org/circular-economy/schools-of-thought/cradle2cradle

EMF. 2016b. Circular Economy overview. Retrieved September 16, 2016 from https://www.ellenmacarthurfoundation.org/circular-economy/overview/concept

ESPP. 2013. *About us*. Retrieved March 10, 2016 from http://www.phosphorusplatform.eu/platform/about-us?start=1

ESPP. 2015a. Proposed EU Fertilizer Regulation criteria for recovered struvite. Retrieved October 17, 2016 from http://www.phosphorusplatform.eu/images/download/ESPP%20struvite%20FR%20criteria%20proposal%20sent%2024-4-15.pdf

ESPP. 2015b. European Sustainable Phosphorus Conference, Scope newsletter March 2015, nr 111. Retrieved from http://www.phosphorusplatform.eu/images/download/ScopeNewsletter_111_special_ESPC2.pdf

ESPP. 2015c. CNP-technology Water and Biosolids GmbH acquired the exclusive worldwide patented licensing for Airprex. Retrieved April 20, 2016 from http://www.phosphorusplatform.eu/scope-in-print/scope-in-print/609-cnp-technology-water-and-biosolids-gmbh-acquired-the-exclusive-worldwide-patent-licensing-for-airprex?print=0&download=1&id=609

ESPP. 2017. *New sludge ordinance passed German cabinet*, 18 January 2017 [press release]. Retrieved from http://www.phosphorusplatform.eu/scope-in-print/news/1395-new-sewage-sludge-ordinance-passed

Glas, P.C.G. 2013. *Reactie op het CDM rapport inzake toelating struviet als meststof,* letter of UvW to Ministry of Infrastructure and Environment, reference 68233/LH. Retrieved from https://www.nutrientplatform.org/wp-content/uploads/2013/08/ReactieUnievanWaterschappenophetCDMrapportinzaketoelatingstruvietalsmeststof.2-3%20copy.pdf

Groenkennisnet. 2016. *Dossier Kaderrichtlijn Water*. Retrieved October 10, 2016 from http://www.groenkennisnet.nl/nl/groenkennisnet/dossier/Dossier-Kaderrichtlijn-Water.htm.

Hooimeijer, M. 2014. De RWZI van de toekomst, *Magazine H2O*, 47(4). Retrieved from https://issuu.com/h2o-magazine/docs/apr14

Horckmans, M. 2014. *EcoPhos investeert in Franse fosfatenfabriek*, 10 October 2014, Express Business. Retrieved from https://nl.express.live/2014/10/10/EcoPhos-investeert-in-franse-fosfatenfabriek-exp-208431/

HVC. 2015. Annual report 2015. Retrieved from https://www.hvcgroep.nl/sites/default/files/160412_hvc_jaarverslag_2015.pdf

ICL Europe. 2016. *ICL- next step towards sustainable innovation*, March 2014 [press release]. Retrieved from http://files.nwp.nl/extranet/NutrientenPlatform/Nieuwsbrief/PressreleaseRecoPhos.pdf

Kabbe, C. 2015. Wrap-up of Final international workshop proceedings of the P-Rex Consortium, Amsterdam, 11 June 2015 [presentation]. Retrieved from http://p-rex.eu/index.php?id=11

Kabbe, C. 2016a. *German sludge P-recycling ordinance notified to Europe*. Retrieved January 12, 2017 from http://www.phosphorusplatform.eu/scope-in-print/scope-in-press/1327-german-sludge-p-recycling-ordinance-notified-to-europe

Kabbe, C. 2016b. ARREA Working Group Nutrients, struvite recovery & recycling learning alliance, 16 June 2016 [presentation], Amersfoort. Retrieved August 1, 2016 from http://p-rex.eu/uploads/media/02_KWB_ARREAU_SRRLA_Kabbe.pdf

Kabbe, C. 2017. Overview of phosphorus recovery from wastewater stream facilities operating or under construction, P-REX implementation table March 2017. Retrieved from http://p-rex.eu/uploads/media/Kabbe_Tech_implementation_Table_20170208.pdf

KNW. 2011. Anphos installatie bij RWZI Land van Cuijk, *Neerslag*, V, p36.

Maurer, A. 2016. Presentation ESPP conference on Phosphorus stewardship in industrial applications, Brussels 01-12-2016. Retrieved April 19, 2017 from https://www.slideshare.net/NutrientPlatform/alexander-maurer-icl-fertilizers-the-RecoPhosprocess-p4-from-sewage-sludge-ashes

NLCH. 2016. Website The Netherlands Circular Hotspot campaign. Retrieved May 2, 2016 from http://www.netherlandscircularhotspot.nl/home.html

Nord France Invest. 2015. *EcoPhos invests €60 million in innovative Dunkerque plant*, 24 August 2015. Retrieved from http://www.nordfranceinvest.com/news/detail/EcoPhos-invests-EUR60-million-in-innovative-dunkerque-plant.html

Nutrientplatform. 2015. *Brief van het Nutrientenplatform over stand van zaken en vervolg Ketenakkoord fosfaatkringloop,* 15 June 2015. Retrieved from https://zoek.officielebekendmakingen.nl/blg-543955

Nutrientplatform. 2016a. Overleg Nutrienten & Circulaire Economie, report meeting 19 april 2016. Retrieved from https://www.nutrientplatform.org/wp-content/uploads/2016/09/Verslag-overleg-Nutri%C3%ABnten-en-de-Circulaire-Economie-19-april-2016-2.pdf

Nutrientplatform. 2016b. Ambitie Nutrienten 2018. Retrieved from https://www.nutrientplatform.org/aftrap-ambitie-nutrienten-2018-door-staatssecretaris-dijksma/

Nutrientplatform. 2016c. Individuele ambities 2018, bijlage bij ambitie Nutrienten 2018. Retrieved from https://www.nutrientplatform.org/aftrap-ambitie-nutrienten-2018-door-staatssecretaris-dijksma/

Nutrientplatform. 2016d. *Herwonnen fosfaat in physiostart P Plus van Timac Agro*, 15 March 2016. Retrieved from https://www.nutrientplatform.org/herwonnen-fosfaat-in-physiostart-p-plus-van-timac-agro/

Nutrientplatform. 2016e. *Fosfaat uit afvalwater van aardappels en huishoudens*. Retrieved March 27, 2016 from https://www.nutrientplatform.org/succesverhalen/waterschap-rijn-en-ijssel/

Nutrientplatform. 2017. *Over Nutrient platform*. Retrieved January 10, 2017 from https://www.nutrientplatform.org/over-np/

OmzetpuntAmersfoort. 2016a. Meerjarige afname kunstmest. Retrieved October 10, 2016 from https://www.omzetpuntamersfoort.nl/nieuws/nieuws/2016/februari/meerjarige-afname

OmzetpuntAmersfoort. 2016b. Discussion and questions during presentation on 16-17 June 2016 at Opening Omzetpunt Amersfoort, personal notes.

P-REX. 2015b. *Project*. Retrieved October 17, 2016 from http://p-rex.eu/index.php?id=1&L=0

P-REX. 2015c. *Policy brief Phosphorus recycling-now*!. Retrieved December, 2016 from http://p-rex.eu/uploads/media/P-REX_Policy_Brief_final.pdf

RecoPhos. 2017a. *RecoPhos* [Factsheet]. Retrieved October 26, 2016 from http://www.RecoPhos.org/c/mid,1364,Media_Centre/

RecoPhos. 2017b. *Basic Facts RecoPhos project*. Retrieved May 10, 2017 from http://www.RecoPhos.org/c/mid,1372,Basic_Facts/

RIVM. 2017. *Over RIVM*. Retrieved May 26, 2017 from http://www.rivm.nl/RIVM

RVO. 2016. *Stimulering Duurzame Energieproductie (SDE+).* Retrieved March 18, 2017 from http://www.rvo.nl/subsidies-regelingen/stimulering-duurzame-energieproductie-sde

RVO. 2017. *Over Rijksdienst voor Ondernemend Nederland*. Retrieved May 10, 2017 from http://www.rvo.nl/over-ons/over-ons.

Schipper, W. 2013. *Groene fosfor*, 15 November 2013 [powerpoint slides]. Retrieved from https://www.zeeland.nl/digitaalarchief/zee1400185

SNB. 2008. ASHDEC en SNB onderzoeken mogelijkheden as-opwerking, *SNB Berichten,* nr38, April 2008.

SNB. 2009. Investeren of afwachten?, *SNB Berichten,* nr45, December 2009.

SNB. 2011. Nieuw Nutriënten platform vraagt aandacht voor schaarste, *SNB Berichten*, nr50, March 2011.

SNB. 2013. *Terugwinning bij slibverwerking*, 16 January 2013 [press release]. Retrieved from http://www.snb.nl/terugwinning-bij-slibverwerking/

SNB. 2016a. *Company information*. Retrieved July 19, 2016 from http://www.snb.nl/wie-zijn-wij/organisatie/

SNB. 2016b. *Unieke fosfaatfabriek in aanbouw*, 15 March 2016 [press release]. Retrieved from http://www.snb.nl/unieke-fosfaatfabriek-in-aanbouw/

SNB. 2016c. *EcoPhos opent testfabriek in Bulgarije*, 27 September 2016 [press release]. Retrieved from http://www.snb.nl/EcoPhos-opent-testfabriek-in-bulgarije/

SNB. 2016d*. Slibas vanaf medio 2018 naar Duinkerken*, 15 November 2016 [press release]. Retrieved from http://www.snb.nl/slibas-vanaf-medio-2018-naar-duinkerken/

SNB. 2017. *Duitsland zet vaart achter recycling fosfaat*, 7 February 2017 [press release]. Retrieved from http://www.snb.nl/duitsland-zet-vaart-recycling-fosfaat/

SusPhos. 2016. *About us.* Retrieved April 20, 2016 from http://www.susphos.eu/about-us

Timac Agro. 2016. *Physiostart P-Plus*. Retrieved July 20, 2016 from http://www.timac-agro.nl/bodem-en-bemesting/physiostart/p-plus

TKI. 2016. *Over ons*. Retrieved April 19, 2016 http://www.tkiwatertechnologie.nl/over-ons
UvW. 2016. *Struviet in Internationale Green Deal,* October 7, 2016 [press release]. Retrieved October 10, 2016. https://www.uvw.nl/struviet-in-internationale-green-deal/
UvW. 2017. *Over de Unie*. Retrieved July 20, 2016 from https://www.uvw.nl/vereniging/
Van Kasteren, J. 2014. Markt voor secundair fosfaat uit rioolwater, March 28, 2014. Also published in *Chemiemagazine* march 2014. Retrieved from http://www.joostvankasteren.nl/markt-voor-secundair-fosfaat
Vilt. 2016. *EcoPhos wil grootste fosfaatproducent ter wereld worden*, September 7, 2016. Retrieved from http://www.vilt.be/EcoPhos-wil-grootste-fosfaatproducent-ter-wereld-worden
Waterforum. 2015. *EcoPhos gaat in Duinkerken fosfaat terugwinnen uit vliegas HVC en SNB*, March 4, 2015 [press release]. Retrieved from http://www.waterforum.net/nieuws/8794/EcoPhos-gaat-in-duinkerken-fosfaat-terugwinnen-uit-vliegas-hvc-en-snb

Interviews and personal communication

Interviews

I1, 2016: Wastewater engineer at a water board. 18 April 2016, by phone

I2, 2016: Commercial operational manager at a company working on the valorisation of by-products and waste. 10 May 2016, by phone

I3, 2016: Secretary of a network organisation for resource recovery. 11 May 2016, at location

I4, 2016: Policy officer at the association of water boards. 12 May 2016, by phone

I5, 2016: Researcher at a research institute. 18 May 2016, by phone

I6, 2016: Consultant. 30 May 2016, by phone

I7, 2016: Vice president of a fertilizer producing company. 10 August 2016, at location

I8, 2016: Policy officer at Ministry of Infrastructure & Environment. 25 August 2016, at location

I9, 2016: Board member at the branch organisation of the chemical industry. 5 september 2016, at location

I10, 2016: Accountmanager at a water board. 13 September 2016, by phone

I11, 2016: Process manager at a water board. 19 september 2016, by phone

I12, 2016: Coordinator at a water board. 29 September 2016, by phone

Personal contact

De Jong, Aalke Lida. 2017. Expert Environment at Aquaminerals, email conversation March 2017.

Gort, Roelof. 2016. Advisor Energy and Sustainability at water board Drents Overijsselse Delta, Personal communication at Opening Omzetpunt Amersfoort, 17 June 2016

Heijmans-van Asseldonk, Marga. 2017. Technologist at water board Aa en Maas, email conversation February 2017.

Peters, Frank. 2017. Accountmanager Resources and Energy at Water board Vallei en Veluwe, email conversation January 2017.

Acknowledgement icons of www.thenounproject.com

Institutional: Anbileru Adaleru

Technological: B Farias, CL. Web elements collection

Financial: Davo Sime, AU

Infrastructural: Vineet Kumar Thakur, IN

Knowledge: Oliviu Stoian, RO. Smashicons Science MD- Solid collection

Social: Hopkins

Appendices

A. Phosphorus reserves, resources and depletion

The discussion on phosphorus depletion leans on three concepts that are important to understand: phosphate reserves, phosphate resources and peak phosphorus. The International Fertilizer Development Centre (IFDC) uses the following definitions in their report (Van Kauwenbergh, 2010, p18):

"Phosphate reserves are the amounts of phosphate rock that can be economically produced using existing technologies at the time of determination.
Phosphate resources are the amount of phosphate rock of any grade, including reserves, which may be produced at some point in the future."

See Table 11 for an overview of the concepts. This means that estimations of phosphate reserves are depending on the price and change in time. As the price goes up, some of the unused resources are economically feasible to mine and then added to the amount of reserves. The world resources of phosphate rock are more than 300 billion ton (Jasinski, 2016). The current reserves are estimated at 69 billion ton. The world phosphate rock production is estimated to increase from 223 million tons (2015) to 255 million tons (2019). The world consumption of P_2O_5 for fertilizer and industrial uses was 43.7 million tons in 2015 (Jasinski, 2016). As soon as the demand for phosphorus overtakes the phosphate production, problems with food supply can appear. In literature therefore the concept of peak phosphorus is often mentioned. There are two definitions for peak phosphorus:

1. The moment that the highest global production of high quality phosphate production will occur (Buckwell & Nadeu, 2016)
2. The demand for phosphate will exceed the economically available supply (Cordell & White, 2011).

These two definitions can lead to confusion when talking about peak phosphorus.

Table 11. Mc Kelvey diagram for reserves and resources[23]

<table>
<tr><td rowspan="3"></td><td colspan="3">Identified resources</td><td colspan="2">Undiscovered resources</td></tr>
<tr><td colspan="2">Demonstrated</td><td rowspan="2">Inferred</td><td colspan="2">Probability range</td></tr>
<tr><td>Measured</td><td>Indicated</td><td>Hypothetical</td><td>Speculative</td></tr>
<tr><td>Economically viable</td><td colspan="3">Reserves</td><td colspan="2" rowspan="2">Resources</td></tr>
<tr><td>Economically unviable</td><td colspan="3"></td></tr>
</table>

In literature various estimates for the current phosphate reserves can be found. The found estimates are between 50 till 400 years, which is quite a broad range (Schipper, 2014). When looking at the amounts and reserves attention must be paid to what the unit is; 1 kg of phosphate, 1 kg of phosphate rock and 1 kg of phosphorus are three different things.

In 2007 a study of Dery and Anderson (Buckwell & Nadeu, 2016) suggested that peak phosphorus had already taken place, while Cordell et al. (2009) estimated that 2033 would be peak phosphorus. And even later studies such as Cordell et al. (2015) expect the peak phosphorus to take place between 2035 and 2075. This shows it is very difficult to estimate the phosphorus availability for the

[23] Presentation of Joana Vaz Pais at MIT Portugal. Retrieved March 17, 2016 from http://pascal.iseg.utl.pt/~jpais/naturalresources/Lecture%201.pdf

coming period. In any case it can be said that the quality and the accessibility of the reserves will decrease and the costs of mining will increase (Cordell & White, 2011).

B. Interview protocol

In interviews, the goal and set-up were adapted to the interviewees and the questions were adjusted based on previous gathered data. Because of that, there is no general questionnaire for the interviews. To get an insight in the type of questions, this Appendix provides two examples of interview questionnaires. During the interviews not all questions have been asked due to time constraints or because the questions did not seem relevant anymore during the interview.

Originally, the aim was to identify communication barriers in the system. Therefore questions on communication were part of the interview protocol. However the scope of the thesis was adjusted and the input on this subject does not come back in this research. Because the interviews were held in Dutch, the interview protocol is in Dutch as well.

Interview

Algemeen doel in de introductie

Ik wil er graag achter komen waar, volgens de actoren in het veld, knelpunten voor het implementeren van fosfaatherwinning zitten, hoe zij duurzaamheid een rol geven in de ontwikkeling en implementatie van fosfaatherwinning en welke rol communicatie speelt bij het sluiten van de ketens.

Doel gespecificeerd naar geinterviewden:

Voorbeeld Interview A: Het doel van dit interview is inzicht krijgen in welke actoren actief zijn met fosfaat herwinning uit afvalwater in Nederland en hoe het de organisatie daarin een rol speelt. Daarnaast is het doel om een algemeen beeld te krijgen van wat er op dit moment gebeurd in de keten, hoe partijen samenwerken en welke barrières in het algemeen worden ondervonden, om zodoende ook de scope van het onderzoek te specificeren.

Voorbeeld Interview B: Het doel van dit interview is inzicht krijgen in de barrières waar de partij tegenaan loopt in het halen van hun doelstellingen van het Ketenakkoord Fosfaatkringloop. Waar zitten de knelpunten en hoe proberen zij deze op te lossen en wat is hun algemene mening over fosfor recycling in de communale afvalwater keten.

Voorbeeld interview A

- Introductievragen

- Wat is uw rol in de organisatie?
- Wat is uw persoonlijke visie op fosfaatwinning (en circulaire economie)?
- Wat is de visie van uw organisatie op fosfaatwinning en circulaire economie?
- Wat doet jullie organisatie aan de ontwikkeling van fosfaatherwinning?

- Algemeen/Actoren

- Waar denkt u dat barrières zitten voor (het implementeren van technologieën en) het sluiten van de ketens?
- Wat is uw functie binnen het bedrijf of organisatie?
- Wie zijn de trekkende partijen in de ontwikkeling van fosfaatherwinning?
- Wat zijn de belangrijkste drijfveren die u merkt vanuit partijen die meewerken?
- Wie zijn de partijen met macht in de ontwikkeling/keten?

- Mist er nog een bepaalde groep in het netwerk?
- Hoe is de industrie erbij betrokken?
- Wie bepaalt de richting? (Bijvoorbeeld technologie ontwikkelaars die zorgen voor push)

  - Duurzaamheid

- Hoe denkt u dat het begrip duurzaamheid wordt meegenomen in fosfaatherwinning? (Op milieu vlak, op sociaal vlak, op economisch vlak)
- (merkt u dat er verschillende duurzaamheidsvisies zijn?)

  - Bijdrage

- Welke rol ziet u voor communicatie om de beperkingen weg te nemen?
- Waar zit een communicatie wens? Waar gaat het goed en waar zitten beperkingen?
- Waar denkt u of zou u willen dat mijn onderzoek (m.b.t. communicatie) aan zou bijdragen?
- Wie denkt u dat ik nog meer zou moeten spreken?

Voorbeeld interview B

  - Introductie

- Wat is uw functie binnen het bedrijf of organisatie?
- Wat zijn jullie huidige doelstellingen? Klopt die doelstelling van ketenakkoord nog steeds?
- Wat is jullie motivatie? Waarom willen jullie gerecycled fosfaat? (drivers)
- Hoeveel secundair fosfaat gebruiken jullie nu/ waar staan jullie nu?
- Wat is jullie product? Is het een bestaande of nieuwe markt? Wie zijn jullie klanten?

  - Algemeen

- Lukt het in andere landen om secundair fosfaat te verkrijgen? Is er binnen het bedrijf een zelfde visie over fosfaat of verschilt dat? In hoeverre zag je afgelopen jaren een verschuiving van het probleem? Of een verschuiving van de visie of houding t.o.v. fosfaatherwinning?
- Op welke technologie zetten jullie in? Welke bron lijkt jullie het beste?
- Wat zijn de belangrijkste stappen afgelopen vijf jaar en welke stappen moeten nog gezet worden? (zijn die al genoeg in ontwikkeling?) Gaat het te snel/langzaam?
- Wat voor onderzoek doen jullie zelf?
- Waar zien jullie zelf kansen en bottlenecks?

  - Vraagkant

- Wie levert er aan jullie? Hoe komen jullie aan nieuwe leveranciers?
- Zijn jullie tevreden over aanbod?
- Hoe zien jullie de markt? Hoe zien jullie de fosfaatmarkt ontwikkelen? Wat zijn de toekomstige fosfaatverwachtingen? (qua concurrenten, prijs, aantal projecten in secundair fosfaat)
- In hoeverre vragen klanten om herwonnen fosfaat en wat zijn de eisen?

  - Knelpunten uit de literatuur

- <u>Wetgeving</u>: Wat is public affairs inspanning? Op wat voor manier proberen jullie juridische barrières te overkomen?
- Hoe zou je willen dat de overheid zich opstelde en hoe is dat nu?
- <u>Technologie</u>: Hoe pakken jullie het knelpunt technologie aan? (Spreken jullie met technologie ontwikkelaars?) hoe ontwikkel je product dat voldoet aan jullie eisen? (is er een kenniskloof?)
- <u>Aanbod kant:</u> Hoe bewerken jullie de markt/vraagkant?
- Hoe maak je afspraken in de waarde/supply chain?

- Is er een game changer? En zo ja, wie? Of van wie verwacht je dat? Of welke hoek?
- Vraag kant: Welke incentives denken jullie dat werken?
- Is labelen interessant? Is duurzaamheid een selling point?
- Verantwoordelijkheid: Tot waar ligt jullie verantwoordelijkheid?
- Wie vinden jullie verder verantwoordelijk voor transitie? Wie moet er stappen zetten? Hoe gaan we het probleem oplossen?
    - Samenwerking
- Met wie werken jullie samen? (onderzoeksinstituten etc)
- Waarom bent u betrokken bij de projecten?
- Wat is jullie rol in de samenwerkingen? (onderzoeken, faciliteren, managen, begeleiden, afwachten, launching customer)
- Hoe kan de samenwerking verbeterd worden?
- Van welke platformen is het bedrijf lid? Wat voegt een platform toe?
- Wat is jullie terugverdientijd voor de fosfaatherwinning technologie? Wat voor termijn kijk je?

C. Attachment barrier list for validation

The barrier list that was send to the interviewees for validation, including the three respondents answers. The bold answers are the outcomes of the analysis of this research.

Beste geïnterviewde,

Graag zou ik u willen vragen om elke barrière een gradatie te geven. De volgende normering is van toepassing:

2	Dit is een sterke barrière
1	Deze barrière speelt mee
0	Deze barrière speelt geen rol
n.v.t.	U heeft geen mening of de barrière is naar uw mening niet van toepassing op deze casus

U kunt uw mening geven over beide routes die op dit moment worden toegepast. Het doel *is het gebruik van gerecycled fosfaat vergroten* en welke barrières er op dit moment voor beide routes spelen om dat doel te bereiken. Sommige barrières zullen voor allebei even sterk aanwezig zijn, andere barrières zullen in meerdere of mindere mate een rol spelen.

De lijst met barrières

De barrières uit de literatuur zijn verdeeld over 6 categorieën; institutioneel, technologisch, financieel, infrastructureel, kennis en sociaal gebied. U kunt uw normering in de laatste twee kolommen schrijven. Indien u uw antwoorden wilt toelichten, dan kunt u onderaan de lijst een korte tekst schrijven. Dit wordt gewaardeerd, maar is niet verplicht.

In de tweede stap kunt u aangeven welke 5 barrières u voor elk van de twee routes het grootst acht. Dit doet u door een **B** in hetzelfde vakje als uw normering te zitten.

	Barrières	**Struviet**	**As**

Institutioneel	1. Het gebrek aan aansluiting met huidige regelgeving	2|1|1|**2**	2|1|2|**1**
	2. Laag niveau van lobbyen	1|0|0|**0**	1|0|1|**0**
	3. Afwezigheid van drukmiddelen vanuit de overheid	1|0|2|**1**	2|0|2|**1**
	4. Wetgeving verandert langzaam	1|1|1|**1**	2|1|1|**1**
	5. Onduidelijkheid over het gebruik van de afvalhiërarchie	2|1|2|**?**	1|1|2|**?**
	6. Recycling doelstellingen richten zich op kwantiteit en niet kwaliteit	1|1|0|**1**	1|1|0|**?**
	7. Regels over kartelvorming hinderen samenwerking tussen bedrijven	0|Nvt|0|**?**	0| Nvt|0|**?**
	8. Er zijn geen Circulaire Economie standaarden voor producten	2|1|?|**2**	2|1|?|**0**
	9. Circulaire Economie is niet geïntegreerd in het innovatie beleid van de overheid	0|1|0|**?**	0|1|0|**?**
	10. Er is geen duidelijkheid over eigendomsrecht en verantwoordelijkheid in nieuwe businessmodellen	0|0|0|**?**	0|0|0|**?**
Technologisch	1. Er worden onzekerheden of risico's gerelateerd aan de technologie	0|1|x|**0**	0| 1|x|**0**
	2. Er worden risico's geassocieerd met het product	2|2|1|**2**	1|2|1|**1**
	3. De kwaliteit van het product is gelimiteerd	0|1|0-2|**2**	1| 1|2|**?**
	4. Er zijn LCA's nodig om het duurzaamheidseffect te bewijzen	1|0|1|**0**	1| 1|1|**0**
	5. Het product is niet ontworpen voor het einde van de levensfase	1 |0|x|**?**	1| 0|x|**?**
Financieel	1. Er zijn weinig concurrenten of nieuwe bedrijven op de markt	0|1|0|**0**	0| 1|1|**0**
	2. Er zijn weinig investeringen in onderzoek	0|1|0|**0**	0|1|0|**0**
	3. Er zijn negatieve landscape ontwikkelingen[1]	0|1|1|**1**	0|1|1|**0**
	4. Er is financiële steun voor lineaire of huidige systemen dan wel een afwezigheid van een financieel ondersteunend belasting systeem	0|0|2|**1**	0|0|2|**1**
	5. Er zijn hoge investeringskosten	1 |0|1|**0**	2|0|2|**1**
	6. Er is een lange terugverdientijd	1| Nvt|1|**0**	2| Nvt|2|**1**
	7. Er zijn niet genoeg financiële bronnen/middelen beschikbaar a. voor producenten b. voor consumenten	a.0| Nvt|x|**0** b.1| Nvt|x|**0**	a.0| Nvt|x|**1** b.2| Nvt|x|**0**
	8. De prijs van primaire grondstoffen is lager dan gerecyclede grondstoffen	1|2|2|**2**	1|2|2|**2**
	9. Externe kosten worden niet in de prijs meegenomen	1|1|x|**1**	1|1|x|**1**
	10. Investeringsberekeningen zijn gebaseerd op 1 levenscyclus in plaats van meerdere	0|Nvt|x|**?**	0|Nvt|x|**?**
	11. Arbeid wordt belast in plaats van materiaal	0| Nvt|x|**?**	0| Nvt|x|**?**
	12. De toepassing van het product is gelimiteerd	1| Nvt|2|**2**	2|1|2|**0**

	13. De prijs/kwaliteit verhouding is slecht	1|Nvt|2|**?**	2|Nvt|2|**?**
Infrastructureel	1. Er zijn geen aanvullende diensten of producten beschikbaar a. voor de producent b. voor de gebruiker	a.0|Nvt|1|**1** b.0|Nvt|1|**0**	a.0|Nvt|1|**0** b.0|Nvt|1|**0**
	2. De productieschaal is te klein	1|1|2|**1**	0|Nvt|1|**0**
	3. Er is een incomplete productielijn voor de technologie	0|0|0|**0**	0|0|0|**0**
	4. De technologie past niet in de huidige infrastructuur	0|1|1|**0**	0|1|1|1
	5. Bedrijven zijn afhankelijk van externe leveranciers om CE principes te kunnen aannemen	0|1|x|**?**	0|1|x|**?**
	6. Er is een gebrek aan ruimte en/of materiaal voor de technologie[24]	0|?|0|	0|?|0|
Kennis	1. Er is een gebrek aan kennis verspreiding	0|1|0|**0**	0|1|0|**0**
	2. Er zijn weinig R&D of pilot projecten	0|1|0|**0**	2|1|1|**0**
	3. Er is een gebrek aan menselijk kapitaal	0|0|0|**0**	0|0|0|**0**
	4. Er is een gat tussen onderzoek en praktijk kennis die nodig is	0|0|1|**0**	1|0|1|**0**
	5. Er is weinig samenwerking tussen bedrijven	1|1|1|**0**	1|1|1|**0**
	6. Er is weinig bewustzijn bij tussenpartijen over de ontwikkelingen	1|1|0|**?**	1|1|0|**?**
	7. Er is een gebrek aan kennis on de technologie te ontwikkelen, produceren en te controleren	0|1|0|**0**	1|1|0|**0**
	8. Er is een gebrek aan kennis of vaardigheden om het product te gebruiken	1|1|1|**0**	2|1|0|**0**
	9. Er is een gebrek aan data over materiaal stromen	1|2|0|**0**	1|2|0|**0**
	10. Er is geen kennis over de rollen van bedrijven in een CE	0|1|0|**?**	0|1|0|**?**
	11. Er is weinig kennis en bewustzijn over CE bij producenten en consumenten	1|1|x|?	2|1|x|**0**
Sociaal	1. Er is geen geloof in de potentie van de technologie	1|0|0|**1**	2|0|1|**0**
	2. Er is geen duidelijke visie vanuit de maatschappij (op fosfaatrecycling)	1|0|1|**0**	2|0|1|**1**
	3. Er zijn negatieve landscape ontwikkelingen[1]	0|1|0|**0**	0|1|0|**0**
	4. Het gevoel van urgentie ontbreekt a. vanuit de producent b. vanuit de consument	a.1|0|0|**0** b. 2|1|2|**2**	a.1|0|1|**0** b.2|1|2|**2**
	5. Aandeelhouders hebben korte termijn denken, gericht op winst	1 |1|x| **0**	1|1|x|**0**
	6. Afvalmanagement is gericht op het wegwerken van afval met minimale maatschappelijke schade in plaats van op recycling	0|1|1|**1**	0 |1|1|**0**
	7. Gevestigde bedrijven zijn niet gewillig om samen te werken (en werken verandering tegen)	1|1|2|**1**	1|1|2|**1**
	8. Het BBP is geen goede meetmethode voor welvaart	0|1 Nvt|x|**?**	0 | Nvt|x|**?**

[24] In the barrier analysis, this barrier is integrated in infrastructural barrier 4.

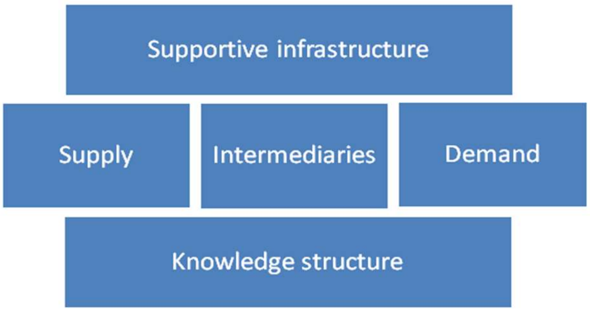
	9. Er is gebrek aan vertrouwen tussen bedrijven	0|1|x|**0**	0|1|x|**0**
	10. Er is een lage acceptatie voor het gebruik van diensten in plaats van het bezitten van producten	0 | Nvt|x|**?**	0| Nvt|x|**?**
	11. De interesse van consumenten in duurzaamheid vertaalt zich niet naar hun koopgedrag	2|1|x|**1**	2|1|x|**1**

1. Landscape ontwikkelingen zijn ontwikkelingen die buiten het systeem plaatsvinden. Denk aan externe prijsontwikkelingen, oorlog, ontwikkelingen op Europees of wereldniveau die de recycling beïnvloeden.

Concluderende barrières

De theorie onderscheidt in het gehele systeem vijf substructuren: de aanbodkant, de vraagkant, de ondersteunde substructuur, de intermediaire substructuur en de kennis substructuur.

De <u>ondersteunende </u>substructuur bevat de overheid, ondersteunende actoren zoals investeerders en wetgeving die het systeem in algemene zin ondersteunen. De <u>intermediaire </u>substructuur omhelst partijen en wetgeving die de verbintenis tussen de aanbod en vraagkant stimuleren. De <u>kennis</u> substructuur houdt partijen en wetgeving in die kennis ontwikkeling en verspreiding stimuleren. Dit kan als volgt worden gezien:



U kunt nu voor de vijf substructuren aangeven in hoeverre u vindt dat deze goed zijn ontwikkeld en bijdragen aan de groei van gerecycled fosfaat. Hierbij staat + voor goed functioneren, +- voor redelijk en - voor een slecht ontwikkelde substructuur.

Concluderend	**Substructuren**	**Struviet**	**As**
	In hoeverre is de aanbodkant ontwikkeld	+- |+-|+-|**+-**	-|+| +-|**-**
	In hoeverre is de vraagkant ontwikkeld	+- |-| -|**-**	-|-|-|**-**
	In hoeverre is de ondersteunende substructuur ontwikkeld	+- |+-|+-|**+-**	-|+-|+-|**+-**
	In hoeverre is de intermediaire substructuur ontwikkeld	- |-| +-|**+-**	-|-| +-|**+-**
	In hoeverre is de kennis substructuur ontwikkeld	+ |+| +-|**+**	+-|+| +-| **-**

Toelichting

Indien u uw antwoorden wilt toelichten kunt u dat hieronder schrijven.
Bijvoorbeeld ‘barrière institutioneel 5: …’

D. Conclusion including other validation rate

If the validation method would have been different, whereby only one respondent would have to rate a barrier as strong to be regarded as a strong barrier, the outcome in Figure 25 would have been the result. The smaller barriers would have been added to the previous conclusion.

The main barriers found for both routes in the system would be:

- The low alignment with the current policy, the lack of regulatory pressures and the lack of data on phosphorus flows. The narrow application of the products, the low price of raw materials, the weak price/quality performance and the favouring of the incumbent industry by current financial structures. The lack of a sense of urgency on the phosphorus problem, the fact that consumers interest in sustainability is not reflected in their buying behaviour and the unwillingness of the incumbent industry to cooperate.

The additional barriers for recycling through struvite would be:

- The lack of Circular Economy standards for products, the lack of clarity about the use of the waste hierarchy, the risks associated with the product and the low quality of the product.

The additional barriers for recycling through ash would be:

- The high investment costs, the related long payback period and the slowly changing regulation. The lack of R&D projects, lack of knowledge on how to use the product, the lack of knowledge by producers and consumers of CE principles and the lack of belief in the technology.

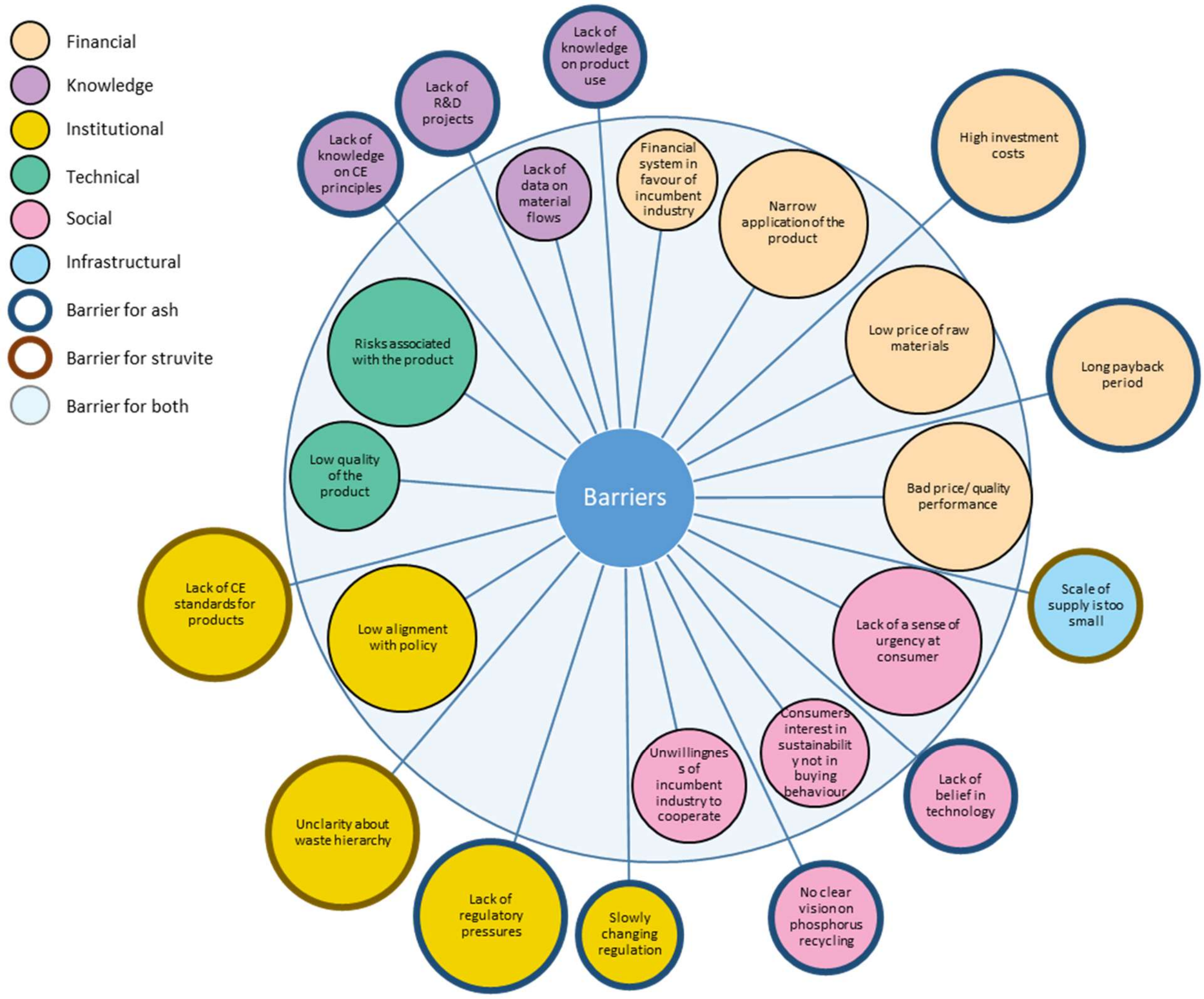
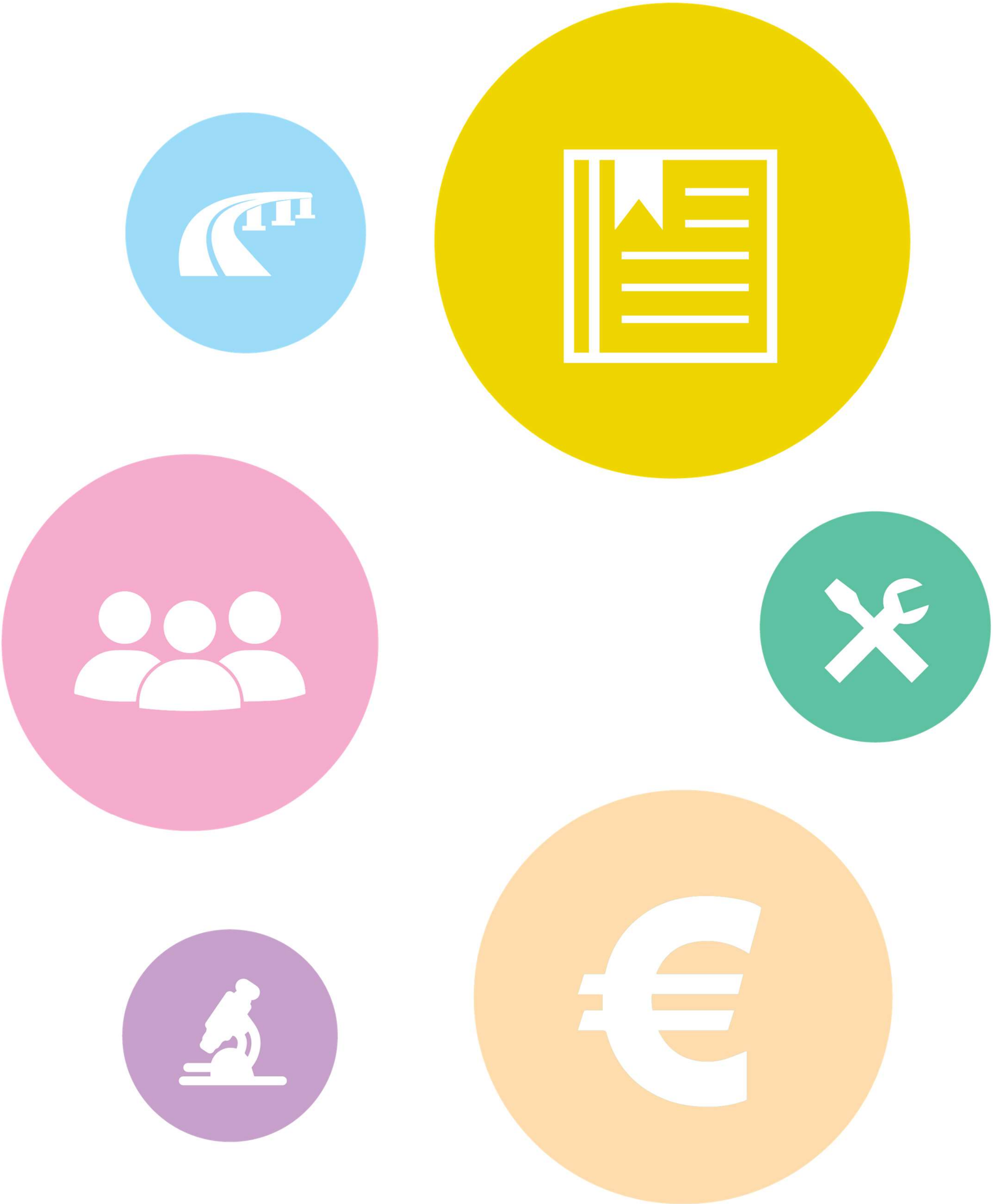


Figure 25. Conclusion of most important barriers with different validation method



Master thesis for the partial fulfilment of the requirements for the degree of
Master of Science in Industrial Ecology
At Delft University of Technology & Leiden University