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An Assessment of the Drivers and Barriers for the Deployment of Urban Phosphorus Recovery Technologies: A Case Study of The Netherlands

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Abstract: Phosphorus (P), being one of the building blocks of life, is essential for a multitude of applications, primarily for fertilizer usage. Sustainable management of phosphorus is becoming increasingly important in light of adverse environmental effects, ambiguous reserves, increasing global demand and unilateral dependence. Recovery of phosphorus from the biggest loss stream, communal wastewater, has the potential to tackle each of these problems. The implementation of phosphorus recovery technologies at wastewater treatment plants is not widespread, despite prolonged efforts primarily done by researchers over the past decade. This study aimed to assess the drivers and barriers of a phosphorus recovery transition. Several key stakeholders involved in this transition in The Netherlands were interviewed. The Netherlands was taken as a case study, since it serves as a frontrunner in the implementation of phosphorus recovery technologies. This study shows that the main barriers from the point of view of fertilizer companies are the different and unclear characteristics of the phosphorus recovery product struvite compared to common fertilizers. Moreover, the end-of-waste status of struvite is mentioned as a prominent barrier for a phosphorus transition, since it hinders free market trade. Many water boards indicate that the main barrier is the high investment cost with an uncertain return on investment for onsite struvite recovery processes. The specified main driver for water boards for onsite struvite phosphorus recovery technology is the reduction of maintenance costs, and for phosphorus recovery from sewage sludge ash, the low organic pollutant in the P recovery product.

Keywords: phosphorus recovery; wastewater treatment plant; drivers and barriers; circular nutrient economy; socio-technical transitions

1. Introduction

1.1. Phosphorus: An Essential Element for Life and Global Food Security

Life on earth depends on the consistent availability of certain key nutrients. It is widely recognized that elements such as carbon and nitrogen are essential for ecosystem functionality, yet the element that remains less acknowledged in its fundamental importance for life is phosphorus (P). On a micro level, phosphorus is essential for cellular function, reproduction (DNA, RNA, and ATP production), and human development [1]. On a macro scale, society is dependent on a continuous and sustainable phosphorus supply for food security since phosphorus is a critical nutrient input for crop and animal production systems [1]. Moreover, it is one of the main nutrient components in commercial fertilizer next to nitrogen and potassium [2].

The increased extraction of phosphate rock, which has been fueled by a demand for synthetic fertilizers and has been exacerbated by trends such as population growth, dietary changes, and a heightened production of biofuels, has led to a human alteration of the phosphorus (P) cycle beyond its natural biogeochemical rate. The natural phosphorus biogeochemical cycle is balanced and recirculates between the lithosphere (in the earth crust) and the hydrosphere (all the waters on the earth's surface) at a rate of millions of years. However, on a human timescale, phosphorus flows in a one-way, non-cyclic, direction at a rate three times faster than the natural flow to create phosphorus resources. This mismanagement and unsustainable direction has led to a widespread alteration of the global phosphorus cycle into a linear flow [3].

The debate over whether there will be a phosphorus peak is highly contentious across the scientific community. Peak phosphorus refers to a point in time when global production of phosphate rock would reach its peak and subsequently decline thereafter [4]. Speculations for peak phosphorus range between 30 and 300 years but are often not supported by valid data [5]. Nonetheless, despite such remarks about differentiating peak production years, there are other important factors at stake that make phosphorus management an important subject area. In 2014, the European Commission created a list of critical raw materials for the EU that have high economic importance coupled with a high risk associated with their supply. Phosphate rock is included in this list. The reason phosphate rock is listed as a critical raw material is due to a multifaceted set of causes, not just due to a matter of scarcity. The price volatility and the geopolitical factors involved in the P issues are important drivers for the EU to include this precious element in the list. The P problem is embedded within all areas of the P supply chain from mine to fork. The excessive use of phosphates without nutrient recycling has additional environmental effects and can lead to uncontrolled eutrophication in water bodies. The background section will elaborate on these previously mentioned prominent drivers that influence different aspects of the process and exacerbate such global problems.

1.2. Envisioning a Circular Nutrient Economy

Technological solutions are in development, and first steps have been taken to create a framework for the sustainable and responsible use of phosphorus in Europe. However, improvements need to be made to create a circular phosphorus economy that mitigates supply dependency and environmental impact. Despite these dimensions of the P problem, a fortunate aspect is that while phosphate rock may be a finite resource with an ambiguous time until depletion, phosphorus itself is an element that can neither be created nor destroyed. As Antoine Lavoisier formulated it in 1785 in his law of the conservation of mass: "Nothing is lost, nothing is created, everything is transformed" [6]. However, while P can fundamentally not disappear, in social-economic practices, it may be wasted beyond (easy, affordable) recovery. Therefore, the optimal path for P management is to switch to a management scheme that closes the P cycle by minimizing loss and optimizing value from waste streams [7]. This forms the basis for envisioning a pathway to facilitate a circular nutrient economy.

By definition, a circular economy is a system that is restorative or regenerative by intention and design that encourages the shift from a linear economy where loss and waste are omnipresent to a circular one. Here, resources are utilized to their full capacity and waste holds significant value for the regeneration into new products, thereby creating a new business model [8]. In support of this new economy, the EU Commission has mobilized collaboration via several initiatives such as the EU Circular Economy Package (2014), the Circular Economy Action Plan (2015), and the European Circular Economy Stakeholder Platform (2017) [9]. These calls for collaboration directly correspond to the necessity to create a circular nutrient economy, which thereby minimizes the reliance on foreign reserves to meet demand in the EU and look locally for solutions for recovering P through efficient management practices.

1.3. Drivers and Barriers of Implementing P Recovery Technologies

Since most of the consumed P ends up in the sanitary system, communal waste streams are a possible starting point for more sustainable P management. Recovery of P from communal waste streams as phosphate minerals, such as struvite or calcium phosphate, has shown to be technically feasible for more than a decade [10]. Since then, the number of technologies has grown considerably [11]. However, these successes have been mainly achieved in small-scale set-ups. To accelerate implementation of these technologies on a bigger scale, these technologies must be economically viable and technically feasible at an industrial scale [12].

Phosphorus can be derived as different P products out of wastewater [11]. Two recovered products are struvite ($NH_4MgPO_4 \cdot 6H_2O$) and sewage sludge ash (SSA), which can act as a derivative of phosphoric acid [13]. Struvite precipitation occurs naturally during biological wastewater treatment and has been traditionally a leading maintenance problem for wastewater facilities via the excess growth of struvite crystals in pipes, thereby resulting in encrustation, scaling, and subsequent high maintenance costs for removal. However, various water boards have found a solution for this problem via the precipitation of struvite out of the wastewater. This can be accomplished via the addition of a magnesium source in the right conditions to avoid scaling, resulting in a reduction of maintenance costs. Additionally, some of these wastewater companies are turning waste into a resource by utilizing the recovered struvite as a slow-release fertilizer [12]. The recovered P in the form of struvite has been shown to function as a fertilizer by increasing yields in pot trials [14].

Of the technologies that are already operating in full-scale, struvite is the main recovered product [12]. The use of sewage sludge ash is also a promising technology [13], but currently not done yet on large scale, although this might change in the near future when the Belgian company EcoPhos starts its operation [12]. The reason for focusing in this study on The Netherlands in particular is due to its frontrunner position. Many struvite precipitators have been integrated in wastewater treatment plants in The Netherlands and several projects in the pipeline. To stimulate the production of struvite at WWTPs it is important to analyze what the drivers and barriers are to implement a P recovery technology and to facilitate a transition to a sustainable use of phosphorus. To date, most studies in phosphorus recovery have focused on the technical aspects, but there is a lack of knowledge on the drivers and barriers for the deployment of phosphorus recovery technologies of involved stakeholders. Therefore, the aim of this paper is to assess the drivers and barriers of the implementation of recovery technologies of phosphates from an interdisciplinary perspective with The Netherlands as a case study.

2. Materials and Methods

An extensive amount of information was collected pertaining to specific drivers and barriers of the implementation of P recovery technologies. To define the drivers and barriers of this transition, several stakeholders were important to incorporate in this interdisciplinary study: the water boards that act as the suppliers of secondary phosphates, the fertilizer industry that act as buyers of these phosphates, a certifying agency of fertilizers, and inter-organizational/semi-governmental agencies active in this field that act as brokers. The Netherlands already has several examples of implemented struvite P recovery technologies, which gave the opportunity to study the drivers for deciding to implement such technologies as well.

This research consisted of two individual parts. The first part of the study shows the attitudes of various involved stakeholders towards struvite precipitation using the six PESTLE categories to get a clear grasp of the wider viewpoint from different perspectives. This research aimed at identifying the drivers and barriers according to various stakeholders.

The second part concerns an in-depth study on the drivers and barriers from the perspective of the P recovery producers, the water boards, since they are the decision makers on the implementation of P recovery technologies. Eight interviews were conducted for this study.

Two P recovery products have been included in the second study, namely struvite and sewage sludge ash. It was decided to not include sewage sludge ash in the first study, since the recycling of P from SSA is not in practice yet, but it is a recent topic for water boards since the recycling of phosphorus from sewage sludge ash will become reality in the nearby future of The Netherlands with the start of the production of EcoPhos. Therefore, this product has been included in study two which focuses on the water boards. Study two collected the data through five interviews and an electronic questionnaire, which was sent to all the Dutch water boards. Direct application of treated sewage sludge was not included, chiefly because this is prohibited in The Netherlands. Socio-technical transitions are difficult to study due to their intangible nature. Accordingly, qualitative research methods were considered more suitable to study the beliefs, values and motivations that underlie the behaviors of the stakeholders in this study.

2.1. Utilizing the PESTLE Framework

The information received and gathered was subsequently structured into different interdisciplinary categories using the PESTLE framework. A PESTLE analysis has been used to classify and structure the obtained results into six dimensions, namely the political, economic, social, technological, legal, and environmental categories.

2.2. First Study–Comprehensive View from the Perspective of Several Main Stakeholders

2.2.1. Data Collection

For the first study, we have conducted eight semi-structured interviews. The respondents of the first study included three representatives of fertilizer producers, three representatives of inter-organizational agencies, a water board representative and an agency involved in certifying agriculture soils (see Table 1). The objective of each semi-structured interview was to explore the drivers and barriers of the incorporation of struvite into their existing production lines or directly as a fertilizer. This entails discussing previous developments, current obstacles and future developments.

Table 1. Interviewees in the first study.

Respondents	
(1) Fertilizer company 1	(5) Knowledge center for nutrients/substrates
(2) Network Platform	(6) Network Platform
(3) Fertilizer company 2	(7) A think tank of water boards (EFGF)
(4) Water board	(8) Fertilizer company 3

2.2.2. Data Analysis

Data gathered during the eight interviews with stakeholders from several sectors were analyzed using the coding software Atlas.ti. The coding process is depicted in the Supplementary Materials. The first step of data analysis was open coding. This entails the labeling of categories and comparing them to contextualize the perspective of the interviewee. Statements are grouped into major categories. No interpretation of the results takes place. Open coding occurred through a five-step process: (i) transcription of data; (ii) familiarization; (iii) focused reading; (iv) review and amend codes and; (v) generation of theory. After open coding, axial coding allows the researcher to explore the relations among categories. Finally, selective coding deals with a higher level of abstraction. The main drivers and barriers derived from the study have been identified and classified.

Internal reliability has been guaranteed via audio recording of each interview. Issues with interpretative reliability has been minimized by iterating statements during the interview. The research design has been tested with two set-up interviews previously to the interviews to test the clarity and objectivity of the questions. The labeled results are classified into the six PESTLE categories and ranked on the frequency.

2.3. Second Study–in-Depth View from the Key Stakeholder, the Water Boards

Data Collection

For the second study, all twenty-two water boards in The Netherlands were contacted by email with an email questionnaire containing four qualitative questions in Dutch (see Supplementary Materials, S3) about the drivers, barriers and opportunities of the deployment of phosphorus recovery technologies.

Responses of the questionnaire were obtained from twenty water boards. All responses were collected and categorized by the PESTLE categories, labeled and ranked by their importance and frequency (Supplementary Materials, S4).

Next to the email questionnaire, five in-depth, semi-structured interviews were conducted with representatives of four different water boards and one expert on P recovery technologies implementation in WWTPs. Criterion sampling was used to select the four interviewees; all interviewees worked at water boards that implemented a struvite precipitator to determine their motives for implementation. All representatives were the person in charge of the implementation of the recovery technology at the WWTP to secure in-depth answers in the interviews. Furthermore, they have pivotal roles in innovation for the respective water board they worked for.

2.4. Data Analysis

A summary of each interview and can be found in the Supplementary Materials, S2. The mentioned drivers and barriers were categorized and ranked as the first study. The PESTLE structure and the ranking on their importance and frequency allows analyzing the greatest trends in responses.

3. Results

The results initiate in Sections 3.1–3.6 with an overview of the existing literature and regulations on each PESTLE topic, following an overview of statements made by the respondents on each topic of several main stakeholders (the first study). The results of the second study concerning the Dutch water boards are discussed in Section 3.7, which includes the barriers and opportunities of the two recovery products, struvite and sewage sludge ash, according to the Dutch water boards.

3.1. Political Aspects

There are various policy documents on P recovery, both at the Dutch national and European level [15,16]. Inclusion of phosphate rock on the European critical raw materials list demonstrates the interest of Europe's governing bodies. As of 2015, the incorporation of an article for recovered phosphate into the Dutch "fertilization law" indicates a political desire to support these developments at the Dutch national level too [15]. Moreover, the presence of various inter-organizational platforms focusing on nutrient recycling can be seen as a stimulating factor. The most important of which includes the European Sustainable Phosphorus Platform (ESPP) on the European level and the Dutch Nutrient Platform (NWP) on national level. In practice, these platforms serve as a hub for information exchange, and they facilitate communication between all cross-sectoral stakeholders. This Dutch platform, along with the ESPP, have promoted several soft legislative tools and research initiatives within the Dutch sector calling for a collaborative research environment across various stakeholder groups involved in P management in Europe. Examples of this include The Dutch Phosphate Value Chain Agreement facilitated by The ESPP in 2011, which called for a commitment to creating a sustainable market for secondary recycled phosphates over the course of two years in The Netherlands. The agreement was signed by twenty industrial companies, knowledge institutions, government authorities, and NGOs [16].

Concerns about dependence of countries outside the European Union on phosphate ore, and thus fertilizers for food production, have increased the interest for alternatives [4]. In fact, in 2011, the EU's import dependency for phosphate rock reached roughly 92% [17]. Currently, around 74% of global reserves are located in Morocco [18]. In terms of production, The United States, China, Morocco, and Russia produce 75% of the world's annual phosphate rock with the highest being China totaling 138,000 tonnes [18]. This market concentration thereby produces volatility and certain political and economic risks, as well as international security risks. This is for instance illustrated during the Arab Spring, where a stable supply from Tunisia, Jordan, and Syria was no longer guaranteed [17]. The phosphate market can be characterized as oligopolistic with monopolistic tendencies due to the limited number of countries acting as supplier but also the limited amount of companies in this sector [17].

Political Aspects: Interview Results

The public sector has developed an increased interest for sustainability. This has been expressed through keywords during the interviews such as "circular economy", "recycling" and "sustainability goals" (see Table 2). Three out of eight of the interviewees emphasized the positive effect of the Dutch Nutrient Platform on the developments at political and legislative level. Six out of eight interviewees indicate that the government and companies can play a critical role in accelerating the implementation of struvite recovery. They mentioned that the government can use tools to accelerate struvite implementation via initiatives such as green deals or via the SER, an advisory board for the Dutch government on the social and economic policy.

Intentions have also been converted into concrete actions. The Netherlands adopted new regulations regarding P recovery in 2015. The implementation process of these laws was experienced by the interviewees as a long, lethargic process (see Table 2). Besides changes in the political involvement on a national level, developments on international level have been indicated by the interviewees as well. There is an increasing political interest in the sustainable use of phosphate on a European level. Interviewees indicate that the incorporation of phosphate rock in the EU critical materials list has placed this subject on the political agenda and therefore this step can be seen as a vital aspect in this respect.

Table 2. Results on political aspects.

Political Aspects	# Respondents
Drivers	
Sustainability goals from government contribute to sustainable developments and implementations, such as struvite recovery. External stimuli, like the green deals stimulate sustainability goals	6
Positive effect of Nutrient platform. The nutrient platform has helped in accelerating developments at the political and legislative level	3
Political interest in phosphate sustainability has grown a lot at the European level. Incorporation in the EU critical materials list is seen as vital in this respect	3
Barriers	
The long process of implementation of passed legislation, especially for the revision of the fertilizer regulation and the end-of-waste (EoW) status	4

3.2. Economic Aspects

There are distinct market fluxes and geopolitical tensions that place direct pressure on the global phosphate market. China imposed a 135% export tariff on phosphate rock in 2008, placing direct pressure as the biggest supplier on the global phosphate market. Due to an increased demand, uncertainty of available reserves of mineral P and the export tariff of China, the price of P spiked eightfold from $50 per tonne to $400 per tonne in 2008 [19]. After this price peak, the price stabilized around $100 per tonne, twice as much as before the peak. The trend of large P producing countries becoming net importers resulted in less competition on the supply side, and more on the demand side, which in turn influenced the price of mineral P. This was significant for the EU, since the EU heavily relies on import of mineral P.

The low market price of phosphate ore can be seen as an economic constraining factor for the development of a struvite value chain [12]. A struvite-based product has to be as efficient, affordable, and predictable in releasing nutrients as existing materials to compete with the established, efficient and relatively cheap starting material phosphate rock [20]. Nonetheless, the market opportunities should still be pursued to keep technological developments going and attract investors [12]. Schipper mentioned that even though P recovery might not currently be economically viable, efforts should be made now to ensure that technologies are ready when scarcity of phosphate rocks starts to play a role [20]. Schipper and Schoumans et al. state that some form of government intervention in the market place will be necessary to create a P recovery market [20,21].

Controlled struvite precipitation can be used as a means to reduce maintenance costs at wastewater treatment plants that use a biological treatment technique [11]. While there are significant costs associated with the chemicals used for struvite precipitation, there are also savings to be considered. This is due to the prevention of incrustations, the reduced chemical demand and the reduced sludge quantity, which results in lower disposal costs. Reported investment costs differ substantially. In general, costs for phosphorus recovery and the return on investment period are highly dependent on the type of technology utilized and size of the plant [22]. Several studies report a return of investment of six years for facilities with capacities of 265 and 3711 m^3/day, respectively [23,24].

Schipper states that upholding the wishes of the market is often overlooked by researchers [20]. This finding is underlined by Kabbe et al., stating that researchers have reinvented the wheel multiple times, and technological efforts are overly complex and the user is not always sufficiently involved in the research process [12]. This indicates that there is a knowledge gap concerning the market applications of struvite.

Economic Aspects: Interview Results

The main driver to recover struvite out of wastewater is the reduction of maintenance costs for the water boards (see Table 3). The reduction of expenditure on chemicals has been the driving factor behind implementing the EBPR technology, a biological wastewater treatment technology, but a disadvantage of EBPR is the increased clogging of pipes, which results in high maintenance costs. Without this operational cost benefit, there is currently no foundation for struvite recovery in The Netherlands.

Struvite as a stand-alone product is seen as not particularly viable by the interviewees from the fertilizer industry. Struvite might serve as a viable solution in niche markets as small, amateur farmers or grassland, but interviewees are skeptical regarding introducing struvite as a product in the fertilizer industry. They agree that the fertilizer industry is a traditional sector and not looking for a new product, while the currently used products have been working efficiently for decades and the price of phosphate rock is low.

Interviewees indicated that one of the main barriers of struvite recycling as fertilizers are the differences in vested interests between the stakeholders. The fertilizer market can be characterized as conservative, rigid, and hard to change. As an interviewee working at a fertilizer company mentioned: "10 years ago they wanted a particular product and in another 10 years they will still want the same product". The competition from established industry is too high to get things off the ground without any additional incentives. The main incentive of water boards is not producing a well-fitted product for the current existing fertilizer industry, rather it involves reducing the maintenance costs via precipitating a product out of their waste water. It will require the collective effort of different consortia to promote the reuse of struvite.

A driver for the use of P recovery products for fertilizer companies and the implementation for water boards is the sustainable label. As a quote of one of the interviewees clearly shows: "We can stick a green sticker on it and it will sell like crazy". Phosphate scarcity and environmental effects are known problems within the industry but there is no need or incentive for industry to act.

Interviewees indicate that the market for fertilizers containing P is not in The Netherlands, due to the surplus of phosphates in the soil, which resulted in strict regulations for fertilizer use. Transport issues could threaten profitability. Feasibility of any value chain will depend on transport costs, both from an environmental and economic perspective.

Other interviewees indicate that entrepreneurs and investors want long-term contracts, but water boards are unable to provide these. This uncertainty on the return on investment is the most important reason long-term investment is currently lacking.

Table 3. Results on economic aspects.

Economic Aspects	# Respondents
Drivers	
Reduction maintenance costs	6
The "green" marketing aspect of struvite is attractive	3
Implementation opportunities for struvite in niche markets	2
Barriers	
Transport issues	5
Conservative market	4
Low price of phosphate rock/fertilizers	4
Vested interests and complexity stakeholders	3
Uncertainties in return on investment	2

3.3. Social Aspects

The public perception of P recovery is scientifically not well documented due to a lack of research in this area. According to Schipper (2014), the low interest from society for this issue is related to the invisible role P has in the environment and the unattractiveness of sewage treatment [20]. Acceptance among the farming community and important market players will be decisive for the introduction of a P product that is based on recovered P [25]. While consumers only represent the end of the phosphorus value chain, they remain important end-user stakeholders who can collectively use their consuming power to contribute to increased phosphorus use efficiency and can move towards a more sustainable phosphorus cycle [26]. Nevertheless, the majority of food consumers are not aware of issues regarding phosphorus, at least in view of it being an essential finite resource nor its environmental effects [1].

Social Aspects: Interview Results

The interviewees agree that there is an overall open and enthusiastic mindset about recycling and innovation in The Netherlands. Sustainability is a buzzword, which is utilized by companies and water boards in marketing campaigns on sustainability (see Table 4). Especially circularity and circular economy are words, which have been mentioned by most of the interviewees in a positive context. The attitude toward recycling is not expected by the interviewees to be equally as receptive. The fertilizer industry is perceived as more conservative. A product that is harvested from waste is not expected to be received with open arms among the public and industry because of hygienic concerns and current views on waste.

Even though the wider public is still hardly aware of phosphorus related issues, there is an increased interest and awareness. As a quote indicates: "If you talked about phosphate recycling 4–5 years ago, nobody had a clue what you were talking about (. . .), now it is much more of an issue". Some of the interviewees indicate that the public opinion is negative concerning struvite since it is a product derived from wastewater and they immediately relate this to health issues. Educating society will be necessary to gain product acceptance. Safety may be guaranteed, but the idea that struvite is harvested from waste sources could be problematic. Other interviewees claim the opposite and mention that there is a very positive attitude towards the "green" product struvite, despite its origin.

It is indicated that the users of fertilizers, farmers (not interviewed in this study), are not aware of the effects of the surplus of phosphates. Growing awareness about the phosphate problem could play a helping hand in the use of recycled phosphates. A research conducted by Hasler et al. (2016) shows that the farmers are the most skeptical towards fertilizer eco-innovation of the whole supply chain [27]. Hasler et al. (2016) concluded that both farmers and suppliers consider legal regulations as a driving force for environmental requirements and eco-innovation [27]. Further research on the opinion of farmers could shed more light on the opinions of farmers towards the use of struvite or other recovered P products.

Table 4. Results on social aspects.

Social Aspects	# Respondents
Drivers	
Popularity of circularity and circular economy	5
The value of struvite as a green marketing tool for the water board	2
Public opinion: A positive public opinion regarding to struvite due to the green label	2
Barriers	
There are no common interest and an integrated approach is missing. A collective vision is lacking	3
Different mind-sets concerning recyclates per country	2
A negative public opinion due to the uncertainties of health issues/safety	3
Low awareness among farmers about struvite	2

3.4. Technological Aspects

Communal waste streams converge at regional WWTPs where water undergoes various treatment steps before it is released to the surface water. These WWTPs are a suitable location to recover P since the high P concentrations and P recovery technologies can often be combined with existing setups. Several types of P removal technologies exist to treat the wastewater and commonly used methods are Bio-P removal or P removal via chemical dosing. The P removal technique Bio-P is commonly used in The Netherlands, but has a negative side effect that it leads to the high release of biologically bound, water soluble P into the aqueous phase of the sludge. At high P concentrations, struvite is unintentionally formed in pipes, pumps and dewatering units of sewage systems and WWTPs, which requires maintenance costs to remove this crystal rock formation. Therefore, the intentional precipitation of struvite before it clogs the pipes reduces the maintenance costs of the pipes. This product, struvite, can afterwards be used as a fertilizer. The P from the P rich sewage sludge can be recovered through either wet chemical treatment via acid or alkali leaching or thermochemical treatment when the P can end up in the sewage sludge ash [14].

Struvite is less soluble in water than traditional fertilizers, making it a slow release fertilizer, which means that the nutrients are only gradually available for crops. Several studies have been conducted on the final yields of crops grown using struvite as well as conventional fertilizers. The use of struvite in combination with conventional fertilizers results in high phosphorus efficiency and P uptake during the early and late growth [28]. To date, there is still a lot of ongoing research on the quality of struvite and the effect on the soil quality.

Technological Aspects: Interview Results

There are diverging viewpoints among the interviewees surrounding the quality of struvite as a fertilizer. There are two opinions about the quality of struvite. Two interviewees indicate that the chemical composition of struvite is favorable, both not working in the fertilizer industry (see Table 5). The interviewees from the fertilizer industry indicate that struvite is not a complete, final product from a market perspective. The characteristics are poor due to the low solubility and the lack of potassium. They conclude that it must be treated before it has value as a stand-alone fertilizer. Besides this, they indicate that struvite is not compatible with the machinery of the farmers.

The low solubility was a reason for one interviewed fertilizer company to discontinue their research into struvite. Another company uses struvite as an additive starting material besides phosphate rock. The customers want a product highly soluble in water. Struvite applications are limited to its use as a side input in the production of regular fertilizer or in the niche market for specialty fertilizers. This means it can be used in niche markets with other requirements, such as grasslands.

Another technological constraint of struvite is the limited rate of recovery from waste streams. Recovery of P via a struvite precipitation method at full scale generates several thousands of tons of P each year. Production of fertilizer takes place at several hundred thousand tons each year. Therefore, struvite does not have a significant contribution to overall production output. A higher recovery rate can be realized when the sanitary infrastructure changes drastically, i.e. separation of urine without the dilution with rainwater, but this is costly.

Fertilizer companies wish to remain far under the minimum requirements for hazardous compounds. Therefore, the lack of clarity on product safety and characteristics are barriers to use struvite as material.

Table 5. Results on technological aspects.

Technological Aspects	# Respondents
Drivers	
Struvite has the chemical composition/characteristics of being a good raw material	2
Barriers	
Product safety is unclear	3
Low solubility of struvite	2
Struvite is not a stand-alone product	2
Negative chemical characteristics struvite	2

3.5. Legislative Aspects

Struvite and more specifically the trading of struvite is subject to several national and European regulations. The recovered P from waste streams is seen as a waste product by law. Reuse in production processes will therefore require adherence to additional criteria.

Two main types of legislations are involved in implementing P recovery technologies, regulations on the installation of P recovery technologies and on the recovered P products. A selection of the most important legislations regarding P products will be discussed.

All companies are obligated to require permits for their P recovery installations. Currently, most WWTPs are classified as "waste management" by two directives: the EIA (Environmental Impact Assessment directive) and the IED (Industrial Emissions Directive) which are in place for companies in waste management and recovering/recycling [25]. Recycling and recovering companies, labeled as waste management, have to follow far stricter rules than fertilizer companies using phosphate rock [25].

To gain a status of "fertilizer producer", extra permits and new installations are both needed for WWTPs, which costs extra time and money. Registering a new (sustainable) fertilizer type can take up to 7 years, which therefore blocks innovation [25]. Consequently, WWTPs often choose to sell the recovered P as waste, instead of turning it into fertilizers.

Next to the two directives concerning this classification, there is the Shipment of Waste Regulation. This regulation applies to WWTPs that would like to export their recovered products, which are labeled as waste, such as sewage sludge or struvite, for recycling across borders. This regulation states that a contract should be set up between the person responsible for the shipment of the waste and the receiver of the waste. Moreover, authorities from both the country of origin and waste product destination should authorize the shipment. This process is time-consuming. Meanwhile, importing phosphate rock does not have to undergo similar processes, making it easier to import phosphate rock than P containing waste [25].

The placement of the recycled materials is divided into two subcategories, namely material type and market segments of recycled materials. Material type legislation looks at whether the designated material is a product or waste. This is examined on a national or regional level via the End-of-Waste (EoW) criteria of the Waste Framework Directive (WFD) [29]. Consequently, a material can be registered as a product in one country, but as waste in the other, which is an obstacle to trade across borders. Waste and product materials need to conform to different regulations and directives, such as REACH [30].

All chemical substances that are traded in Europe must be approved through the European Chemical Regulation (REACH) legislative framework. This approval for struvite has been obtained in 2015, alleviating an important legislative hurdle. Currently, an important obstacle for reuse of secondary phosphorus-containing products is the lack of an end-of-waste status.

Next to material type, there is legislation on market segments of recycled materials. An important regulation is The Fertilizers Regulation [31]. This regulation imposes certain requirements on fertilizers.

For example, the fertilizer may not be harmful towards the environment or human health. If fertilizers meet all requirements, they can be labeled as EC fertilizers (safe and effective fertilizers on the EU market). This can improve a fertilizer's marketing position drastically. Unfortunately, it is often the case that gaining this label for a fertilizer can cost half a decade. Moreover, there are criteria in The Fertilizers Regulation on the source of materials used for fertilizers instead of regulations on the final fertilizer product, and a procedure for organic fertilizers is lacking. This creates a barrier for new innovative (phosphorus-friendly) fertilizers. Some countries, such as The Netherlands, pay special attention to recycled fertilizers by changing their national regulation in a favorable way for the use of struvite. However, other countries have more rigid regulations on pollutant concentrations, such as heavy metals which can have a negative effect for struvite due to the difference in composition of struvite compared to traditional fertilizers. This results from the fact that there are no regulations on pollutant concentrations at the European level, again imposing a barrier for the EC fertilizer label. Struvite has been registered as a fertilizer in The Netherlands from 15 December 2014. Conforming to all regulations in all countries is extremely difficult, costly and time-consuming. Kabbe et al. (2015) state that designing supportive legislation for the circular economy should be a priority [12]. The working group STRUBIAS is trying to make headway with this issue through proposed amendments to The Fertilizer Regulation. The proposed EU fertilizers regulation revision includes to add struvite, biochars, and ash-based recycled nutrient products to the new regulations, which will grant an end-of-waste status to fertilizers using these recovered phosphorus products. Phosphorus taxes for usage in agriculture have already been experimented with in several European countries: The Netherlands, Sweden, Denmark, Austria, Norway, and Finland. The aim of these taxes was largely to decrease phosphorus usage on farms for environmental reasons [32,33]. More information on phosphorus taxes can be found in the Supplementary Materials.

Legislative Aspects: Interview Results

Interviewees indicated that the REACH classification is an important contribution to struvite development (see Table 6). However, these developments are very recent. The Netherlands has adopted new regulations concerning P recovery in 2015. The implementation of P recovery products in the fertilizer regulation would also be a big step forward. Other improvements at the public policy level would be removing trade barriers between countries. Influencing the water boards through legislation is very difficult because they act as an independent governing body. The EFGF (Energie en grondstoffenfabriek) is a cooperative effort of the water boards in The Netherlands. There are one or two moments in the year when the EFGF meets physically. However, only the water board members participating in the EFGF meet here so the diversity in opinion is not very broad. Most interviewees think that governmental intervention will be necessary to stimulate market formation, as has been the case with bioplastics and green energy.

Using struvite as a raw material in existing processes is possible under the condition that fertilizer quality standards are met. Current legislation is seen as problematic, since struvite cannot legally be transported across national boundaries unless both countries approve it. This is troublesome since firms are not allowed to transport or accept the material. Registration of struvite as a fertilizer or waste product is therefore necessary. However, the end-of-waste label is currently governed under national legislation, it often cannot be transported across borders. For proper waste management, waste needs to be seen as resource and therefore EU-wide EoW criteria are needed.

Table 6. Results on legislative aspects.

Legal Aspects	# Respondents
Drivers	
Certification of struvite might alleviate fears around product safety	2
REACH classification	5

Table 6. *Cont.*

Legal Aspects	# Respondents
Barriers	
The political interest in phosphate sustainability has grown a lot at the European level. One thing that is lacking at the political level is the implementation of passed legislation, especially revision of the fertilizer regulation and so the end-of-waste (EoW) status	4
Trade barriers of waste between countries hinders the trade in P recovered materials (EoW status)	2

3.6. Environmental Aspects

Life cycle assessments have shown that struvite based fertilizer has a lower environmental impact than phosphate rock [34,35]. Looking at P efficiency, using sewage sludge directly on farmland is the most desirable, since all P is reapplied to farmland. However, from a toxicity perspective, phosphate ore has been found to be more favorable than direct application of sludge due to the medicines and pathogens in sludge [36]. The lack of heavy metals in struvite makes struvite even more favorable from a toxicity perspective than phosphate ore [36].

A steep increase in the use of P rich fertilizer has led to the production of more food but also more waste. Together with deforestation, this has caused displacement of large amounts of P throughout the environment [37]. Today, 1.9 terragrams (Tg) of P flows into the EU from outside sources each year and 80% of this influx can be attributed to P rock imports to be processed for use as fertilizers, in the food industry and detergents [1].

Excess amounts of P can be found in water bodies that are sourced from agricultural runoff and the outflow from industrial and municipal wastewater facilities, which subsequently leads to the development of eutrophication. This problem is stimulated by soil erosion, which carries a significant amount of soil-bound phosphorus into surface waters. A 2013 model developed by the EU estimated that roughly 1.3 million km^2 of land was affected by soil erosion in the EU-27 [4]. Rodriguez-Garcia showed that the environmental benefit with regards to eutrophication is significant when P recovery technologies will be implemented, especially when different technologies are combined at the same location [38].

Regarding loss, this is exhibited readily throughout different areas of the P supply chain. Kimo van Dijk et al. (2016) examined all categories of loss for the EU, which included consumption, non-food production, food processing, animal production, and crop production [39]. Out of all sectors, consumption demonstrated the highest level of loss is the waste water sector (32% of the total system losses).

Environmental Aspects: Interviews Results

P recycling could help to correct the large regional differences in P in the soil. In The Netherlands, there is a large surplus of P in the ground, whereas much soil in Eastern Europe has a phosphorus deficiency. This has also been indicated as a driver by two respondents (see Table 7). This can work as an incentive to export to Eastern Europe. Exporting surplus P could help The Netherlands adhere to European soil guidelines in the future. There are concerns about the efficiency of struvite recovery since a large amount of P is not recovered from the waste streams and remains in the sludge. Other technologies will be necessary to recover the rest.

Table 7. Results on environmental aspects.

Environmental Aspects	# Respondents
Drivers	
High P content in soils	2
The value of struvite as a green marketing tool for the water board	2
Barriers	
Low maximum recovery yield	3

3.7. Results from Study 2: Drivers and Barriers from the Key Stakeholders' Point of View, the Dutch Water Boards

This paragraph contains the results of the second study. All the data retrieved in the second study from the questionnaires and gathered during the interviews with the Dutch water boards are visualized in Tables 8 and 9. These responses picture the trends for opportunities and barriers for both struvite recovery and treated sewage sludge ash products, which were the two routes identified by the water boards as the two most promising technologies for P recovery.

The most common response (five responses) for the drivers of struvite recovery are the avoided maintenance costs (see Table 8). This fits into the economic category of the PESTLE framework (see Section 3.2). The positive effect on the image of the water board is also mentioned three times, which is part of the social category of the PESTLE analysis. Besides this, several water boards have indicated that they have future plans for onsite P recovery in the form of struvite, which is an indication that the amount of implemented struvite precipitators will increase in the nearby future. The implementation of a struvite precipitator also results in greater process limitations, which has also been mentioned as a key driver by two respondents.

Regarding ash products, the highest number of responses (five) claimed that the largest benefit of engaging in sewage sludge ash treatment for P recovery is that it destroys organic matter and, as a result, lowers the potential risk for contamination of organic pollutants and pathogens, which therefore fits into the environmental and technological category of PESTLE. Three respondents also indicated that they are optimistic about the potential for the production of recovered products with the new EcoPhos and SNB/HVC partnership that will start in 2018.

Table 8. Trends in opportunities according to the water boards.

Struvite Recovery Drivers		
Response	**PESTLE Category**	**# Respondents**
Struvite recovery results in avoided maintenance costs	Economic	5
Onsite P recovery technologies lead to positive results for shaping water boards' image and promoting circular economy practices	Social and Economic	3
Various water boards have future plans for onsite recovery and subsequent struvite production	Technological	3
P recovery results in greater process optimization	Technological and Economic	2
Sewage Sludge Ash Product Drivers		
Response	**PESTLE Category**	**# Respondents**
Destroys organic matter and as a result lowers risk for contamination of organic pollutants and pathogens	Environmental and Technological	5
The water boards are optimistic about the potential for the production of recovered products with the new EcoPhos and SNB/HVC partnership that will start in 2018	Technological and Economic	3

In contrast to these drivers, a reported barrier for struvite recovery was the relatively high investment costs with a low certainty for return on investment (Table 9). Besides this, the end-of-waste status of struvite has been mentioned as a barrier for the trade of struvite across borders, which is a legal aspect. Moreover, two water boards indicated that it is not favorable for them to implement struvite recovery technologies, since the population equivalent of their wastewater treatment plants is too small and therefore economically not feasible to implement a struvite precipitator. Another driver which has been mentioned was that Dutch water boards are often publicly owned and funded entities. This gives conflicts as soon as they start to produce commercial products as struvite. Therefore, the products are often sold by another company, aquaminerals.

A reported barrier for struvite and total P recovery mentioned was that water boards that already have an incineration partnership with SNB/HVC and as a result are affiliated with EcoPhos, have little motivation to use on-site P recovery technologies since they are part of a bigger more centralized scheme for P recovery.

Table 9. Trends in barriers according to the water boards.

Struvite Recovery Barriers		
Response	**PESTLE Category**	**# Respondents**
High investment costs and low certainty of the return on investment pose a predominant barrier for more water boards	Economic	4
End-of-waste status and subsequent difficulties posed for trading struvite with other nations is a difficult barrier	Legislative	4
Small WWTPs are less inclined to implement P recovery technologies due to the low quantity of sludge production output. Therefore, there is not a very strong business case for these plants	Technological and Economic	2
Sewage Sludge Ash Product Barriers		
Response	**PESTLE Category**	**# Respondents**
The water boards that already have an incineration partnership with SNB/HVC and as a result are affiliated with EcoPhos, have little motivation to use on-site P recovery technologies since they are part of a bigger more centralized scheme for P recovery	Technological and Social	2

4. Discussion and Outlook

This research shows that the key constraints for a transition toward a circular phosphorus economy in The Netherlands are of an economic, legal, and technological nature. The opportunities and barriers for P recovery are not independent; rather they are part of an interdependent scheme and related to several dimensions. For example, the end-of-waste status of struvite (legislation) causes a transport issue, which directly affects the marketability of the product across boarders (economics). An overview of the main drivers and barriers derived from this research can be found in Table 10.

Table 10. Main results derived from the interviews and questionnaires.

Political	**Economic**
Drivers • Sustainability goals of the government • Growing political interest • Nutrient platforms	Drivers • Reduction maintenance costs • Opportunities in niche markets • SSA: destroys organic matter Barriers • Transport issues • WWTPs with too low sludge production • Low price phosphate rock • Conservative market • Vested interest stakeholders • Investment costs • Uncertainties return on investment

Table 10. *Cont.*

Social	**Technical**
Drivers • Popularity circular economy • Green marketing image • Both positive and negative public opinions Barriers • Integrated approach is missing • Different mind-sets concerning recyclates among the EU • Low awareness among farmers	Drivers • Struvite composition to be used as fertilizer • Struvite precipitation results in greater process optimization Barriers • Low solubility of struvite • Struvite not a stand-alone product • Negative chemical characteristics struvite • Product safety unclear
Legal	**Environmental**
Drivers • REACH classification • Certification might alleviate fears Barriers • Lack of implementation of passed legislation • End-of-waste status struvite	Drivers • High P content in soils Barriers • Low maximum recovery yield

Three main players involved in the deployment of P recovery technologies are the water boards who supply the P recovery products, the Dutch national and European governments that are responsible for legislation, and the fertilizer companies that are responsible for introducing the recovered P on the fertilizer market. All three stakeholders have other vested interests, which hinders a phosphorus transition. The individual grounds of the behavior of these main stakeholder groups found in this research, followed by our recommendations and outlook to accelerate the implementation of P recovery technologies will be discussed below.

4.1. Water Boards

The primary task of water boards has always been the purging of wastewater, and not the selling of products. Therefore, the water boards are somewhat unfamiliar to the new role of serving as a raw material producer. The main reason to incorporate a struvite precipitator is mainly not the production of a high quality secondary product, but rather the reduction of maintenance costs. Kabbe et al. also confirm that the main driver is the lowered maintenance costs [12]. The reduction of maintenance costs is obtained when 10–15% of the P influent has been recovered as struvite, so there is no financial incentive to recover more. From a sustainable perspective, it would be ideal to recover more and this is technically possible (up to 46% in combination with a WASSTRIP [40]).

As for the WWTPs, it is key to avoid clogging of the pipes, while the quality of the recovered product has received less attention from the water boards. This results in different types of quality of the produced struvite and no uniformity of the product. The attitude of water boards has the potential to change in the nearby future, especially due to the current trend of privatization of the water boards in The Netherlands. Focus on innovation and allocating more of their budget for this could become more readily apparent. The water boards indicate that a positive side effect of the implementation of a struvite recovery technology is the effect on the (sustainable) image of the water board. Other incentives are necessary to encourage water boards to recover more than only necessary for the reduction of maintenance costs and to uniform the quality as well as industry acceptance of the obtained product. This can be achieved via regulations or an economic stimulus from the market when the recovered product is seen as a valuable product and is marketed as such.

4.2. Government

The European fertilizer regulation has been subject to extensive revision and a contentious debate. Soft legislative measures are easier implemented, including initiatives such as the Phosphorus Value Chain Agreement, which offered non-binding and relatively incremental initiatives to engage in better P recovery management processes. Currently, there is little consistency between legislation at the national and international levels. The interviewed parties from different sectors indicate that the end-of-waste status is the main impediment for international P recovery products trade. Due to this status, it is not allowed to ship these products across national borders, which hinders free market trade.

Legislation concerning P recovery and the resulted products are continually developing in Europe. Recently, Germany and Switzerland changed their legislation to stimulate P recovery via obligating P recovery for WWTPs in the nearby future. This legislation change urges WWTPs to consider P recovery possibilities and can serve as the first step to the transition of standardizing P recovery from wastewater.

Water boards can already earn renewable energy certificates (RECs) for trading renewable energy, but there is no credit system for recovered P. A phosphorus recovery certificate may function as an incentive and push to recover P, which can be a stimulus for the P recovery market. Legislation should not only focus on P recovery, but on several aspects related to sustainability. Such as a method to create an economic incentive package for WWTPs that are willing to switch to biological removal, which offers support for renewable biogas generation and P recovery as struvite or low metal containing SSAs at the same time, will encourage sustainability in its broader definition.

4.3. Fertilizer Companies

The fertilizer market is difficult to modify. Moreover, there is currently little financial incentive for fertilizer companies to invest in P recovery for several reasons. The amount of struvite or other recovered P products that is available to date is limited in comparison with the quantities the fertilizer companies work with. Additionally, the current low price of phosphate rock creates a difficult environment for struvite to compete with traditional products.

The economic aspect is not the only factor that plays a role for the resistant attitude of fertilizer companies. The differences of technical properties as the low solubility of struvite, the nutrient content and the fact that struvite is not seen as a stand-alone product affects the image of struvite (see technical barriers in Table 10. The market for struvite in its current form as a slow release fertilizer is much smaller than the market for regular fertilizers. Closing the cycle is impossible without market acceptance and a sufficient quantity of P recovered products. A demand of the consumers' side that can create a pull effect at fertilizer companies, a trustworthy product, and a bigger quantity of P recovery products to make it worthwhile to consider is necessary to make it attractive for the fertilizer industry. Notwithstanding, several companies have expressed interest in secondary P sources, have participated in setting up P recovery sites, and see the added value of the green and sustainable status of struvite.

4.4. The Current Value Chain Is Linear and Not Circular

There is no one size-fits-all solution, since the most suitable and efficient P recovery process depends on the region, regulations, as well as type of wastewater treatment plants. Tailor-made regional targets for P recycling incorporating both the new suppliers (the water boards) and the fertilizer industry are necessary to achieve P recycling. To create a European market on secondary phosphates, legislative adaptions are crucial to help to facilitate a no-waste, circular nutrient economy for the phosphate market across various national borders. A challenging task for future research is the comparison with the drivers of other countries besides the Netherlands.

The main barriers for closing the cycle are transport issues due to the end-of-waste status, different interests among stakeholders, the low price of phosphate rock, and the uncertainties regarding the return on investment. The conflict of interest results in a mismatch regarding the quality of the product; the water boards want to reduce the maintenance costs via struvite precipitation and selling the struvite as a slow release fertilizer, while the fertilizer companies want to have a known, high-quality and inexpensive product. The national and European government could play a leading role in harmonizing the interests via soft and hard regulations on European level.

Research shows that the use of struvite in combination with conventional fertilizers results in high phosphorus efficiency and P uptake during the early and late growth of the crops. Finding niche markets for the recovered P products and bigger quantities of recovered P products is crucial to make it profitable and appealing for fertilizer companies.

The use of P recovery products is crucial to promote the sustainable use of phosphorus, but the reality of the markets suggests that this practice is still very much operating at a niche scale. Nonetheless, while there are barriers to implementation, the opportunities presented across the Dutch and European market suggest that this practice holds a high degree of potential for expansion, adoption, and implementation in the near future.

5. Conclusions

As the research in this paper shows, the drivers and barriers for the implementation of P recovery methods and their associated products are of a multi-faceted nature, stemming from political, economic, social, technological, legislative, and environmental categories. As such, this research used a PESTLE analysis to interpret such drivers and barriers. Methods included conducting qualitative interviews with important stakeholders across each of the PESTLE categories. Qualitative coding of responses was utilized to examine the most important trends in the drivers and barriers. The results indicate that while there are specific drivers and barriers that are central to each of the PESTLE categories in the framework, many of the overall trends in the results of drivers and barriers are highly intertwined across multiple aspects. Regarding the greatest trends in the drivers and barriers for the two P recovery products examined: the greatest response for a struvite driver is that it results in avoided maintenance costs yet it is also subject to high investment costs with uncertain return on investment. Whereas, for sewage sludge ash products the greatest indicated driver was that many water boards are optimistic about a future incineration partnership for producing sewage sludge ash, but in terms of the largest barrier, small plants are less likely to participate in the production of this specific P recovery product. As these P recovery methods are still in the beginning stages of implementation, this research serves as an important overview of which areas to address in terms of moving forward for further upscaling into the European market.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/6/1790/s1, Scheme 1: The steps followed during the analysis of the interview data methodology of Gray (2013) in Study 1, S2: Interview summaries Study 2, S3: Questionnaire script for Study 2. Table S1: Drivers and barriers of each water board.

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