Aalto University
School of Engineering

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# Recovery and reuse of phosphorus from municipal wastewater – applications and attitudes in Finland

Master's thesis submitted for examination for the degree of Master of Science in Technology

Espoo 27.11.2017
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**Abstract of master's thesis**

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**Title of thesis** Recovery and reuse of phosphorus from municipal wastewater – applications and attitudes in Finland

**Degree programme** Civil and environmental engineering

**Major/minor** Water and environmental engineering/ Environmental ecology **Code** R3005

**Thesis supervisor** Prof. Riku Vahala

**Thesis advisor** D. Sc. Anna Mikola

**Date** 27.11.2017 **Number of pages** 42+2 **Language** English

**Abstract**

Phosphorus is a non-renewable resource that is mostly used as a fertilizer in agriculture all around the world. To be able to secure a food production that is going to satisfy the needs of the growing population of humans on earth, a more efficient recycling of phosphorus in human society is needed. One source of phosphorus in communities is wastewater, which is interesting in the context of phosphorus recycling because of its characteristic of gathering the resources from a large area to a specific point, the wastewater treatment plant. There are many techniques in the world for recovering and reusing phosphorus from wastewater. Some techniques recycle the phosphorus as a part of the by-products of the wastewater treatment plant, while others separate the phosphorus to a different fraction. No phosphorus recovery techniques that separate phosphorus to an individual fraction are in use in Finland. When implementing a new technology into already existing processes and infrastructure, many aspects need to be taken into consideration. The existing technology can limit or favour certain options above others, as might attitudes of the people involved. Also, economic realities limit the possibilities of suitable solutions.

In this study the main questions to be answered were the current state of the phosphorus recovery techniques in the world, techniques that are suited for Finnish conditions and current practices and also the canvassing of attitudes of water treatment experts towards the different recovery paths.

The results showed that phosphorus recovery techniques that are suited as such to Finnish practices do not exist yet. In countries where phosphorus recovery techniques have been developed, biological phosphorus removal and sludge incineration are common which means that recovery techniques have been adapted to work with the sludge treatment methods in question. The attitudes towards phosphorus recovery technologies among wastewater experts in Finland favour techniques that are easily implemented to the existing systems. To enable more efficient phosphorus recovery in Finland would require big changes to current practices and development of new kinds of recovery technologies.

**Keywords** phosphorus, recovery, municipal wastewater, recycling

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**Diplomityön tiivistelmä**

| | | |
|---|---|---|
| **Tekijä** Tanja Pihl | | |
| **Työn nimi** Yhdyskuntien jäteveden fosforin talteenotto ja hyötykäyttö – sovellukset ja asenteet Suomessa | | |
| **Koulutusohjelma** Yhdyskunta- ja ympäristötekniikka | | |
| **Pää-/sivuaine** Vesi- ja ympäristötekniikka/ Ympäristöekologia | | **Koodi** R3005 |
| **Työn valvoja** Professori Riku Vahala | | |
| **Työn ohjaaja** TkT Anna Mikola | | |
| **Päivämäärä** 27.11.2017 | **Sivumäärä** 42+2 | **Kieli** englanti |

**Tiivistelmä**

Fosfori on uusiutumaton luonnonvara, jota suurimmaksi osaksi käytetään lannoitteena ympäri maailman. Jotta kasvavan ihmisväestön ruoantuotannon tarpeet saataisiin turvattua, tarvitaan yhteiskuntiin tehokkaampaa fosforin kierrätystä. Yksi kiinnostava fosforin lähde yhteiskunnissa on jätevesi. Se on kierrätyksen kannalta kiinnostava, koska se kerää yhteen fosforin suurelta alueelta yhteen pisteeseen, jätevedenpuhdistamolle. Maailmalla on olemassa monia tekniikoita joilla fosfori voidaan ottaa talteen ja kierrättää jätevedestä. Jotkin tekniikat kierrättävät fosforia osana jätevedenpuhdistamon sivutuotteita, kun taas toiset erottavat fosforin erilliseen jakeeseen. Mikään tekniikka, joka erottelee fosforin erilliseen jakeeseen, ei ole käytössä Suomessa. Monta näkökantaa pitää ottaa huomioon, kun pyritään yhdistämään uutta teknologiaa jo olevassa oleviin prosesseihin ja infrastruktuuriin. Käytössä oleva teknologia voi rajoittaa tai suosia tiettyjä vaihtoehtoja, kuten ihmisten asenteet. Myös taloudelliset realiteetit voivat rajoittaa sopivien vaihtoehtojen käyttöönottoa.

Tutkimuskysymykset tässä työssä koskivat tämänhetkistä fosforin talteenottotekniikoiden tilaa maailmassa, tekniikoiden soveltuvuutta Suomen oloihin ja nykyisiin toimintoihin ja jätevesiasiantuntijoiden asenteita eri fosforin talteenottovaihtoehtoja kohtaan.

Tutkimuksen perusteella Suomen oloihin sellaisenaan sopivia fosforin talteenottotekniikoita ei vielä ole olemassa. Maissa, joissa talteenottotekniikoita on kehitetty, on yleisesti käytössä biologinen fosforinpoisto ja lietteen poltto, joten talteenottotekniikat on mukautettu toimimaan kyseisten lietteenkäsittelymenetelmien kanssa. Asenteet fosforin talteenottoa kohtaan suomalaisten jätevesiasiantuntijoiden joukossa suosivat tekniikoita, jotka ovat helposti integroitavissa jo olemassa oleviin järjestelmiin. Tehokkaamman fosforin kierrätyksen mahdollistaminen Suomessa vaatisi suuria muutoksia nykyisiin toimintoihin ja uusien talteenottotekniikoiden kehitystyötä.

**Avainsanat** fosfori, talteenotto, yhdyskuntien jätevesi, kierrätys

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**Sammandrag av diplomarbetet**

**Författare** Tanja Pihl

**Titel** Tillvaratagande och återanvändning av fosfor ur kommunalt avloppsvatten – tillämpningar och attityder i Finland

**Utbildningsprogram** Samhälls- och miljöteknik

**Huvud-/biämne** Vatten- och miljöteknik/ Miljöekologi **Kod** R3005

**Övervakare** Professor Riku Vahala

**Handledare** TkD Anna Mikola

**Datum** 27.11.2017 **Sidantal** 42+2 **Språk** engelska

**Sammandrag**

Fosfor är en icke-förnybar naturresurs som världen över främst används som gödslingsmedel i jordbruket. För att försäkra en matproduktion som täcker behoven av en växande befolkning, behövs det en mera effektiv återanvändning av fosfor i samhället. Ur ett fosforåteranvändningsperspektiv är avloppsvatten en intressant fosforkälla i samhället, för dess egenskap av att samla resurser från ett stort område till en specifik punkt, avloppsreningsverket. Det finns många tekniker i världen för tillvaratagande och återanvändning av fosfor ur avloppsvatten. En del tekniker återvinner fosfor som en del av sidoprodukterna av avloppsreningsverket, medan andra avskiljer fosforn till en separat produkt. Inga tekniker som avskiljer fosfor till en skild produkt är i användning i Finland idag. När man skall införa ny teknologi till redan existerande processer och infrastrukturer, måste många olika aspekter tas i beaktande. Den existerande teknologin kan begränsa eller främja vissa alternativ före andra, liksom attityden hos de involverade människorna. Ekonomiska realiteter begränsar också möjligheterna vid val mellan olika alternativ.

I denna studie var målet att utreda det rådande utvecklingsstadiet av tekniker för tillvaratagande av fosfor i världen, tekniker som passar till finska förhållanden och kutym, samt att utreda vattenbehandlingsexperters attityder gentemot de olika återvinningsmöjligheterna.

På basen av studien existerar ännu inte tekniker för tillvaratagande av fosfor som passar som sådana till finska förhållanden. I de länder där fosfortillvaratagande tekniker har utvecklats, är biologiskt fosforavlägsnande och slamförbränning allmänna, vilket betyder att teknikerna har utvecklats för att fungera tillsammans med de rådande metoderna för slambehandling. Finska avloppsvattenexperter är positivt inställda mot tekniker som är lätta att införa i redan existerande system. För att möjliggöra ett effektivare fosfortillvaratagande i Finland, krävs stora förändringar i nuvarande kutym och en utveckling av nya tekniker för att tillvarata fosfor.

**Nyckelord** fosfor, tillvaratagande, kommunalt avloppsvatten, återvinning

## Acknowledgements

Parts of this thesis was also included in the report ” Phosphorus recycling from waste water – technologies and policy instruments “, part 62/2017 of the publications of the Government’s Analysis, Assessment and Research Activities. The report was published in September 2017. The report was written as collaboration between Aalto University and Tyrsky Consulting and supervised by representatives of the Ministry of the Environment and the Ministry of Agriculture and Forestry. The project was funded by the Finnish Government. I would like to thank all the people involved in the project for their feedback, encouragement and support in the writing process. I would also like to thank the wastewater experts in Finland and Sweden, who so kindly shared their knowledge and expertise with me.

Had it not been for the amazing engagement and unbelievable patience of my thesis advisor Anna Mikola and supervisor Riku Vahala, this thesis would never have seen the light of day. I thank you both from the bottom of my heart for helping me finally graduate.

For making my time in TKK and Aalto the most memorable and happy time of my life, I would like to extend my most sincere and humble thank you to Teknologföreningen. The time spent hanging, working, talking, partying, hosting, presenting and laughing inside and outside of the concrete walls of Urdsgjallar has taught me more and given me more than I can ever repay, thank you for everything.

I would also like to thank my supporting family and all my friends, of whom many have showed me a good example in graduating, some way ahead of me. Thank you to our four-legged darlings Molly, Ronja and Pixie, for not letting me forget what is truly important in life. And last, but absolutely not least, I would like to thank my partner in crime, my comfort, my rock, my beloved Macke, for always being there for me, supporting and encouraging. Thank you.

Espoo 26.11.2017

*Tanja Pihl*

Tanja Pihl

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## Terminology and abbreviations

| | |
|---|---|
| Airprex | P-recovery technique used on sludge, produces struvite |
| Anphos | P-recovery technique for reject waters |
| apatite | A group of phosphate minerals |
| Ash Dec | P-recovery for sludge ash, produces easily bioavailable P |
| bioavailability | A measure by which organisms can enclose various substances in its environment |
| biochar | Artificially produced char from biomass, produced in pyrolysis |
| composting | Decomposing by bacteria in aerobic conditions |
| cyanobacteria | Photosynthesizing bacteria |
| dewatering | Removal of water from sludge |
| digestion | Decomposing by bacteria in anaerobic conditions |
| DAP | Diammonium phosphate |
| DCP | Dicalcium phosphate |
| DNA | Deoxyribonucleic acid |
| eutrophication | When a water body is enriched with nutrients |
| HSY | Helsinki Region Environmental Services Authority |
| igneous rock | magmatic rock, formed from magma or lava |
| Kemicond-treatment | Addition of chemicals to sludge, so that phosphorus precipitates and water can come loose from the structure of the sludge |
| lime stabilization | Addition of calcium compounds to sludge, to increase pH |
| MAP | Monoammonium phosphate |
| MCP | Monocalcium phosphate |
| Mephrec | P-recovery technique for sludge, produces P-rich briquettes |
| mesophilic digestion | Digestion in temperatures around 37 $^{o}C$ |

| | |
|---|---|
| MKP | Monopotassium phosphate |
| Ostara Pearl | P-recovery technology for reject waters |
| P | Chemical symbol for phosphorus |
| PAKU | P-recovery technology for sludge ash, produces P-rich ash |
| PASH | P-recovery technology to first leach P from ash, then precipitate it with calcium |
| Phosnix | P-recovery technology for reject waters |
| Phospaq | P-recovery technology for reject waters |
| population equivalent | The average wastewater production of one human in a household during one day. It is also used when examining other sources of wastewater than households |
| precipitation | the formation of solids from a solution |
| primary production | The binding of chemical energy in organic compounds by organisms |
| pyrolysis | Sludge is heated to high temperatures in anaerobic conditions |
| Ravita | P-recovery technology for P precipitation from effluent |
| reject water | Water separated from sludge during sludge treatment |
| sedimentary rock | Rock formed from sediments |
| struvite | Magnesium ammonium phosphate |
| SWOT-analysis | A method to evaluate the strengths, weaknesses, opportunities and threats |
| TCP | Tricalcium phosphate |
| thermal drying | Drying of sludge using heat |
| thermophilic digestion | Digestion in temperatures around 55 $^{o}$C |
| thickening | Separation of solids and fluid, and obtaining the solids |
| WHO | World Health Organization |

# 1 Introduction

Phosphorus is a limited resource in the world. It is mainly used as a fertilizer in agriculture, where it is one of the most important plant nutrients and non-replaceable by any other substance. As the phosphorus is not renewable, it would be crucially important to ensure that the amount of phosphorus fertilizer also in the future is enough to secure a steady growth of food for the increasing amount of people on earth. This could be done by recycling the phosphorus already present in society.

Some phosphorus is already recycled today. Animal manure, household organic waste and wastewater sludge are examples of phosphorus containing waste streams that can be reused as phosphorus fertilizers. However, a lot of fertilizers in the world come from phosphorus mines, where finite reserves of phosphorus are extracted from the ground to be used as a mineral phosphorus fertilizer, or to be used in some other application by the phosphorus industry. In addition phosphorus is used in the manufacturing of e.g. detergents and pharmaceuticals.

This thesis focuses on the potential use of the phosphorus in wastewater as a source of recycled phosphorus fertilizer in Finland. In Finland, the amount of phosphorus in wastewater treatment plant sludge that was used as fertilizer was 221 tonnes of a total of 3 935 tonnes of phosphorus in sludge in the year 2012 (Säylä, 2015). The average phosphorus content in the sludge is 3.1 %. One reason for the small amount of sludge used as fertilizer is the fact that the phosphorus is not easily available to plants. Another major reason is that the attitude towards products that originate from the wastewater treatment plants is changing in Finnish society at the present time. A big fear is that organic pollutants and heavy metals in the sludge would transfer from the soil into the plants causing a health hazard to humans. Also, the risk of the pollutants being harmful to the environment is a concern. Because of these worries, some companies in the food processing industry have banned the use of wastewater sludge as fertilizer on the fields where the raw material for their industry is grown. This has led to growing interest to seek alternative methods to make use of the phosphorus in wastewater as a fertilizer.

Recovery of phosphorus from phosphorus rich waste streams is a possible solution in making the recycling of phosphorus more acceptable. This can be done by different recovery techniques that separate the phosphorus to a different phase than the harmful substances in the wastewater sludge. At the current time none of these techniques is in use in full-scale in Finland.

The work presented in this thesis is part of a project for the Government's Analysis, Assessment and Research Activities and has also been published as a part of the project's final report in September 2017. The questions that this work aims to answer are:

1) What is the current state of phosphorus recovery technologies?
2) What are the attitudes towards these technologies in the field of wastewater treatment?
3) How well suited are the phosphorus recovery technologies to Finnish conditions?

Also, the current flows of phosphorus are described and the scale of the recovery potential of wastewater phosphorus is presented.

# 2 Theoretical background

## 2.1 Phosphorus as a fertilizer

Phosphorus is an essential element to all forms of life. It is a constituent in DNA, teeth and bones and also vital to photosynthesis. The phosphorus on earth is stored mostly in the earth's crust and on the bottom of the oceans (Smil, 2000). Most of the phosphorus that humans need is extracted from phosphorus mines, in form of mineral phosphorus, calcium phosphate or apatite (Levlin et al., 2014). The phosphorus compounds needed for pharmaceuticals, detergents, fertilizers and others are refined from mineral phosphorus. Almost all of the mined mineral phosphorus, up to 90% (European Commission, 2013) is used in agriculture as feed and as fertilizer in the world.

Phosphorus in one of the main plant nutrients along with nitrogen and potassium. In many ecosystems phosphorus is the limiting factor, meaning the resource that limits the plant growth in that particular ecosystem (Chapin et al., 2011).When humans harvest crops from the field, they also remove the phosphorus inside the biomass of the plants. The soil in the field only has a certain amount of phosphorus stored in it, and the natural sources of phosphorus are decomposing biomass or weathering phosphorus from rocks. If no additional sources of phosphorus are introduced, the soil will become more and more phosphorus poor and plants will not be able to grow their biomass. This is also applicable to other plant nutrients. For plants to be able to continue to grow on the fields, fertilizers that restore the lost nutrients to the soil need to be added. Without the addition of fertilizers to the fields, the food production in the world would decrease greatly.

Any phosphorus containing biomass can be used as phosphorus fertilizer, like animal manure, or inorganic phosphorus that is available for plants. Plants can absorb only specific phosphorus molecules, which means that all the phosphorus in the soil is not automatically available to plants, no matter how much of it there is. Phosphorus compounds are not usually soluble in water, which means that they do not readily leach from the soils with water. Phosphorus is more strongly bound to the soil particles and therefore stays on the application site, as long as the soils particles do.

## 2.2 Phosphorus flows

Phosphorus cycles on earth between the earth's crust and sediments on the bottoms of oceans and lakes. When phosphorus containing mineral rocks start to erode coming in contact with water, air or other weathering circumstances, the phosphorus compounds are able to move more freely and react with the environment around them. Phosphorus can be absorbed by plants and be integrated into biomass, or can be washed away from the soil because of erosion and end up in a river. Either way, it is most likely that the phosphorus in the end ends up on the bottom of a seabed as a part of the sediments gathering there. The phosphorus containing sediments are then lifted along with the tectonic uplift back up on the continents. It takes approximately 10 to 100 million years for phosphorus to perform one natural cycle (Smil, 2000). From a human time perspective, the phosphorus cycle goes only in one direction, from the soils on earth to the bottoms of the oceans.

The biological cycling of phosphorus has a much faster turnover. Plants absorb phosphorus from the soil, and from plants and other autotrophs the phosphorus ends up in all other organisms. The phosphorus then returns to the inorganic cycle when decomposers mineralize the phosphorus bound in the organic molecules.

### 2.2.1 Global phosphorus flows

Naturally occurring weathering of phosphorus from rocks in the soil is a slow process and it releases phosphorus into the soil for plants to use. Harvesting of crops removes the phosphorus that the plants have absorbed from the soil, and that phosphorus needs to be replaced by adding fertilizer to the fields.

Humans have speeded up the natural cycle of phosphorus by mining phosphorus rich minerals from the ground. In 2016, 261 million tons of phosphorus was mined from the mines of the world (U.S. Geological Survey, 2017). The greatest phosphorus deposits are concentrated to a few countries in the world, namely Morocco, China and USA. <in 2011 EU was dependent on imported phosphorus to about 92 % (European Commission, 2013). Mined mineral phosphorus usually occurs with different sorts of impurities, like heavy metals or radioactive materials (Svenskt Vatten Ab, 2015). Usually the phosphorus in sedimentary rocks occurs with more heavy metals than phosphorus from igneous rocks (European Commission, 2013).

The phosphorus reservoirs in the world are finite, and they depend on the technological advances in mining and extraction and the economic realities. There is also no exact knowledge of the amount of phosphorus in the known and yet undiscovered deposits. A lot of estimates of the phosphorus resources have been discussed in recent decades, and they vary greatly depending on the assumptions that have been made in the calculations. Apart from the technological advances and the actual size of the resources also the predictions of future human phosphorus needs make the calculations complicated to carry out. Depending on the source the estimates usually are between 60 and 1500 years, most calculations arriving at timespans of a couple of hundreds of years (Desmidt et al., 2015; Liu et al., 2008; Maa- ja metsätalousministeriö, 2011; Marttinen et al., 2017).

Human activities have escalated the phosphorus streams in the world. By mining mineral phosphorus from deep within the ground and spreading it on agricultural fields humans have greatly increased the rate at which phosphorus from rocks become available to plants. All of the phosphorus used as fertilizer is not absorbed by plants, some of it stays in the soil in the fields, and some is transported away from the fields because of erosion. Water is usually the cause of erosion on the fields, and the phosphorus used as fertilizer ends up in the nearby water bodies, streams, rivers, lakes and eventually the sea. Because phosphorus in many ecosystems is the limiting nutrient, a lot of water ecosystems experience an upswing in primary production following an addition of phosphorus, which then leads to eutrophication. Eutrophication is a state where the primary production of an ecosystem increases, and as a result the biological activity also increases. Eutrophication leads to e.g. decrease in biodiversity, cyanobacterial blooms, turbidity increase in the water and local anaerobic areas on the bottoms of the water bodies.

### 2.2.2 Other phosphorus flows in the world

Another escalated phosphorus stream in the world caused by human activity is the erosion of soils into water ecosystems. Soil erosion is a naturally occurring phenomenon, but human activities have made the erosion of soils greater. The amount of phosphorus that now is transported to the oceans is at least two times as high as naturally (Smil, 2000). Deforestation removes plant roots that stabilize the soil and make the soil more exposed to the eroding effects of wind and water. Also, land use changes mobilize the phosphorus in the soils. The erosion of soils, leading to the mobilization of phosphorus is a diffuse source of phosphorus pollution, and therefore a very difficult stream to control. The phosphorus in these diffuse sources is not easily recovered by humans and the best way to minimize the phosphorus amount in these streams is by preventive measures.

Rapid phosphorus flows that have a higher concentration of phosphorus and are more geographically concentrated are usually human caused. These flows are e.g. cattle manure, industrial and household food waste and wastewater at wastewater treatment plants. These flows are well suited for phosphorus recovery and recycling. Some of these flows can be used directly as fertilizers, while others need different types of treatment before they can be applied onto agricultural fields.

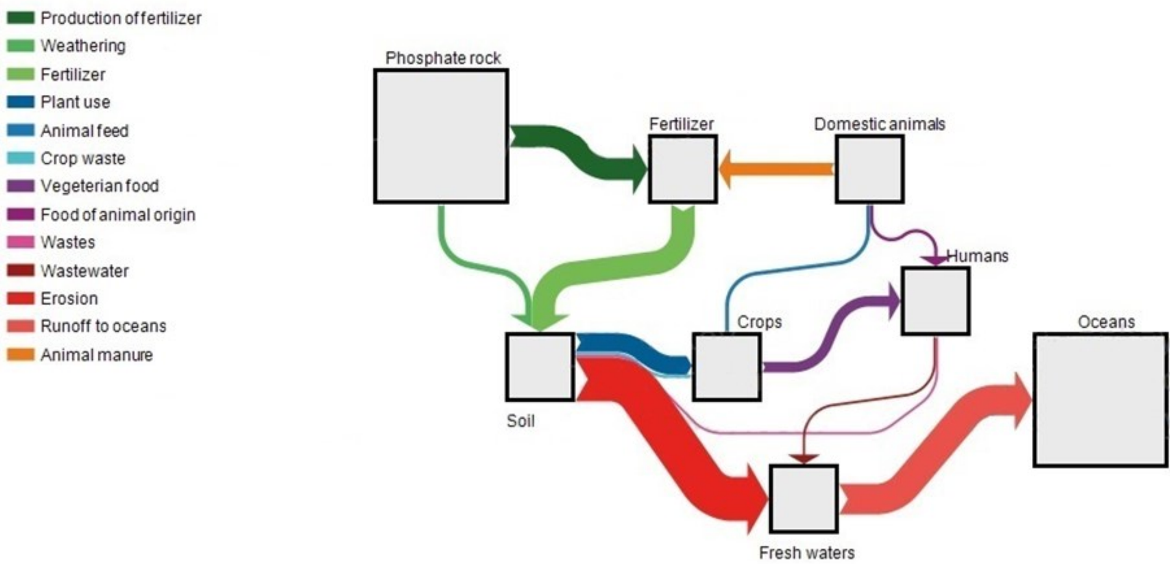


**Figure 1: Phosphorus flows in the world**

It is very difficult to estimate the exact magnitude of the global phosphorus flows, both because of the lack of sufficient data and because some flows, like the worldwide erosion rate of phosphorus, are almost impossible to measure precisely. In figure 1 is presented a simplified picture of the flows of phosphorus in the world. As is seen, most phosphorus weathers or is mined, goes into the soil, is eroded and enters the water streams and finally ends up in the ocean. In the ocean the phosphorus eventually ends up in the bottom sediments. The biological cycling of phosphorus concerns only a small fraction of the total flow.

### 2.2.3 Phosphorus flows in Finland

The phosphorus flows in Finland are very similar to the global flows, the most part of phosphorus is used as fertilizer in agriculture. Approximately 30 000 tons of phosphorus is used in fertilizing crops, mainly of which about 20 000 tons is from animal manure and a bit over 10 000 tons is from mineral fertilizer (Marttinen et al., 2017). The wastewaters contain about 4 000 tons of phosphorus, of which over 95 % is removed at the wastewater treatment plants (Säylä, 2015). The phosphorus in wastewater originates from urine and detergents washed down into the sewage. From the wastewater treatment plants the phosphorus is mainly used in landscaping, like covering old landfills or green construction. Depending on the origin of the information, estimates of the amount of wastewater phosphorus used as fertilizer in agriculture varies between about 5 per cent and around 40 per cent (Säylä, 2015; Vilpanen and Toivikko, 2017). There are some difficulties in the collection of the information concerning the end use of the wastewater phosphorus because the information is gathered in several places, the information gathered is not always comparable and the information may be uncomprehensive (Vilpanen and Toivikko, 2017).

During the 20th century the agricultural lands in Finland were fertilized with phosphorus over their needs, both in aim to create a phosphorus storage in the soil and in unawareness of the phosphorus need of the plants. As a consequence of this, the average amount of phosphorus in soils in many parts of Finland to this day exceeds the natural content of the soil. Nowadays the application of phosphorus to the fields has decreased, both because of the growing awareness of the eutrophicating effects of phosphorus and the observation that in some places additional phosphorus does not raise the productivity of the fields. This is because the soil has a high enough phosphorus content to satisfy the need of the plants. Phosphorus in these areas is no longer the limiting factor to plant growth.

Phosphorus in Finland is used mainly, as earlier mentioned in agriculture. Other uses for phosphorus are in landscaping, forestry and fish farming, all of which use only about 5 % of the total amount of phosphorus. Figure 2 presents the applications of phosphorus in different areas.

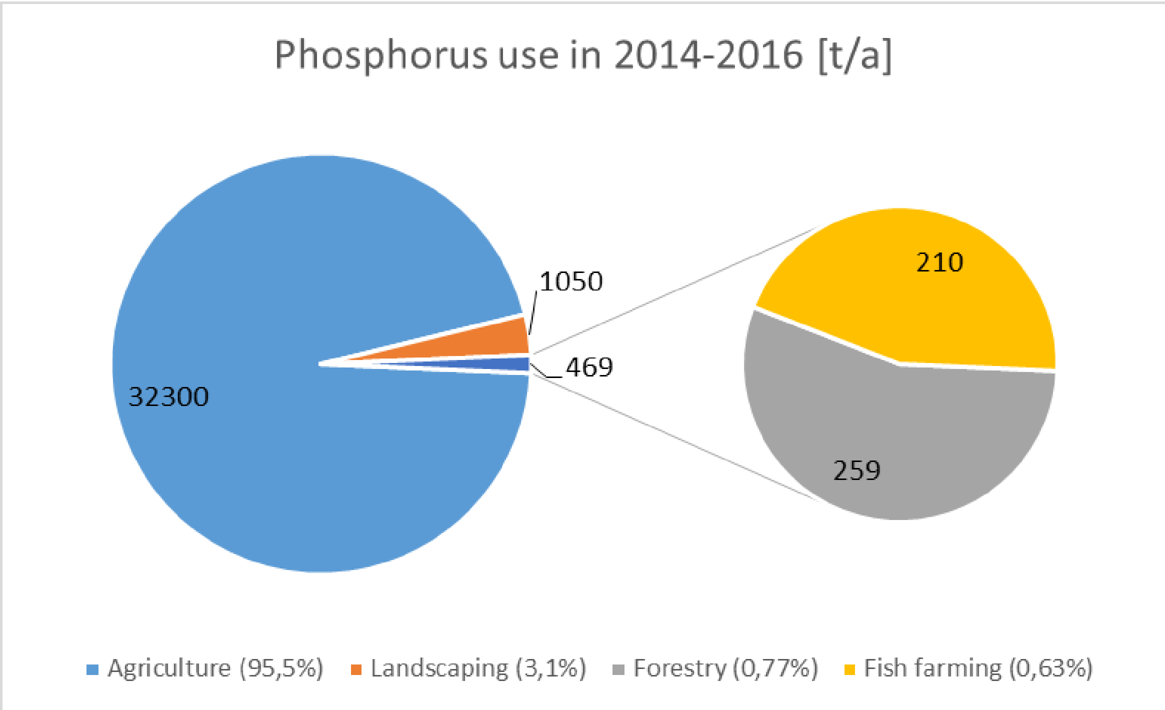


**Figure 2: Annual phosphorus use in Finland during 2014-2016 (Marttinen et al., 2017)**

Agricultural use of phosphorus contains both the use of phosphorus as a fertilizer and the use of phosphorus in animal feeds. Figure 3 presents the proportion of phosphorus used as fertilizer and as animal feed. The phosphorus used in animal feed originates for the most part from plants grown in Finland (77 %), meat and bone meal (3 %) and the rest (20 %) is from other sources, like food processing industries' by-products, mineral phosphorus and imported raw material.

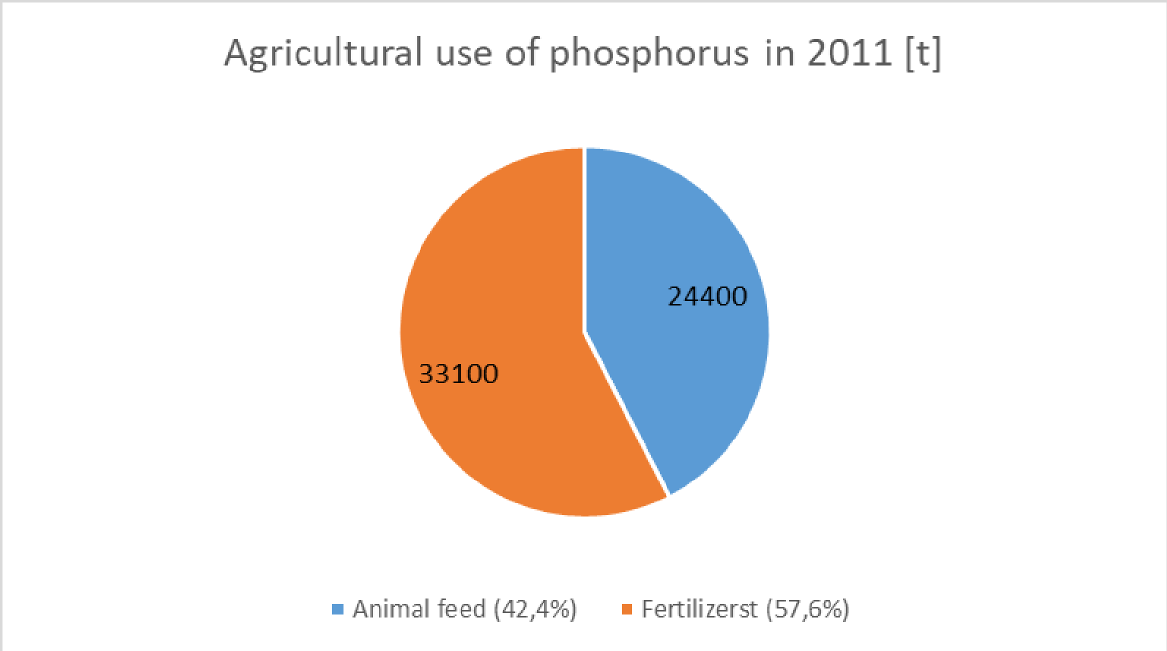


**Figure 3: The use of agricultural phosphorus as fertilizer and animal feed (Maa- ja metsätalousministeriö, 2011)**

Over half of the phosphorus used as fertilizer in agriculture originates from recycled sources as seen in figure 4. Most of this recycled phosphorus is animal manure, in 2005-2009 only 0.3 % was of another origin than manure (Maa- ja metsätalousministeriö, 2011).

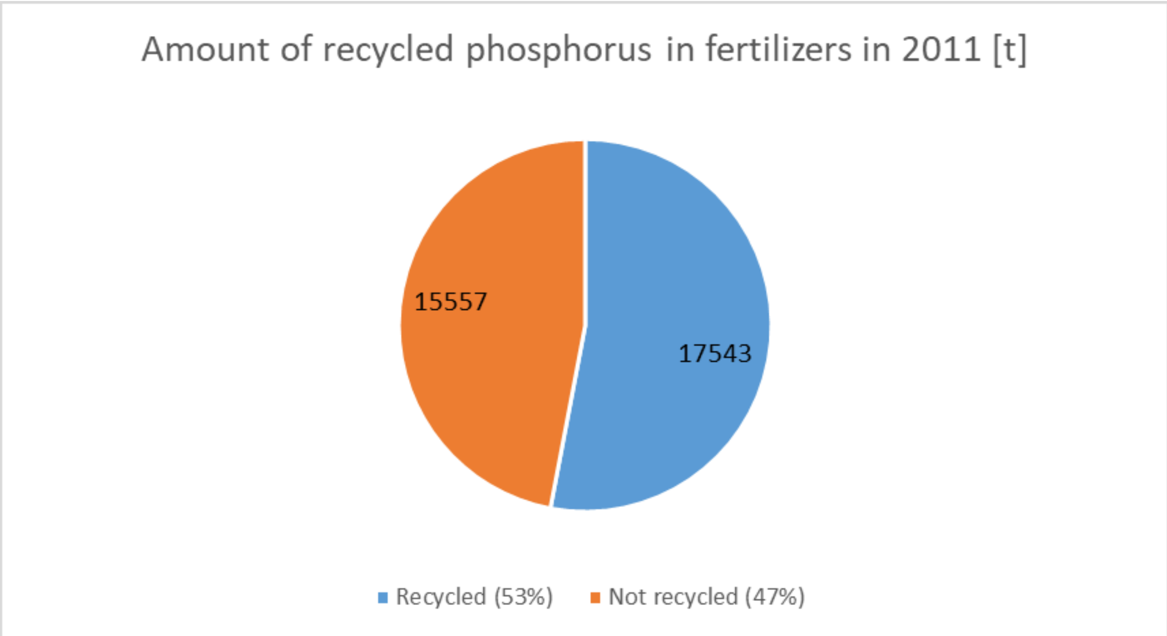


**Figure 4: Phosphorus used as fertilizer divided by origin in Finland in 2011 (Maa- ja metsätalousministeriö, 2011)**

Most of the recyclable phosphorus in waste streams in Finland is in animal manure as presented in figure 5. The second largest stream is in municipal and industrial wastewater sludge with 2 880 tons a year between 2014 and 2016. Almost as much phosphorus is in surplus grasses, 2 540 tons a year. Surplus grass is grass growing on for example the buffer strips of water systems and nature management fields that can not be used as animal feed. Nature management fields are managed, uncultivated fields that are established to decrease the nutrient load from the field and to increase the diversity of nature and the landscape. They are regularly reaped (Maaseutuverkosto, 2015). Much smaller are the phosphorus flows in the municipal and industrial organic wastes (730 tons), the by-flow of the food processing industry (360 tons) and the sludge from forestry (230 tons) as shown in figure 5.

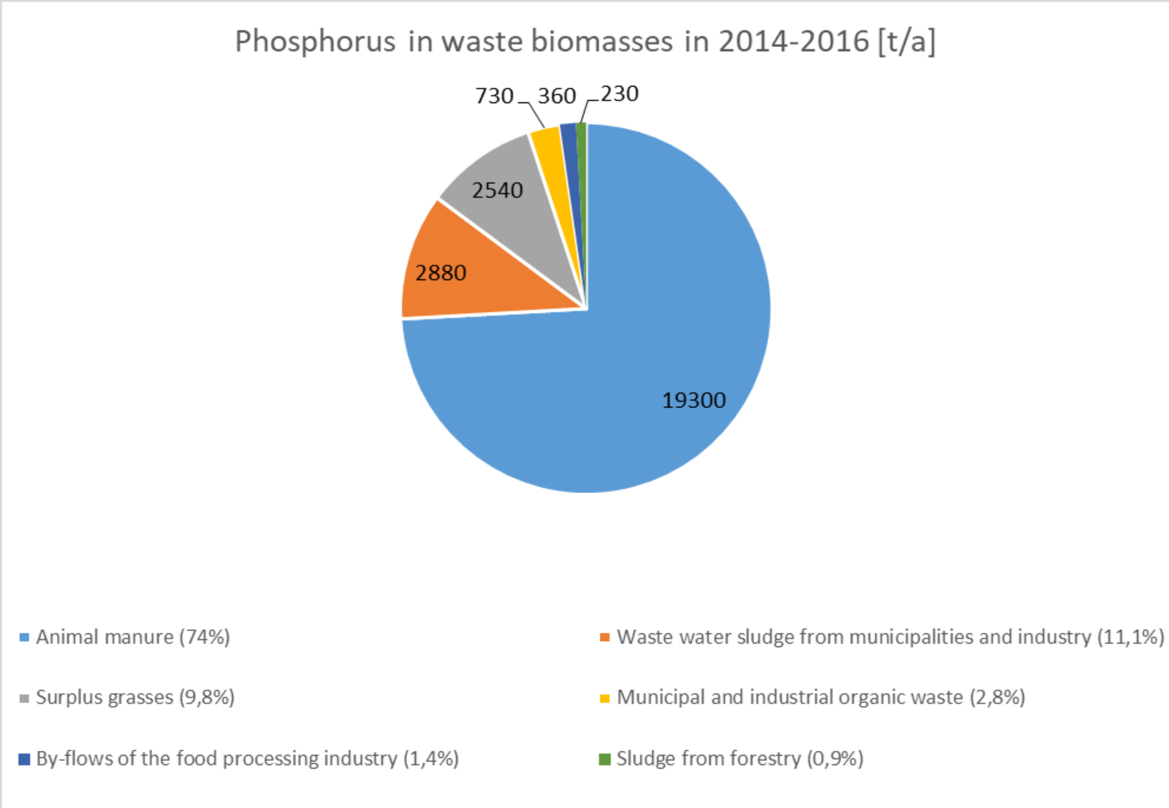


**Figure 5: Annual phosphorus amounts in different biomasses in Finland during 2014-2016 (Marttinen et al., 2017)**

Because animal husbandry is very geographically concentrated at specific areas in Finland, the potential fertilizer from animal manure is also centred in the same areas. The problem with transporting animal manure is the high water content, and therefore great volume of the manure, In case the manure is not treated in some way to lower the water content, it is not economical to transport it any long distances.

## 2.3 Phosphorus in municipal wastewater

In Finland wastewater needs to be treated before it can be released into receiving water ecosystems. Most wastewater is treated in big centralized wastewater treatment plants and the main goal of the treatment is to protect the receiving water ecosystems from the potentially harmful effects of the components of the wastewater. The components of the wastewater that are removed at the wastewater treatment plants are the plant nutrients nitrogen and phosphorus, and organic matter. All of these cause increased biological activity in the receiving ecosystems, causing problems like eutrophication, oxygen depletion and algal bloom. Also suspended solids are removed, so that they don't end up in the water bodies.

The most used method in Finland for treating wastewater is a combination of a biological and a chemical process. The organic matter and nitrogen are removed with bacteria in the biological process and the phosphorus is removed by precipitation with iron or aluminium based precipitation chemicals. It is also possible to remove phosphorus biologically, with bacteria that can accumulate more phosphorus in their cells than what they need for their metabolism. The biological phosphorus removal process is in Finland in use in only on a couple of wastewater treatment plants that also have the possibility to use chemical precipitation if needed. The general opinion is that the biological phosphorus removal is not as robust and does not guarantee an even result and therefore is unable to remove phosphorus in quantities that fulfil the treatment requirements of wastewater treatment plants in Finland at all times. The concern for the removal efficiency is especially true in the wintertime; when the activity of the bacteria is lower because of low temperatures and the amount of easily biodegradable organic matter is lower in the influent wastewater. Usually the biological phosphorus removal in Finland is paired with the possibility to precipitate phosphorus chemically, in case the biological treatment is not efficient enough. Globally, the biological phosphorus removal is in common use.

Regardless of the phosphorus removal process, the most part of the phosphorus in the wastewater end up in the sludge. The sludge is removed from the water phase and treated with different sludge treatment processes. The sludge that is generated with chemical phosphorus precipitation is called chemical sludge, and the sludge that is generated in the biological phosphorus removal is called biological sludge. These two types of sludges have different kinds of characteristics and the phosphorus recovery potential from each one is different, as the phosphorus in the sludges is in different kinds of compounds.

## *2.4 Wastewater sludge*

### 2.4.1 Nutrients in wastewater sludge

Wastewater sludge contains both nitrogen and phosphorus, which both are plant macro nutrients. It also contains different sorts of plant micro nutrients, nutrients that the plants need only in small doses, and organic matter, which improves the quality of soil by increasing the biological activity and maintaining a good structure of the soil (Österås et al., 2015). The sludge usually contains about 2- 4 % phosphorus of the dry weight (Turunen, 2016). Compared to the nitrogen, the sludge contains too much phosphorus for the plants' needs, plants need only a fraction of their nitrogen need in amount of phosphorus (Chapin et al., 2011). In the sludge coming from Finnish wastewater treatment plants, the phosphorus is bound to iron or aluminium in the sludge, which means that it is not easily available to plants. But because plant availability of phosphorus is also dependent on the characteristics of the sludge and the soil, it is possible to increase the availability by changing the conditions of the sludge and the soil. In the soil the phosphorus can react with positively charged sites on soil particles and soluble iron compounds forming compounds that are poorly available to plants. The pH also affects the availability of phosphorus, with soils having pH around 6,5 containing the most plant available phosphorus. In low pH the phosphorus reacts with iron, manganese and aluminium in solution and in high pH phosphorus forms calcium phosphate with calcium (Chapin et al., 2011) Also according to a study, phosphorus in biological sludge is in a form that is more easily available to plants than phosphorus in chemical sludge (Krogstad et al., 2005).

### 2.4.2 Heavy metals in wastewater sludge

Heavy metals end up in the wastewater treatment plants from e.g. human faeces and from products containing heavy metals.. Before the heavy metal content was much higher, but nowadays in Finland the heavy metal content of the wastewater sludge is relatively low. Some heavy metals are toxic in the environment already in small doses, and the most harmful are cadmium, lead and mercury. The heavy metals end up in the sludge fraction during the wastewater treatment process. They need to be separated from the phosphorus fraction, if the phosphorus is going to be used as a fertilizer. The Fertiliser Product Act sets limits to how much heavy metals there can be in fertilizers or soil amendments, and therefore these limits also apply to sludge used as fertilizer. The limits to heavy metal content in sludge used as fertilizer is agriculture are described in the Council of State Decision on the use of sewage sludge in agriculture and are presented in table 1.

**Table 1: Limits for heavy metal content in wastewater sludge used as fertilizer (MMMa 24/11)**

| Heavy metal | Limit (mg/kg of dry matter) |
|---|---|
| Cadmium | 1,5 * |
| Chromium | 300 |
| Copper | 600 ** |
| Mercury | 1,0 |
| Nickel | 100 |
| Lead | 100 |
| Zinc | 1 500 ** |

*) The restrictions on the cadmium concentration in sludge and sludge mixtures may be exceeded temporarily by no more than 20 per cent. The restrictions on concentrations of other heavy metals may be exceeded temporarily, but the significance of the excess must be assessed separately in each case.
**) Sludge and sludge mixtures may contain no more than twice this concentration of copper and zinc considered as a nutrient if the soil for which the sludge or sludge mixture is to be used is poor in the nutrient in question. This, however, must not result in higher concentrations in the soil on which the sludge or sludge mixture is used. For copper the limit is 100 mg/kg of dry matter and for zinc it is 150 mg/kg of dry matter.

### 2.4.3 Organic pollutants in wastewater sludge

A variety of organic pollutants end up at the wastewater treatment plants. They originate among others from household products like pharmaceuticals, detergents and dust from inside buildings. A part of these organic pollutants are destroyed during the treatment process, a part end up in the sludge fraction, while others end up in the effluent and with it to the receiving water bodies. If the wastewater sludge is used as fertilizer, there is a concern about the organic pollutants ending up in the environment and the crops, causing harm to humans, animals and the environment.

Studies have been performed to clarify the faith of the organic pollutants that end up on the agricultural fields. Österås et al. (2015) concluded in a study on sewage sludge amended agricultural fields, that even with a long time exposure to sludge fertilizer, there is no threat to the wellfare of the environment or humans. Even if some organic pollutants were found in the soil and some even in the crops, the concentrations in which they were present, did not exceed the limits for safety risk for humans or the environment. Though in the study in question, they only tested the organic pollutant concentrations in winter wheat grown on one of the tested fields, and it is mentioned that organic pollutants enrich more greatly in root vegetables.

### 2.4.4 The image of wastewater sludge

Bad reputation and concerns for health hazards are associated with the use of wastewater sludge as fertilizer and with wastewater in general. Wastewater is seen as something disgusting and people do not want to come in contact with it after it disappears into the sewer. Also the image of clean lands and clean food in Finland is strong, and something industries relying on domestic production are not ready to risk losing by contamination of wastewater pollutants. (Ikävalko, 2017; O'Neill, 2012)

The wastewater sludge is not a very convenient fertilizer also because of its viscous state. The equipment used to apply fertilizer to agricultural fields is adapted to spreading fertilizer in liquid or in pellet/grainy phase. This might make the distribution of sludge onto agricultural fields challenging and might contribute to the bad reputation of the sludge. (Egle et al., 2016)

## *2.5 Current sludge treatment*

The sludge from wastewater treatment is treated differently depending on the wastewater treatment plant. Sludge is treated to make it suitable to be used as a fertilizer or as a soil amendment. The treatment improves the storability, handling, spreadability and the hygienic quality of the sludge and reduces the odour. Generally it takes more than one treatment step to convert the sludge into such a shape that it can be used and so that it fulfils the requirements of the law (Turunen, 2016).

### 2.5.1 Pretreatment

The sludge is first pretreated by thickening and/or dewatering to lower the water content and concentrate the dry matter content. The thickening can be done either with a settling tank, where the sludge particles settle on the bottom of the tank or by raising the sludge particles to the surface of the tank with air bubbles. The dewatering of the sludge can be done mechanically for example with a centrifuge.

### 2.5.2 Digestion

After the pre-treatment the sludge can be digested in an anaerobic reactor, where bacteria decompose the organic material in the sludge and produce methane, also called biogas. The bacteria convert the nutrients in the sludge from organic forms to inorganic forms that are more easily available to plants. The digestion can be either mesophilic or thermophilic, the difference being the temperature at which the process takes place. The mesophilic digestion takes place in temperatures around 37 ºC and the thermophilic digestion has a temperature of about 55 ºC, which means that the bacteria functioning in these different processes are of different kind. In Finland most of the digesting is done by mesophilic digestion (Pöyry Environment Oy, 2007)

Digestion destroys pathogens in the sludge and makes it stable and more easy to dewater. Some of the organic pollutants decrease during digestion, but not all. Digestion does not increase the availability of the precipitated phosphorus to plants (Metcalf & Eddy, 2002) After the digestion the sludge is dewatered and the reject water is usually directed to the start of the wastewater treatment process. Sludge that has been treated with mesophilic digestion needs to be further treated with e.g. composting or lime stabilization, because the low temperature of the digestion has not made the sludge hygienic enough to fulfil the requirements. (Pöyry Environment Oy, 2007)

Sludge that has been digested in thermophilic conditions and dewatered can in Finland be used as a soil amendment. There are no consistent results of the faith of the pollutants and the change in phosphorus availability in the sludge after thermophilic digestion.

### 2.5.3 Composting

In the composting process, bacteria decompose the organic matter in the sludge in aerobic conditions. Usually the sludge is thickened and dewatered before the composting. After that some stabilizing medium is added and the humidity is adjusted, so that the sludge has adequate moisture content and is airy enough. The traditional way of composting is in windrows, but there are also different composting reactors in use. Organic matter is lost and carbon dioxide is produced during composting.

Composting can be done in steps, so that the first step, initial composting, is done in e.g. a reactor and the second step is maturation in windrows. Because the composting process is aerobic, the compost is either aerated or turned so that the air is exchanged in the compost. Minerals, like sand, can be added to the compost after the composting process, depending on the end use of the compost.

Compost that fulfils the requirements of the Fertilizer Product Act 24/11 of the Ministry of Agriculture and Forestry can be used for example as soil amendment. The composting process does not significantly increase the availability of the phosphorus to plants. Composting removes organic pollutants more efficiently than digestion, but does not remove them completely, and it does not affect all kinds of organic pollutants. (Smith 2009)

### 2.5.4 Chemical treatment

The sludge can be treated chemically with e.g. oxidizing chemicals or lime stabilization. The sludge is hygienized after the oxidizing treatment and can be used as a fertilizer. One chemical treatment is the Kemicond-treatment that uses sulphuric acid and hydrogen peroxide. There has been some indications that the Kemicond-treatment would increase the availability of phosphorus to plants (MTT, 2013). It is not known how the treatment affects the organic pollutants in the sludge.

When using lime stabilizing as a treatment, calcium compounds are added to the sludge to increase the pH, and therefore stop the biological activity and hygienize the sludge (Metcalf & Eddy, 2002). Lime stabilized sludge can be used in landscaping and as a fertilizer in agriculture. Generally the treatment reduces the bioavailability of the phosphorus in the sludge, but can improve overall phosphorus availability in acidic soils. The organic pollutants in the sludge are not greatly affected by the lime stabilization.

### 2.5.5 Thermal drying

Thermal drying of the sludge means evaporating the water from the sludge with heat energy. The product is hygienic sludge that can be used as a fertilizer or as fuel. Thermal drying decreases the plant availability of the phosphorus, and it does not affect the levels of organic pollutants in the sludge. (Smith et al., 2002)

### 2.5.6 Incineration

The sludge can also be incinerated after it has been dewatered. The sludge can be incinerated separately or with other materials like fuel wood. The ash that is left after the incineration can't be utilized as fertilizer, because it is not approved for fertilizer use, and is classified as waste. The phosphorus in the ash is poorly available to plants. The organic pollutants are efficiently removed as is the organic matter in the sludge. (Pöyry Environment Oy, 2007; Turunen, 2016)

## *2.6 Phosphorus recovery*

Phosphorus recovery means separating phosphorus from the water phase or the sludge phase into a separate fraction, separating the phosphorus from eventually harmful substances and transforming the phosphorus into raw material to either phosphorus industry or the fertilizer industry. There are a number of different processes for recovering phosphorus, but usually they are using methods of precipitation, crystallisation, wet chemical process or thermal chemical process. Some techniques are still in the testing phase, while others have advanced to pilot-scale testing and even full scale operation. Aspects that can have an impact, on which techniques will advance to greater scale, are price and complexity of the process.

The phosphorus can be separated from different stages of the wastewater treatment process. It can be separated from the sludge (3,1 % phosphorus (Säylä, 2015)), the reject waters of the plant (20-100 mg/l phosphorus (VVY, 2016)), the ash from incinerated sludge (6-11 % phosphorus (Adam et al., 2009)) or from the effluent of the treatment process (5 mg/l phosphorus (VVY, 2016)).

### 2.6.1 Phosphorus from sludge

Phosphorus can be recovered from the sludge phase of the treatment process directly after the anaerobic digestion or after the digested sludge has been dewatered. Below are some recovery techniques presented shortly:

- Mephrec: The sludge is carefully dried and then compacted into briquettes. The briquettes are then heated to temperatures that liquefy or evaporate the heavy metals in the briquettes and destroy the organic pollutants. The product is briquettes that contain 10-25 % mineral phosphate. This technique can be used with chemical sludge. One testing facility in Germany is operational from 2016 (VVY, 2016).

- Airprex: Phosphorus and ammonium in the sludge react with added magnesium, forming struvite that is removed from the sludge and washed. This technique can only be used with biological sludge (Nieminen, 2010). The technique is in use on eight full scale operational plants in the world (Kabbe, 2017)
- Pyrolysis: The sludge is heated to high temperatures in anoxic conditions. The products of this treatment are biochar, gases and oil (Fonts et al., 2012). The phosphorus concentrates in the biochar fraction. The biochar can have a relatively high phosphorus concentration, but it is in a form that is slowly released to be available to plants. The organic pollutants are destroyed in the pyrolysis, but the heavy metals concentrate in the biochar along with the phosphorus.

### 2.6.2 Phosphorus from reject waters

When the wastewater sludge has been digested, it is common practice to remove excess water from it before it goes to the next step of the treatment. This excess water is called reject water. Especially after the digestion of biological sludge, the reject water is high in phosphorus. Examples of methods recovering phosphorus from reject water are Anphos, Phospaq, Phosnix and Ostara Pearl. All of the methods, except for Phosnix, have full scale operational plants in the world, in countries like the Netherlands, USA and the UK (Kabbe, 2017).

There are numerous techniques that recover phosphorus from reject water and they are only suitable to biological sludge. Some of the methods crystallize the phosphorus and ammonium in the water with added magnesium to struvite.

Phosphorus from reject waters can also be crystallized to calcium phosphate by adding calcium hydroxide to the water after the removal of carbonates (VVY, 2016).

### 2.6.3 Phosphorus from sludge ash

When the sludge is incinerated, the organic pollutants are destroyed, but the heavy metals end up in the ashes alongside the phosphorus. For the phosphorus to be used as fertilizer, the heavy metals need to be removed from the ash, or the phosphorus needs to be separated from the ash. The following techniques are aimed at solving this problem:

- PAKU: The sludge is incinerated at 850 ºC and the heavy metals are directed to a separate small ash fraction. This means that most of the ash can in theory be used as a fertilizer. The phosphorus is in a form that is slowly available to plants. (VVY, 2016)
- Ash Dec: Magnesium and calcium chloride are added to sludge ash and the mixture is heated to about 1 000 ºC. The heavy metal chlorides evaporate from the ash and the phosphorus reacts with e.g. magnesium to form compounds that are easily available to plants. The method can be used both with chemical and biological sludge. (Havukainen et al., 2012)
- PASH: Hydrochloride acid is added to sludge ash to leach the phosphorus. Then the leached phosphorus is precipitated with added calcium. The method has only been tested in laboratories and with pilot-testing. (Nieminen, 2010)

### 2.6.4 Phosphorus from effluent

The phosphorus can be removed as a last step of the wastewater treatment process. It can be precipitated with iron or aluminium salts, in the same way that it is precipitated in most Finnish wastewater treatment plants earlier in the treatment process. When recovering phosphorus from the effluent, the precipitation in the earlier phases of the treatment is given up and the phosphorus is only absorbed and used by the bacteria in the biological nitrogen process. The separation and dewatering of the chemical sludge is challenging. The sludge can be used as it is, or it can be treated to separate and recover the phosphorus that it contains. This technique has been tested in the world, but it is not in use anywhere in full scale.

In Finland phosphorus recovery from effluent has been tested by Helsinki Region Environmental Services Authority (HSY) in their Ravita-technique (HSY, 2017). Also adsorption of phosphorus to different adsorption materials and nanofiltration has been tested. Neither has been taken into use in larger scale.

### 2.6.5 Source separation of urine

One problem in the recovery of phosphorus from wastewater is the low concentration of phosphorus in the water. 50 % of the phosphorus in wastewater is from urine, so a possible solution would be to separate urine from the wastewater at the source, that is separation and recovery of urine directly from the toilets. This solution would require a toilet seat that separates solid and liquid wastes, a storage container for the separated urine and the transport of the urine to a treatment facility. The transport could be arranged e.g. with pipes or with a collection truck. There would need to be separate pipes in the buildings, so that the urine can be piped to storage containers. Transportation with pipes would require installation of new parallel sewer pipes with the already existing ones. The entire infrastructure making source separation of urine possible is however missing. The realization of the investments and the construction needs to be clarified, along with the organizing of the transport and treatment and most of all, the readiness of the toilet users to changes in the operation of the toilets.

Source separation of urine would in Finland in the current situation be a big and costly change. Source separation and collection or urine could be started in a smaller scale in e.g. big public events, scattered settlement areas and new residential areas. It is possible to collect and recycle four times more phosphorus from scattered settlements with source separation of urine than is possible today. (Viskari et al., 2017) It would advance the source separation if substances that prevent or reduce the odour of the urine were in use. Another subject for further development would be the technique for storing the urine.

According to World Health Organization (WHO) urine that has been properly treated and stored can be used as it is as a fertilizer. Though, problems may arise because of the possible detrimental elements in the urine, for example hormones and medicinal substances (World Health Organization, 2006). These have at the present no specific boundary values, and urine has no legal status as a fertilizer. In practice it means that urine can’t be used as a fertilizer. The urine could also be treated so that the phosphorus could be recovered as e.g. struvite. For recovery of phosphorus from urine mainly the same phosphorus recovery techniques as for wastewater can be used. A technique for nitrification of the ammonium in urine and evaporation has been tested at pilot-scale. The product of the technique is a condensed phosphorus-nitrogen nutrient solution for plants. (Fumasoli et al., 2016)

## 2.7 Recovered phosphorus as a fertilizer

It is important to have the recovered phosphorus in the right form, both chemically and physically, for the recycling and the usability of the phosphorus product. Plants can only utilize phosphorus in certain forms. The fertilizer industry is interested in compounds that contain easily plant accessible phosphorus as much as possible. Also the presence of other plant nutrients in the same compound raises the value of the product (Levlin et al., 2014). Table 2 presents different phosphorus compounds used by the fertilizer industry and compounds gained from different recovery processes.

**Table 2: Different phosphorus compounds in the fertilizer industry and in phosphorus recovery processes *.**

| Compound | Abbreviation | Formula | Phosphorus content (%) |
|---|---|---|---|
| Monocalcium phosphate | MCP | $Ca(H_2PO_4)_2$ | 8-9 (26) |
| Dicalcium phosphate | DCP | $CaHPO_4 * H_2O$ | 17 (20) |
| Tricalcium phosphate | TCP | $Ca(H_2PO_4)_2$ | 19-20 (26) |
| Monoammonium phosphate | MAP | $NH_4H_2PO_4$ | 21-24 (27) |
| Diammonium phosphate | DAP | $(NH_4)_2HPO_4$ | 20-23 (23) |
| Monopotassium phosphate | MKP | $KH_2PO_4$ | 17 (23) |
| Magnesium ammonium phosphate | Struvite | $MgNH_4PO_4*6H_2O$ | 13 (13) |
| Calcium phosphate | - | $Ca_3(PO_4)_2$ | 13-17 (20) |
| Phosphoric acid | - | $H_3PO_4$ | (32) |
| Trisodium phosphate | - | $Na_3PO_4$ | (19) |
| Magnesium phosphate tribasic | - | $Mg_3(PO_4)_2$ | (24) |
| Ferric phosphate | - | $FePO_4$ | (21) |
| Aluminium phosphate | - | $AlPO_4$ | (25) |
| Zeolites | - | Aluminosilicate minerals | Varies |

* The first six are compounds produced in the fertilizer industry. The rest are products from different phosphorus recovery processes. The numbers in parentheses represent theoretical amounts of phosphorus in a completely pure sample. In practice there seldom exist completely pure substances; the per cent figure represents the amount of phosphorus that has been analysed from the products. In the recovery processes the pureness of the products may vary. The per cent figure does not describe the viability of the phosphorus product as a plant nutrient.

The state of the phosphorus product also has an impact on the usability of the fertilizer product. The fertilizer needs to be distributed easily with as little loss as possible (Levlin et al., 2014). Table 3 presents the characteristics of products from phosphorus recovery processes and their degree of productization.

**Table 3: The state of the phosphorus products of the phosphorus recovery processes (Egle et al. 2016)**

| Grain size/state | Process |
|---|---|
| Pellets/Grain size 2-5 (ready-for-sale) | Ostara, AscDec granulated, RecoPhos, mineral fertilizer from fertilizer industry |
| Coarse grained (ready-for-sale) | PRISA, AirPrex, P-Roc |
| Crystalline, powdery (not ready-for-sale) | Aqua Reci, PHOXNAN, Gifthorn, LEACHPHOS, PASCH untreated AshDec, ash of incinerated sludge |
| Liquid (ready-for-sale) | EcoPhos |
| Solid (ready for sale) | Thermphos |

Table 4 presents the prices of a kilogram of phosphorus recovered with different technique. It also describes how many per cents of the potential amount of phosphorus that is recovered using the specific technique. As a point of reference the price for mined mineral phosphorus can be used, which in 2016 was 0,9 ± 0,3 €/ kg (Egle et al., 2016). It can be seen that the price for recovered phosphorus varies considerably. Even the most inexpensive kilogram of recovered phosphorus is for the time being about two times more expensive than mined phosphorus.

**Table 4: Price of the phosphorus and the recovery potential for different recovery techniques**

| Recovery technique | Euro/kg P | % P recovered | Reference |
|---|---|---|---|
| Pash *(calcium phosphate)* | 5 | 76 | Egle ym. 2016 |
| Crystalactor *(struvite)* | 7 | 45 | Egle ym. 2016 |
| Phosnix *(struvite)* | 7,7-9 | Data missing | Pinnekamp ym. 2011 |
| P-Roc *(calcium phosphate)* | 6 | 15 | Egle ym. 2016 |
| Fix-Phos *(calcium phosphate)* | 2,0-7 | Data missing | Pinnekamp ym. 2011 |
| Phoxnan *(phosphoric acid)* | 27 | 45 | Egle ym. 2016 |
| SesalPhos *(calcium phosphate)* | 7,5-9 | Data missing | Pinnekamp ym. 2011 |
| Ostara *(struvite)* | 10 | 15 | Egle ym. 2016 |
| Berlin/ Airprex *(struvite)* | 8 | 15 | Egle ym. 2016 |
| Seaborne *(struvite)* | 46 | Data missing | Nieminen 2010 |
| Asc Dec *( phosphates)* | 2 | 91 | Egle ym. 2016 |
| Mephrec *(phosphates)* | 13 | 45 | Egle ym. 2016 |
| Post-precipitation | 10-40 | Data missing | HSY 2017 |

## 2.8 Selection of phosphorus recovery process

When choosing a phosphorus recovery process, different things need to be taken into consideration. Different processes suit different places depending on a number of reasons. Cordell et al. (2011) have defined an eight step systems framework to help in the decision making for a sustainable phosphorus recovery system.

The first step is about recognising the main drivers for the phosphorus recovery. There are a lot of different reasons for wanting to separate the phosphorus from a waste stream. Reasons can be prevention of eutrophication or need to provide fertilizer to local farmers. Depending on the driver, the recovery process and the recovered product can have very different requirements. If the main driver is the prevention of eutrophication, the qualities of phosphorus product are less important than if the product will be used as fertilizer.
The second step concerns the system boundary. Is the recovery process for a town, a household or a whole country? Also questions like who will be involved in the recovery process, how the collection is arranged, what are the required transports, are a part of defining this system boundary.

The third step is about calculating the amount of available phosphorus from different waste fractions. Apart from municipal wastewater, possible other phosphorus sources could be household biodegradable wastes, animal manure or human urine and faeces.

When the key drivers have been identified, the system boundary set and the phosphorus sources quantified, the fourth step is to take a look at the phosphorus recovery techniques and processes. Depending on the technique in question, the requirements and resulting products differ. A process that is appropriate for a large scale operational plant may not be suited to a small one household setting. And a technique that is suitable for phosphorus recovery from wastewater may not be suited for recovery from animal manure.

The fifth step considers the logistics of the whole recovery process, from collecting, to end use. How far away from the source can a phosphorus recovery plant be located for the process to still be cost effective is one question that needs answering in step five.

In the sixth step the life cycle costs of the whole recovery process are in focus. Not just the monetary costs are important, but also the energy consumption and the required raw materials and the by-products of the process are aspects that need to be considered in calculating the costs. In the world of today, the use of fossil fuels should be avoided and the toxicity of the by-products should be at a minimum.

In step seven, the focus lies on the possible cooperation of the phosphorus recovery system with other systems in society, like sanitation or energy production. Also conflicts can arise between different systems like the conflict between biomass use for energy or for phosphorus recycling. The aim is to seek out as many possibilities for cooperation between different systems and avoid conflicts as much as possible.

The eight step is concerned with the people and institutions affected by the phosphorus recovery process. These can be wastewater treatment plants, fertilizer producers or consumers. Also regulations, different policies and the financers affecting the recovery process are a part of this group.

# 3 Methodology

The research methods used in the thesis are a literature review of earlier studies on the subject, a questionnaire to people working in water services and an interview with people working in water services.

The study of the different sludge treatments and phosphorus recovery methods was performed during the spring and summer of 2017, mainly as a literature review. The basis for the literature review was research reports on phosphorus recovery and especially the P-Rex platform of the European Union.

The SWOT analyses, the charting of the strengths, weaknesses, opportunities and threats of a certain method were done by interviewing representatives of Finnish wastewater treatment plants by telephone or bye-mails. A list of experts that were interviewed is in the beginning of the reference list. The questions of the interviews and more elaborate answers of the interviewees are presented in appendix 1.

The evaluation of the different techniques was performed using an electric survey that was sent to representatives of Finnish waterworks. The sample of representatives was quite comprehensive and represented almost all parts of Finland, with a larger representation of Southern Finland as seen in figure 6. Since Southern Finland also is the largest producer of wastewater, the distribution of representatives was considered to reflect the reality with acceptable accuracy. Half of the experts represented wastewater treatment plants that are considered big, with > 100 000 population equivalent and half represented medium sized treatment plants with population equivalents of 10 000 to 100 000. There were no experts representing small treatment plants, with populations equivalents of under 10 000.

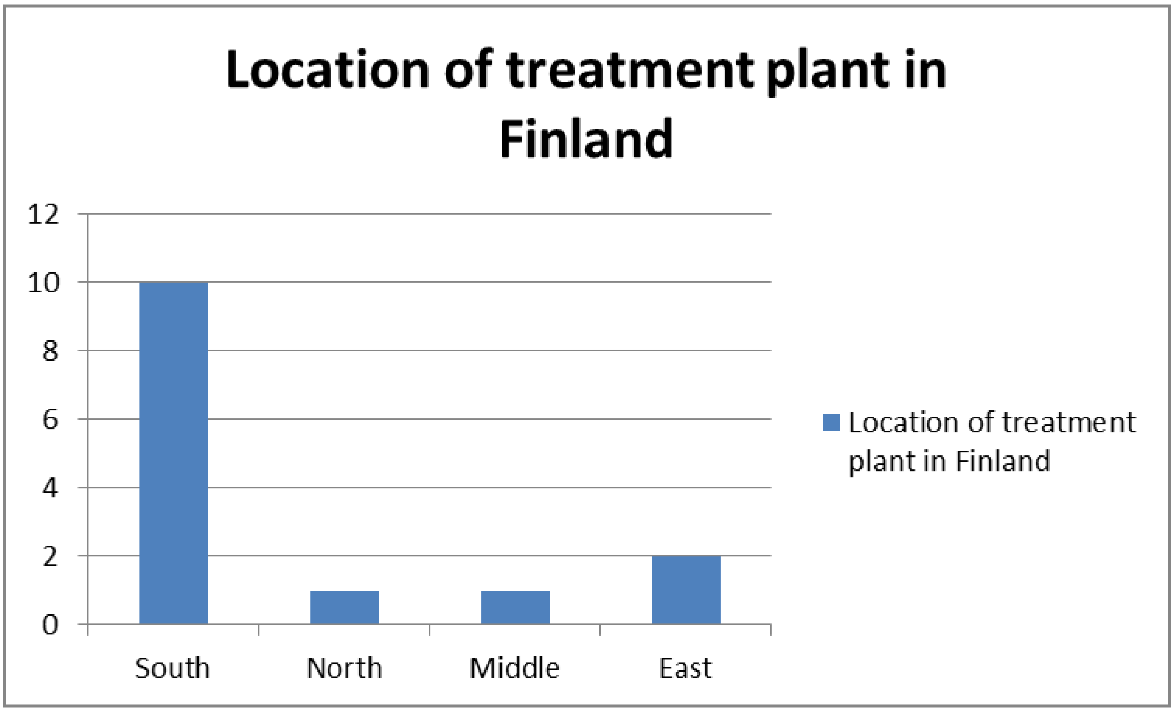


**Figure 6: Locations in Finland of the wastewater treatment plants that the experts represented**

The aim of the survey was to figure out the Finnish waterworks' views on different phosphorus treatment techniques and on different means of recycling phosphorus in agriculture. The treatment techniques were divided as follows:

- The direct use of incinerated sludge ash, when the phosphorus is in a very slowly plant available form
- Techniques in which the phosphorus is separated from the sludge ash
- Techniques in which biologically removed phosphorus is recovered from the sludge or from the reject
- Phosphorus removal by precipitation from effluent and the reuse of the sludge
- Techniques where the phosphorus is separated from chemically precipitated sludge

An interview was also carried out with a representative of The Swedish Water and Wastewater Association on the phone. The interview was in free form and topics were chosen from a few questions that were defined beforehand. The questions mainly concerned state of phosphorus recycling in Sweden and the public attitude towards it. The questions and more elaborate answers can be found in appendix 2.

# 4 Results

## 4.1 SWOT analyses of the treatment and recovery techniques

The current sludge treatments and different phosphorus recovery techniques all have both good and bad qualities. Estimates of the strengths, weaknesses, opportunities and threats (SWOT analysis) of the different treatment methods have been gathered from a group of water sector experts, and are summarized in tables 5 to 12 below.

**Table 5: SWOT analysis of sludge digestion**

| Anaerobic digestion of sludge | |
|---|---|
| **Strengths**<br>- a lot of practical experience<br>- combined with biological sludge, there exists recovery techniques<br>- a comprehensive network of biogas plants that the sludge can be sent to to be treated<br>- relatively low-cost | **Weaknesses**<br>- high grade recycling difficult<br>- only sludge that has undergone thermofilic digestion can directly be used as fertilizer<br>- there is little use for the sludge end product<br>**- the plant availability of the chemical sludge is weak** |
| **Possibilities**<br>- a common practice, to which possible new more efficient solutions are developed to improve the quality of the products.<br>- enhances the dewatering of the sludge | **Threats**<br>- organic pollutants<br>- the applications for the sludge cease to exist completely |

**Table 6: SWOT analysis of sludge composting**

| Composting of sludge | |
|---|---|
| **Strengths**<br>- a lot of practical experience<br>- a comprehensive network of existing composting plants<br>- well suited for landscaping<br>-even quality of the product | **Weaknesses**<br>- not suited for all kinds of landscaping, e.g. because of too high phosphorus content<br>- high grade recycling difficult<br>- needs much space<br>- odour<br>**- the plant availability of the chemical sludge is weak** |
| **Possibilities**<br>- reasonably priced<br>-organic matter to soil amendment | **Threats**<br>- limitations on agricultural use of composed sludge<br>- the bad reputation of sludge related fertilizers can transfer also to the use in landscaping<br>- organic pollutants |

**Table 7: SWOT analysis of phosphorus recovery from effluent**

| Phosphorus recovery from effluent | |
|---|---|
| **Strengths**<br>- suits many processes and different sized treatment plants<br>- the precipitation chemicals can be recycled<br>- does not contain organic pollutants or heavy metals<br>- does not require biological phosphorus removal<br>- lots of experience of the precipitation process | **Weaknesses**<br>- low phosphorus content of the water<br>- not suitable with primary precipitation<br>- enables the recovery of only 50% of the total phosphorus<br>- process only in development stage<br>- requires an efficient suspended matter removal before the precipitation |

**Table 8: SWOT analysis of biological phosphorus removal and recovery**

| Biological phosphorus removal and recovery | |
|---|---|
| **Strengths**<br>- good practical experience of the technique<br>- could be implemented in many treatment plants that have the capacity and a carbon source with minor changes to the process<br>- the amount of sludge would decrease and therefore also the treatment costs | **Weaknesses**<br>- some treatment plants do not have the space required for biological phosphorus removal<br>-smaller biogas production than chemical sludge<br>- would require in many places in Finland an accompanying chemical precipitation and addition of organic matter<br>- not suitable for the smallest treatment plants<br>- susceptible to disturbance |
| **Opportunities**<br>- possible fertilizer status in the EU for struvite<br>- common technique elsewhere, meaning presumably active development of the techniques<br>- greater possibility of getting approval also for other products | **Threats**<br>- difficult to reach a stabile process<br>- the product may contain small amounts of pollutants<br>- sensitive to change<br>- the costs depend on the recovery method |

**Table 9: SWOT analysis of sludge ash recycling**

| Sludge ash recycling | |
|---|---|
| **Strengths**<br>- the mass decreases<br>- the organic pollutants are destroyed<br>- inexpensive | **Weaknesses**<br>- the ash can't be recycled for the time being<br>- needs a centralized incineration facility and cooperation between many parties<br>- the plants availability of the phosphorus is very poor |
| **Opportunities**<br>- using the ash as forest fertilizer | **Threats**<br>-the use of ash as a fertilizer is not allowed |

**Table 10: SWOT analysis of phosphorus recovered from sludge ash**

| Phosphorus recovered from sludge ash | |
|---|---|
| **Strengths**<br>- clean and risk-free product<br>- incineration is common in e.g. Central Europe | **Weaknesses**<br>- expensive<br>- needs a centralized incineration facility<br>- no working references, only pilot versions have been carried out |
| **Opportunities**<br>- development of new methods is probable, because incineration is a common practice | **Threats**<br>- the problematic reject contains the harmful substances of the process<br>- possibly problematic by-products of the process |

**Table 11: SWOT analysis of sludge pyrolysis**

| Sludge pyrolysis | |
|---|---|
| **Strengths**<br>- enables also the use of the carbon in sludge<br>- most of the organic pollutants are destroyed | **Weaknesses**<br>- consumes a lot of energy<br>- too much phosphorus for fertilizer use<br>- concerning sludge the technique is still under development |
| **Opportunities**<br>- much research interest towards biochar, which might lead to the technique becoming more common<br>- a future possibility | **Threats**<br>- there is no use for the end product<br>- heavy metals |

**Table 12: SWOT analysis of source separation of urine**

| Source separation of urine | |
|---|---|
| **Strengths**<br>-the recovery of phosphorus is more cost efficient than from wastewater | **Weaknesses**<br>- too many factors of uncertainty as to how it would work in practice<br>-comprehensive change that would require commitment from people<br>- only a fraction of the phosphorus from wastewaters could be recovered |
| **Opportunities**<br>- enables also the recovery of nitrogen | **Threats**<br>- are the amounts big enough to have profitable processes?<br>- the properties pay and decide, not the treatment plants<br>- big initial investment<br>- the hazardous substances in the urine<br>- will there become necessary service production? |

## *4.2 Questionnaire about recovery techniques*

The views of the water treatment plant experts about the phosphorus recovery methods were established with a questionnaire. The questions on the questionnaire focused on the usability of the methods, the changes required to current practices and systems in case a method would be taken into use and the desirability of the different methods.

The results of the question about the usability if the different methods are presented in figure 7. By usability is meant here the development stage and usability of the method. It is possible though that the respondents have interpreted the questions as an evaluation of the willingness of the treatment plants to take the methods into use. The further processing of chemically precipitated phosphorus got the best evaluation. The option of recovering phosphorus from sludge ash was evaluated to be the worst option by availability. This may be due to the fact that sludge incineration is not in use in Finland. The reuse of incinerated sludge ash was evaluated fairly good in its usability, but some respondents evaluated it as bad. One explanation for this might be that the respondents were thinking of different kinds of use for the sludge ash. It is discussed that sludge ash could be used as a slow working fertilizer in forestry. Post-precipitation of phosphorus and reuse of chemical sludge was evaluated as being a little better alternative than the use of sludge ash.

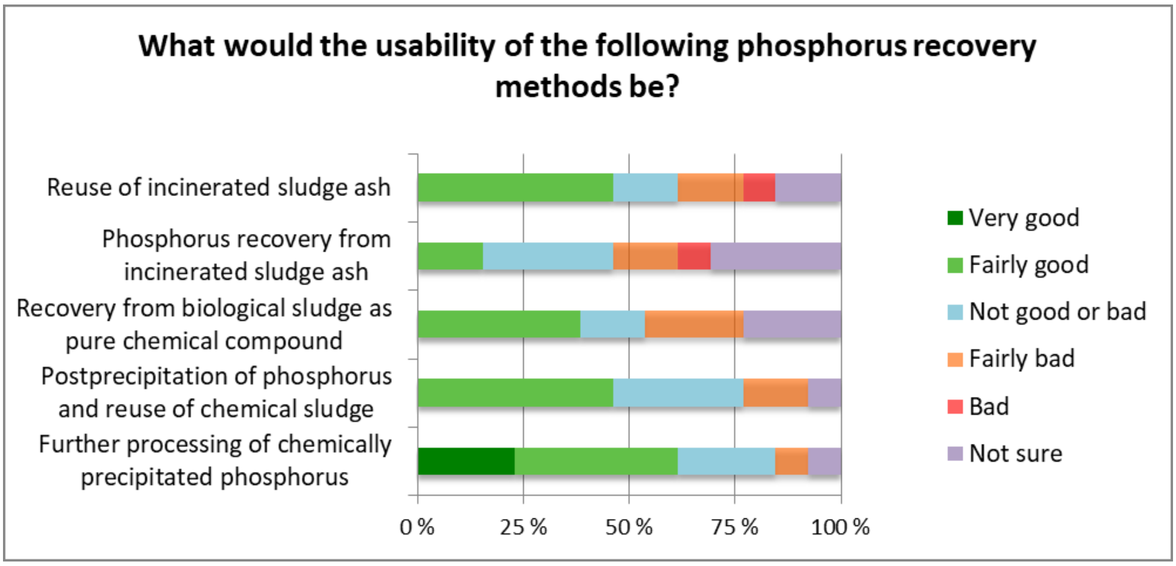


**Figure 7: Evaluation of the usability of phosphorus recovery methods by 13 water works experts**

Figure 8 presents the results of the needed changes. The biggest changes are required for the recovery of phosphorus from sludge ash. Both the reuse of incinerated sludge ash and post-precipitation of phosphorus and reuse of chemical sludge were by some evaluated to require only fairly small changes, while by others they were evaluated as very big. This might be due to, again different end uses that the respondents had in mind or the already existing processes and infrastructures in different treatment plants. All in all, all methods were evaluated to cause relatively large changes.

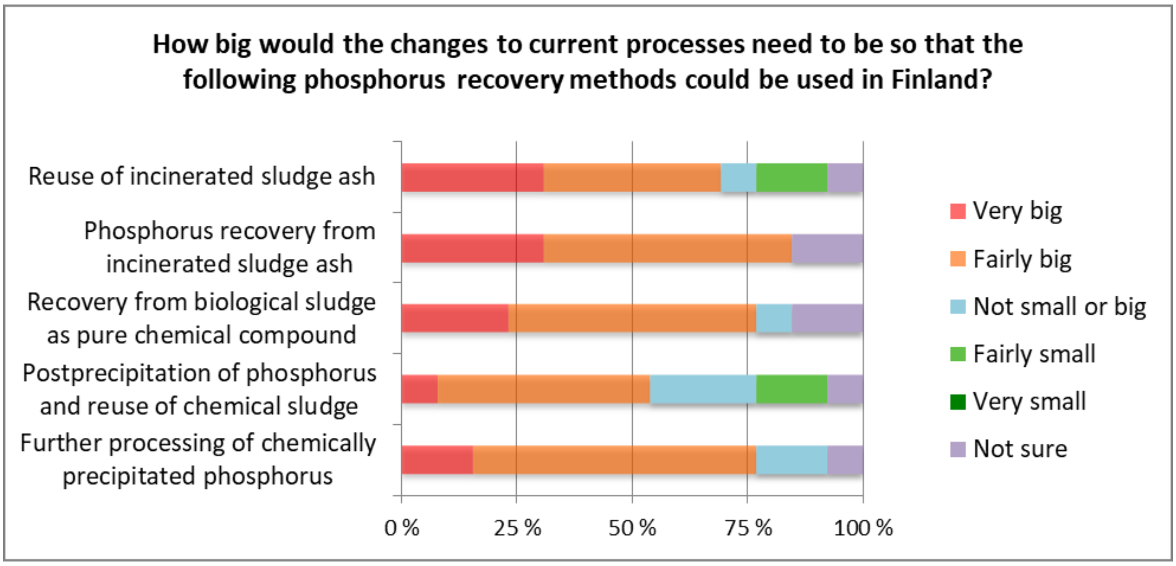


**Figure 8: Evaluation of the magnitude of change to current processes in case of implementation of phosphorus recovery methods**

Figure 9 presents the wastewater treatment plants' representatives' views on which phosphorus recycling methods would be desirable. The most desirable was the current system and phosphorus recovery by other means. The least desirable was source separation of urine, although more respondents evaluated the recovery of phosphorus from source separated urine as very undesirable than those evaluating source separated urine as very undesirable This might be because of the undoubtedly big changes that these two alternatives would require to current systems. Desirable was also the recovery of phosphorus from sludge ash.

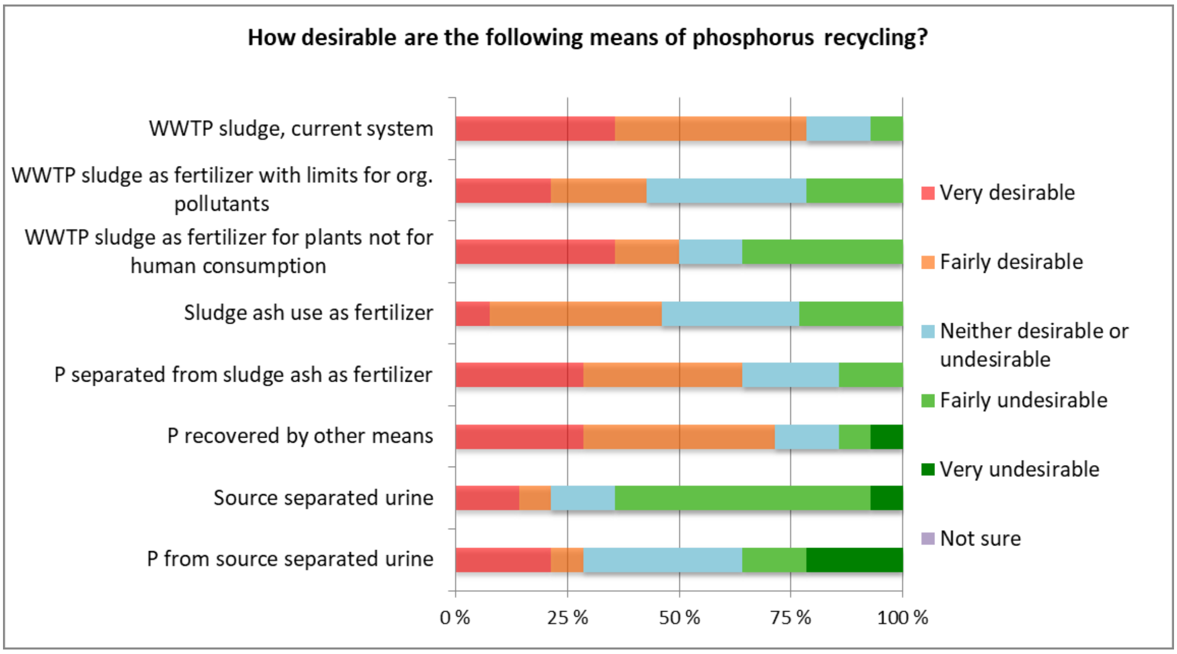


**Figure 9: Evaluation of the desirability of phosphorus recovery methods**

## *4.3 Interview with representative of Swedish Water and Wastewater Association*

The main themes of the interview with the representative of Swedish Water and Wastewater Association were the Revaq certificate that can be given to a wastewater treatment plant that fulfils the requirements of the certificate. The Revaq certification started in 2008 and today 84 treatment plants are Revaq certified, which means that over half the population in Sweden have their wastewater treated in a certified treatment plant. In Sweden only Revaq certified sludge can be used as a fertilizer in agriculture, which means that there is a quality control of the fertilizer sludge. 60 % of the Revaq-certified sludge is used in agriculture, and 40 % is used in landscaping. This means that around 25 % in 2014 (Statistiska Centralbyrån, 2016) of the produced sludge and therefore phosphorus in wastewater is used in agriculture, which, depending on source of reference is more than in Finland. The agricultural use in Sweden also includes use on forests for energy production. Several studies have also been performed in Sweden on the impact of sludge use as fertilizer on the quality of the soil and the plants that grow on sludge amended soils. These results could be taken advantage of also in Finland, as the wastewater treatment process, the soils and climate are very similar to Sweden.

A concern that came up was the cadmium content of fertilizers. This is a topic that is not often mentioned in the discussions about Finnish fertilizer use. Cadmium is a common impurity in mined phosphorus, and it ends up in the fertilizers alongside phosphorus. There is naturally occurring cadmium in the soil that is very immobile and once cadmium is added in the fertilizer, it accumulates. Cadmium in high concentrations is harmful to the plants growing in the soil. (European Commission, 2013)

In Sweden the use of recycled phosphorus instead of mined phosphorus is seen as a way of minimizing the cadmium addition to the agricultural soils, and also a way of increasing the self-sufficiency in terms of phosphorus. Presently Sweden imports 100 % of the mineral phosphorus that it uses as fertilizer. (Svenskt Vatten Ab, 2015)

# 5 Discussion

## 5.1 Current situation

There are many different phosphorus recovery techniques in use in the world today. While some of them are in use in full scale and in several countries, none of them are widely used in the world. Most of the more successful methods require a biological phosphorus removal and are therefore viable options only to treatment plants that have the biological removal as part of their process. This means that as in Finland the great majority of wastewater treatment plants use chemical phosphorus removal, these methods are as such not suited for direct implementation. To enhance the phosphorus recovery, Finnish treatment plants could either transfer to complete or partial biological phosphorus removal, or further develop and put up to testing some of the techniques that can recover phosphorus from chemically precipitated sludge.

One point that came up in the interviews was the old age and need for upgrade of some of the wastewater treatment equipment. As old equipment is exchanged to new, implementation of new processes and techniques can be more cost efficient and might be realized in a shorter time. Of course not all techniques are suited for every treatment plant, as also was mentioned in the interviews, due to for example limitations of available space. This is especially true for biological phosphorus removal that requires more space than chemical precipitation.

## 5.2 Concerns

In Finland the concerns for the efficiency of the biological phosphorus removal are also many. The requirements of phosphorus removal from wastewater are strict, because of the phosphorus sensitive, already eutrophied, receiving water ecosystems. The biological removal is more sensitive to disturbances, and the equilibrium of the process efficiency is achieved through careful calculations. Also in the winter the low water temperature makes the biological process more slow and the low organic matter content of the water may require an addition of organic matter to the water before the biological process.

One interesting topic that came up with the waste sector expert in Sweden was the concern of addition of cadmium to the soils in Sweden, when using mined mineral phosphorus as a fertilizer. There is a rising awareness of the impurities associated with some mineral phosphorus fertilizers that may be enriched in the soils, because of their low mobility. In many cases especially cadmium is of concern because it is most commonly found in association with phosphorus in the phosphorus ore. The high amount of cadmium in some agricultural fields in Sweden is a consequence of addition of low quality phosphorus fertilizer during the 20$^{th}$ century. This seems not to be the case in Finland, where the topic of cadmium in soils is not an important part of fertilizer discussions. It might be that in the future, when high quality phosphorus is more and more scarce, this is an issue that needs to be dealt with even in Finland.

## 5.3 Attitudes towards phosphorus recovery techniques

The attitude of the wastewater experts towards the different phosphorus recovery techniques varied. The techniques that are most easily adjusted to the current treatment system were favoured whereas techniques that require greater changes in current processes and practices were not thought of as equally plausible. Depending on the current system at different treatment plants, the post-precipitation from effluent or the recovery from sludge ash, were seen as possible options. Also the current systems of sludge digesting and composting were favoured because of the long experience and existing markets for the end products. Though in these cases, there were concerns about the tightening legislation and the public opinion about the possible harmful substances in the end product. These could lead to declining demand and problems in finding a use for the products. The common use and experience of the process in the world and the probable further development of the recovery techniques were seen as the positive aspects of the biological phosphorus removal. Source separation of urine was seen as too comprehensive and perceived to contain too much uncertainty in the real world realization. Nevertheless according to the representatives, all recovery methods require quite a lot of changes to the current setup at facilities. In addition to technical changes, also a change in attitudes and getting accustomed to new methods are needed.

## 5.4 Validity and reliability of the study

All of the answers that the water sector experts have provided to this study are subjective, and also the very small sample of people (n=14) affects the results of the study, as the answer of each person has a lot of weight and affects the result greatly. The geographical distribution of the sample was concentrated in the South of Finland, which means that location specific attitudes were emphasized. Also the understanding of what the questions really meant can have differed among the respondents which of course reflects on the answers. With a bigger sample the answers of individuals would have been less protruding and the results would have reflected a more average value of the answers.

This study was conducted with the assumption that the reputation of wastewater sludge as fertilizer will continue to be bad or even that it gets worse, and all use of sludge as fertilizer will seize. If the reputation and quality of the sludge would improve and the use of sludge in agriculture would increase the need for implementing other forms of phosphorus recovery techniques would not be so important.

# 6 Conclusions

The research questions for this thesis were:

1) What is the current state of phosphorus recovery technologies?
2) What are the attitudes towards these technologies in the field of wastewater treatment?
3) How well suited are the phosphorus recovery technologies to Finnish conditions?

Based on the literature review and the opinions of water sector experts, the answers, in their short form for the research questions are as follows.

**What is the current state of phosphorus recovery technologies?**
The current state of the phosphorus recovery technologies in the world is very diverse. The ones that are most developed and have most full-scale applications can recover phosphorus, in most cases as struvite, from biological sludge. Other techniques can recover phosphorus from sludge ash, or as post-precipitation from treatment plant effluent, but these do not have full-scale plants in operation yet. Even though some techniques already have full-scale implementations, no technique is widespread and mature enough to be called the new rising star of phosphorus recovery techniques. Furthermore the price of recovered phosphorus is not competitive with the price of mineral phosphorus.

**What are the attitudes towards these technologies in the field of wastewater treatment?**
The attitudes towards the recovery techniques among Finnish water sector experts are also quite varied. The current set up of the wastewater treatment process seems to affect the attitudes towards implementation of new recovery techniques. The more easily the new technique is implemented, the more positive the attitude is towards it, it seems. Also large changes in current infrastructure and treatment processes were seen undesirable by most respondents.

**How well suited are the phosphorus recovery technologies to Finnish conditions?**
As the current phosphorus removal in wastewater treatment in Finland is almost entirely based on chemical precipitation, the most used techniques in the world do not fit into Finnish conditions as such. One possibility of increasing the potential for phosphorus recycling would be to change the phosphorus removal process to a sequential process with both biological and chemical removal. This sequential removal of phosphorus both biologically and chemically is in use in a few Finnish wastewater treatment plants, but is a potential alternative for even more treatment plants in Finland. The biological sludge from the process would be suited for phosphorus recovery techniques and the chemical precipitation would guarantee the required efficiency in removing phosphorus. Another option would be to implement some of the less developed techniques, like Ash Dec, PAKU or pyrolysis and further develop it for Finnish conditions.

There are a lot of aspects to take into consideration when aiming at increasing the recycling of phosphorus in communities. The recycling of other nutrients and other substances, competing uses of the same resource, like energy production from phosphorus containing waste streams and existing infrastructure, as mentioned before, put different demands on a new system to recycle phosphorus. In some cases making big infrastructural changes to enhance nutrient recycling can be easier, like when outdated systems and processes need to be changed to new or when building completely new residential areas or wastewater treatment plants or planning new waste handling facilities. These are the opportunities to try something new, a new system of treating wastewater or a new way of looking at waste as a resource rather than a burden.

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## List of appendices

# Appendix 1: The questions and elaborate answers of the interviews with water sector experts in Finland

The interviews with the Finnish water sector experts were very free-form in their style, and they were done by phone or by e-mail. The interviewees got to answer the questions freely, and they didn't have to answer all the questions. Some questions received more attention while others received less, depending on the interviewee's own interests and knowledge.

**The interviews were based around the following questions:**
What is the current method for sludge treatment at (your) wastewater treatment plant?
What are the strengths, weaknesses, opportunities and threats of the method?

What are the strengths, weaknesses, opportunities and threats of the following phosphorus recycling methods?
-Biologically removed phosphorus and its recovery and recycling?
-The use of incinerated sludge ash?
-The recovery and recycling of phosphorus from incinerated sludge ash?
-Pyrolysis of sludge and the recycling of the phosphorus in the end product?
-The source separation and recycling of phosphorus from urine?

**In the interviews following points of interest were discussed:**
-The old age of current sludge treatment equipment, like sludge centrifuges
-The uniform quality of the current digested and composted sludge
-The low price but the odour problems and big space requirements of current composting of sludge
-The ease of another facility treating the sludge when producing biogas

-The suitability of the post-precipitation of phosphorus to a lot of different types of wastewater treatment facilities, also in other countries

-The sensitivity to disturbances of biological phosphorus removal
-The possible fertilizer status for recovered struvite in the EU and how it might enhance the development of recovery techniques with struvite products

-The need for a centralized incineration plant, if phosphorus would be recovered from sludge ash or if the sludge ash itself would be used as fertilizer
-The high price of some recovery techniques, like leaching phosphorus from sludge ash
-The high energy consumption of pyrolysis
-The product of pyrolysis containing too much phosphorus for fertilizer use

-All the uncertainty concerning the source separation of urine, like what would be done with the urine, would the urine after phosphorus recovery still go to the wastewater treatment plants, what institution would take care of the collection and treatment of urine?
-The great initial investment in the infrastructure when source separating urine

# Appendix 2: The questions and elaborate answers of the interview with water sector expert in Sweden

The interview with a water sector expert in Sweden to compare the state of phosphorus recycling and attitudes towards it in Finland and Sweden was done with a representative of the Swedish Water and Wastewater Association. The interview was done by telephone and was in free form. Not all of the questions were discussed in detail.

**The interview circled around the following questions:**

-What is the most common treatment for sludge in treatment plants in Sweden?

> The most common is digestion, which is used on up to 90 % of the sludge.

-Is treated wastewater sludge used as fertilizer in Sweden?

> Yes, 25 % is used in agriculture.

-What is the attitude of the farmers towards using wastewater sludge as fertilizer?

> In general the farmers are divided in their attitude towards sludge used as fertilizer, but the union for farmers in Sweden is a pursuer of the Revaq-certification system.

-What is the attitude of the public towards wastewater sludge used as fertilizer?

> The attitude of the public is in general positive towards sludge as fertilizer.

-What is the attitude of the wastewater treatment plants towards sludge use as fertilizer?

> The biggest wastewater treatment plants in Sweden have the Revaq-certificate, and therefore can use the sludge they produce in agriculture.

-What is the share of biological phosphorus removal from wastewater compared to chemical in Sweden?

> Because of strict removal requirements the chemical removal is the predominant method

-Are there any so called phosphorus recovery techniques in use in wastewater treatment plants in Sweden?

> Only pilot-stage recovery techniques are currently being tested, like in Sandviken, where there is testing with sludge ash. There is a rising interest towards recovery techniques among some treatment plants that are not Revaq-certified, and who therefore can't use the sludge they produce in agriculture.

-Where is the Revaq-certified sludge used in Sweden?

> 60 % is used in agriculture and 40 % is used in landscaping, mostly in northern Sweden to fill and landscape old mines.

-Are there any limits for harmful substances in the Revaq-sludge?

> There are limits for 60 different metals. The organic pollutants are not measured. The industries placed in the area work with the wastewater treatment plants to minimize the use of harmful substances that end up on the wastewater treatment plants.