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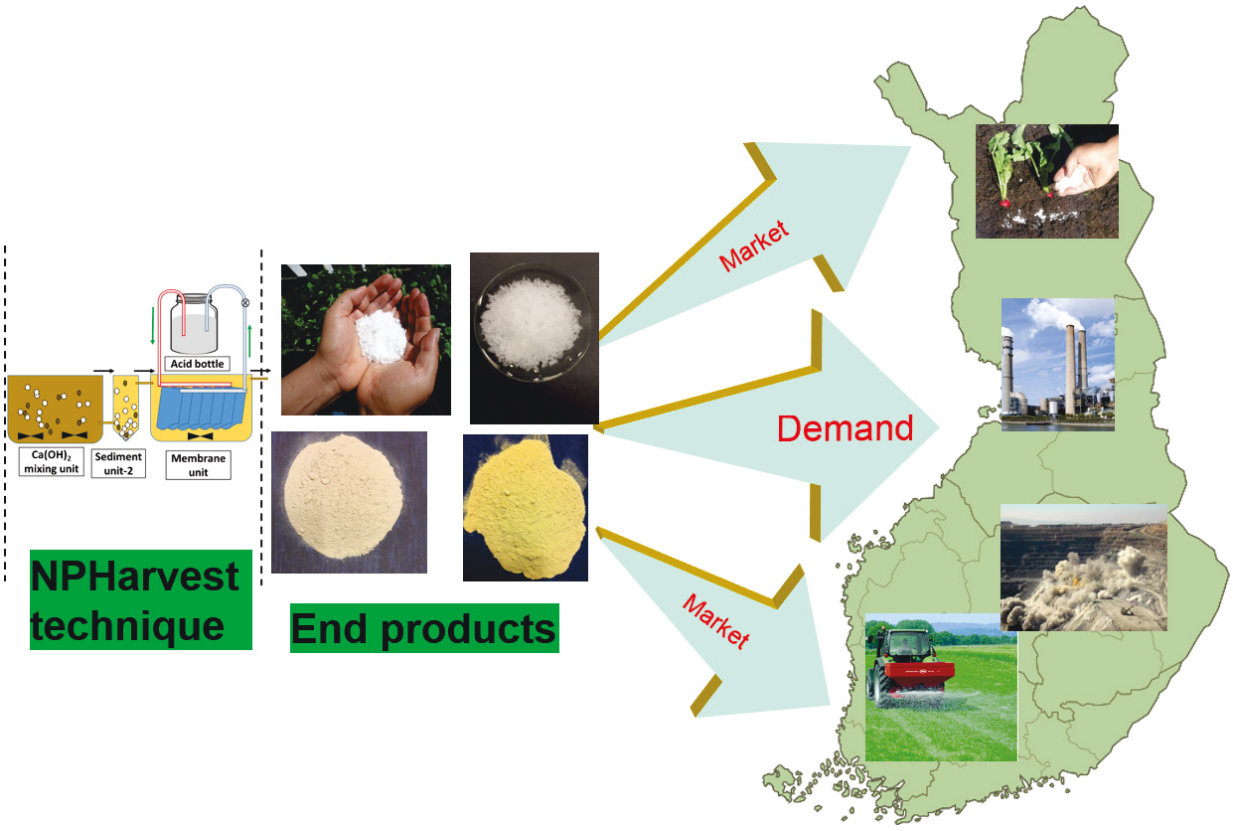

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Abstract
Nutrient recycling is an important segment of the circular economy. There are several techniques used in the field of nutrient recycling from different types of waste. Recently, nutrient recycling technique is receiving more attention on the production of mineral fertilizer from waste. Several types of mineral fertilizer products can be produced from waste but ammonium-based mineral fertilizers or ammonium sulfate is the dominant recycled mineral fertilizer. Our NPHarvest project also produces the ammonium-based fertilizer by harvesting nitrogen from waste. It also produces calcium, phosphate and organic matter based products. Besides the production of recycled fertilizers, it is very important to study the market potential of these recycled products to make this idea sustainable.
This report covers the market potential of recycled mineral fertilizers in Finland. The study was carried out by gathering literature and contacting the stakeholders. Recycled liquid and granular ammonium sulfate are used in Finnish agriculture on a small scale. As sulfate is not suitable for Finnish soil the demand for ammonium sulfate fertilizers is small. This study found that ammonium nitrate has a higher market value compared to other recycled mineral fertilizers. Ammonium nitrate is highly demanded fertilizer for farmers as well as the large fertilizer companies like Yara international. This report will help the nutrients recycling sector to understand the market of different types of fertilizers in Finland so they can change their products and expand their market.

Keywords - Fertilizer, Liquid waste, Market study, Membrane, Nutrient recovery, Nitrogen, Phosphorus

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Foreword

This report is published in Aalto University's NPHarvest project. NPHarvest project studies and develops technology to recover nutrients from liquid waste as well as the market potential of the technique and its end products. This project report includes the market situation and market potential of recycled mineral fertilizer in Finland. NPHarvest is a part of a larger project called "A breakthrough in the circular economy and clean solutions" by the Finnish government.

The project is supported by a consortium of companies including Nordkalk Ltd, Gasum, HSY, Biolan and Sulzer. The Ministry of Environment has funded NPHarvest with 457499.7 euros in the program "Enhancing nutrient recycling and the condition of Saaristomeri". NPHarvest has also been financially supported by Nordkalk Ltd and Gasum. We would like to thank Gasum, Soilfood, Nordkalk, HSY, Finnish energy association, and other institutes and individuals for their valuable information and suggestions in preparing this report.

Table of Contents

1. Introduction

Demand for fertilizers is increasing due to population growth. Increasing population produces a vast amount of waste which contains a high amount of nutrients such as nitrogen and phosphorus. There are several techniques to treat waste for safe reuse. Some of the techniques recover nutrients from waste as mineral compounds, such as struvite, nitrogen as ammonium salts and phosphorus as calcium phosphate. Nowadays, nutrient recycling is gaining more attention as recycled mineral fertilizers are easy to transport and use, have a low risk of pathogens, can be stored for a long time and are seen as an ecological option. However, it might be difficult for the recycled mineral fertilizers to compete with the ones manufactured by multinational companies. Therefore, it is important to study the value and demand for recycled mineral fertilizers.

This report discusses the market of NPHarvest end products and the use of recycled mineral fertilizers in Finland, and evaluates the cost of mineral fertilizers produced with the NPHarvest technique. The results will help to select and prioritize suitable liquid streams for the NPHarvest process. Furthermore, the result will give an overview of the mineral fertilizers with high demand which can be produced by NPHarvest technique. Research for this report was carried out by searching for literature, technical papers, companies' websites and seminar presentations. Besides literature research, several data were collected by contacting companies via email, phone or meeting the stakeholders.

2. End products of the NPHarvest process

The NPHarvest process is developed to harvest nitrogen and phosphorus from liquid waste to produce mineral fertilizers, among other products. NPHarvest technique has been tested with urine, reject water and bio-washer water from tunnel compost plants' exhaust air. The end products are described in Table 1 and shown in Figure 1.

Table 1. Possible end products of the NPHarvest technique.

Product	**Description**
Ammonium sulfate ($(NH_4)_2SO_4$)	Ammonium sulfate (AS) is produced with the NPHarvest technique by extracting ammonium nitrogen from liquid waste and mixing it with a diluted sulfuric acid solution. This solution can be used as a liquid fertilizer or this dried to produce crystal mineral fertilizer. Dried ammonium sulfate contains 21% of nitrogen and the pH is 5.5.
Ammonium phosphate ($(NH_4)_2PO_4$)	Ammonium phosphate (AP) is produced with the NPHarvest technique by extracting ammonium nitrogen from liquid waste and mixing it with a diluted phosphoric acid solution. This solution can be used as a liquid fertilizer or dried to produce crystal mineral fertilizer. The phosphorus in this fertilizer comes from the

	phosphoric acid. Ammonium phosphate contains 21% of nitrogen and 24% of phosphorus and the pH is 4.3-5.
Ammonium nitrate (NH_4NO_3)	Ammonium nitrate (AN) is produced with the NPHarvest technique by extracting ammonium nitrogen from liquid waste and mixing it with a diluted nitric acid solution. This solution can be used as a liquid fertilizer or dried to produce crystal mineral fertilizer. Ammonium nitrate contains 35% of nitrogen and the pH is 5.4.
Ammonia solution (NH_3-soln),	Ammonia solution can be produced by extracting ammonium nitrogen from the liquid waste in the water. As ammonia is highly volatile, production of highly concentrated ammonia solution might be challenging. However, the solution can be evaporated to produce a concentrated ammonium solution with 10-35% of nitrogen. This product is not commonly used as fertilizer.
Sediment/Phosphorus products	
Calcium carbonate, calcium phosphate and sludge	This is the most common sediment type produced with NPHarvest. During the harvesting process, the applied calcium ($Ca(OH)_2$ or CaO) reacts with P and form calcium phosphate. Similarly, the calcium also reacts with dissolved carbon dioxide and turns into calcium carbonate. The end product contains 99% of calcium carbonate and some phosphate. The sediment can be dewatered and used as lime in composting or agriculture. Or the sediment can be dried and milled to produce the prime product.
Calcium carbonate and calcium phosphate	These products are formed in a similar process as the previous one when the treated liquid waste contains a low concentration of suspended solids, such as urine, exhaust air bio-washer water from tunnel compost plant or pre-treated liquid waste.
Skimmed sludge (pre-treatment- dissolve air flotation (DAF))	Sludge is produced during pre-treatment depending on the characteristics of the treated liquid waste. In this process; PAX and polymer are used to coagulate and flocculate the suspended solids (SS) and eventually DAF remove the SS. The sludge is expected to contain a high concentration of organic matter and phosphorus. This sludge can be dewatered and reused for composting or biochar. This sludge can also be turned into briquettes when mixed with sawdust and used in energy production.
Calcium carbonate, calcium phosphate, sludge and sand (pre-treatment- ballasted sediment)	In this process; PAX and polymer are used to coagulate flocculate the SS and the lime kiln dust (LKD) is used for quick sedimentation of the SS. The sludge contains calcium carbonate, phosphate, sludge but it also contains a significant amount of sand. The sediment can be dewatered and used as lime in agriculture or in landscaping.

Figure 1. Ammonium sulfate produced from urine (left) and phosphorus and calcium carbonate rich sediment produced from urine (right).

3. Fertilizer production in Finland

Yara International is the leading chemical fertilizer manufacturer in Finland. Yara produces 824 million tons of ammonium sulfate per year (2012). Yara occupies 85% of the Finnish fertilizer market, while the remaining 15% is covered by Belor Agro's net, Cemagron and A-Rehu, but these companies only import fertilizers (Käytännön maamies, 2018).

Nordkalk, Lhoist, and pulp and paper industries produce lime products in Finland. Nordkalk is the main lime producer and recycler which produces different types of calcium products used in agriculture, forestry and other industries. Nordkalk also sells the calcium carbonate ($CaCO_3$) produced as a side product in pulp and paper industries to wastewater treatment plants (personal communication to Nordkalk). Besides chemical fertilizers and lime products, 2 million tons of manure and 1 million ton of sewage sludge is produced in Finland per year (see Report NPHARVEST market potential).

Different types of nitrogen and phosphorus mineral fertilizers used in Finland include the following (Fertilizer market in Finland, 2015):

- Ammonium nitrate
- Ammonium nitrate limestone mixes
- Ammonium sulfate
- Ammonium sulfate-nitrate mix
- Calcium-ammonium nitrate mix
- Sodium nitrate

- Urea
- Urea-ammonium nitrate mixes
- Other nitrogenous fertilizers
- Superphosphates
- Other phosphatic fertilizers
- Fertilizer mixes in tablets
- Diammonium phosphate
- Mono-ammonium phosphate and mixes with di-ammonium
- Nitrogen-phosphorus-potassium fertilizers
- Other fertilizer mixtures

Companies also manufacture other products by changing the ratio of nitrogen, phosphorus, potassium and other micronutrients based on demand. Other products used as fertilizers in Finnish agriculture include compost from organic waste, compost from industrial waste (fiber from pulp and paper industries), compost from sewage sludge, digestate, liquid organic fertilizer, septic waste, urine, dry toilet compost and recycled ammonium sulfate (liquid and solid).

About half of the nitrogen fertilizers demand are produced using recycled nitrogen. The amount of recyclable nitrogen fertilizers could be higher as nitrogen is easily lost through evaporation before recycling. Finland produces a significant amount of recyclable phosphorus fertilizers which could meet all the phosphorus demand in Finnish agriculture if managed properly (Figure 2). In Finland, phosphorus fertilizer use rate has decreased from 16 kg/ha to 6 kg/ha between 1995 and 2015 (Niemi and Väre, 2017). However, about 11 000 tons of mineral phosphorus fertilizers are still used in Finland per year. Most of the recyclable organic fertilizers are used locally by farmers, which makes the estimation of the amount of recycled nutrients challenging.

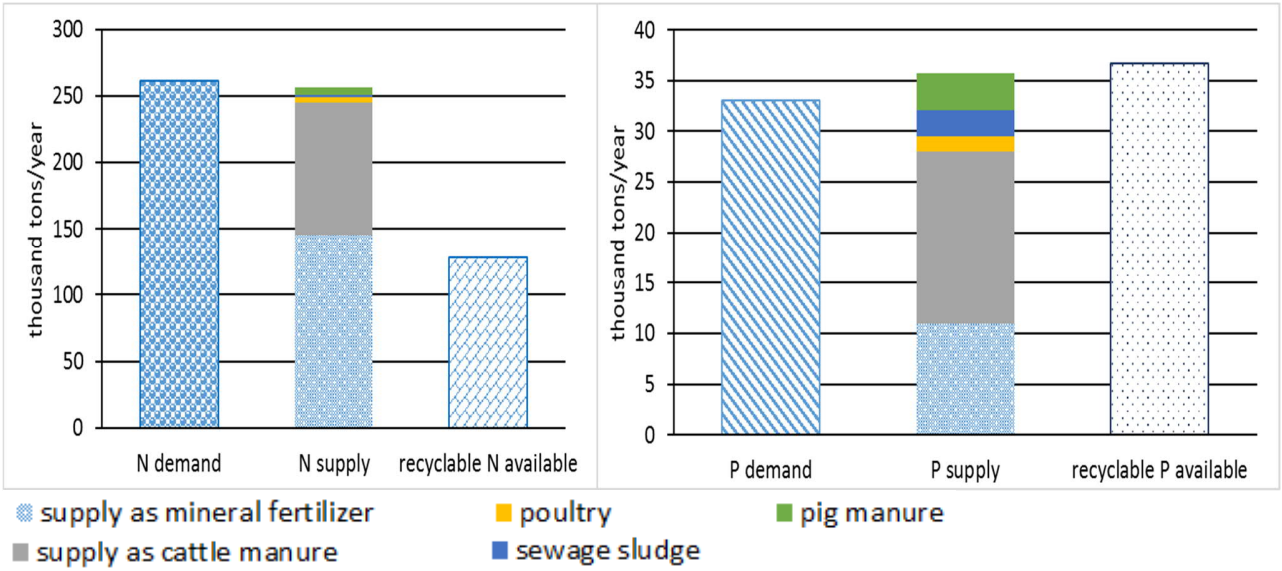

Figure 2. Demand and supply of nitrogen and phosphorus in Finnish agriculture (details in Annex 2).

4. Market for recycled nutrients

4.1 Recycled nutrient production and market globally

In global fertilizer consumption, only 4% of ammonium sulfate is used mainly due to its relatively low nitrogen content (21%) in comparison to other nitrogen-based fertilizers such as urea (45% of nitrogen) (Figure 3). Recently, the ammonium sulfate supply has increased, partly due to the production of recycled ammonium sulfate. The additional ammonium sulfate supply has been absorbed quickly in the markets (UNSD, 2014).

Currently, ammonium sulfate recovered by stripping or air scrubbing is most often sold as a liquid fertilizer. The price of ammonium sulfate varies with the product quality which depends on particle size. The price of granular (2-3 mm) crystals is three times higher compared to 1 mm crystals. Overall, global demand for recycled ammonium sulfate will continue to increase by about 2% annually (Glauser et al., 2013). The technical and economic feasibility of producing granular ammonium sulfate from waste requires further investigation.

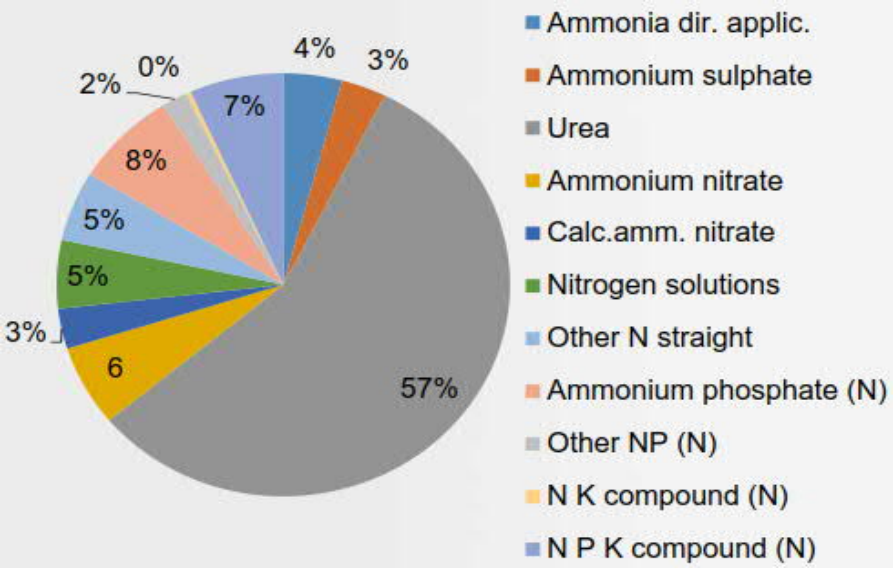

Figure 3. Global demand for different types of nitrogen fertilizers in 2013-2014 (Heffer and Prudhomme, 2016).

There are several biological and chemical methods for removing and recovering phosphorus from wastewater. For example, phosphorus can be precipitated using different chemicals such as calcium, iron and aluminium as shown in Equations 1, 2 and 3. Phosphorus precipitated with iron or aluminum is not easily available for plants (Kahiluoto et al., 2015). Phosphorus can also be recovered as calcium phosphate. In this process, calcium hydroxide ($Ca(OH)_2$) is used as a source of calcium and the precipitation occurs in pH above 10. The molar ratio of calcium and phosphate may vary between 1.3

and 2.0 because calcium phosphate can precipitate in different forms (Vesilind, 1998). The phosphorus recovery efficiency is lower (39%) at a low calcium dosage (1.3 g/L) compared to a high calcium dosage (6.6 g/L), with which the efficiency is 78% in one hour's contact time (Young, 2003).

$10\ Ca^{2+} + 6\ PO_4^{3-} + 2OH \leftrightarrow Ca_{10}(PO_4) * 6(OH)_2$ Equation 1[1]

$Fe^{3+} + H_nPO_4^{3-n} \leftrightarrow FePO_4 + nH^+$ Equation 2[2]

$Al^{3+} + H_nPO_4^{3-n} \leftrightarrow AlPO_4 + nH^+$ Equation 3[3]

$Mg^{2+} + NH_4^{+} + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4.6H_2O$ Equation 4

Struvite ($NH_4MgPO_4 \cdot 6(H_2O)$) precipitation (Equation 4) is one of the most extensively studied technologies in the field of nutrient recovery. Struvite precipitation recovers both nitrogen and phosphorus from liquid waste. This process is more efficient at pH between 8 and 9 (Celen, 2001). Maximum struvite recovery occurs at pH 8.8 and magnesium concentration of 120 ppm. In general, a wastewater treatment plant can recover 1 kg of struvite from 100 m^3 of wastewater (Münch and Barr, 2001). Several companies produce struvite on a large scale. For example, Ostara has 15 full-scale plants in Canada, USA, UK, Germany and Spain. Other major struvite producers are Multiform harvest in the USA, Nuresys in Belgium, Sustec and Paques in the Netherlands and Suez and Veolia in France.

The market for struvite is growing and struvite is registered as a fertilizer product in 34 states in the USA, Canada and the UK (Cullen et al., 2013). Struvite obtained from wastewater is sold for 250 €/ton in Japan (Ueno and Fujii, 2001) and 464 €/ton in Australia (Shu et al., 2006). Nieminen (2010) reports that struvite was sold to fertilizer companies with 250 €/ton and that the struvite was mixed with other nutrients and sold for 100-200 € per 20 kg. However, some countries are still worried about the risk of heavy metal and pharmaceutical residues in struvite produced from wastewater.

There are a few studies about mineral phosphorus recovery from sludge and incinerated sludge ash. The KREPRO process was developed by Kemira to recover phosphorus as ferric phosphate ($FePO_4$) from sludge. This technique was planned to be used in Sjölunda wastewater treatment plant in Malmö, Sweden, but the project was canceled due to P legislation was changed (Robertsson, 2008).

4.2 Recycled nutrient production in Finland

Several techniques are used to recycle nutrients from different types of waste streams in Finland. One of the most common treatment methods is composting. However, as composting is not feasible in several cases, other ways of recycling waste are required. Kemira has developed a chemical sludge conditioning process called KemiCond. Kemira is treating dewatered sludge from Oulu Waterworks and Pori and the treated sludge is composted. The KemiCond sludge is approved for soil amendment by EVIRA (The

[1] https://www.lenntech.com/
[2] https://www.lenntech.com/
[3] https://www.lenntech.com/

Finnish Food Safety Authority) (SITRA, 2014). One plant of the KemiCond process can treat 12 000 tons of dry sludge solids per year. The upside of ChemiCond is that the sludge treated by this technique can be used for any crops. On the downside, the treatment is comparatively expensive costing 40 € per ton of wet sludge (Thunberg, 2010).

Endev Finland is developing a process for sludge incineration and nutrient recovery as ash. Endev has also developed PAKU process and planning NEVE project in Rovaniemi. A study about phosphorus recovery from effluent wastewater is ongoing in the Ravita project. This project is piloting for phosphorus recovery as the phosphoric acid from sludge in the Viikinmäki wastewater treatment plant in Helsinki (HSY, 2017).

In Finland, about 180 000 tons of recycled ammonium-based mineral fertilizers are produced per year as a side product in different industries (Table 2). Among them, biogas companies are producing only about 3500 tons of ammonium sulfate (personal communication Soilfood Finland, 2018). These recycled ammonium-based products are reused mainly in agriculture.

Table 2. Recycled nitrogen-based fertilizers in Finland. Details are in Annex 1.

Producer	**State**	**Nitrogen amount (tons/year)**	**Nitrogen content (%)**	**Phosphate phosphorus kg/m^3**	**Reference**
NNH (Norilsk Nickel Harjavalta)	granular	100 000	21% ammonium sulfate		http://ntlmtd.com/product, personal communication with Soilfood
Gasum (Riihimäki biogas plant)	liquid	500	35% ammonium sulfate		
Gasum, Turku WWTP	liquid	183	3% ammonium water		Gasum 2016.
Biogas plant in Tuorla	liquid	115	35% ammonium sulfate		Ductor, 2016
Envor	liquid	500	35% ammonium sulfate		Personal communication with Envor

The company Soilfood is promoting the use of recyclable fertilizers and recycling a significant amount of nutrients yearly (Table 3). Soilfood is the leading company working with recycled fertilizer producers and consumers in Finland. Soilfood treats liquid and solid recyclable fertilizers, for example, ammonium sulfate, ammonium solution, biogas slurry, manure and sewage sludge. Soilfood recycles 400 000 tons of waste material per year, which contains about 230 000 tons of slurry from biogas or ethanol industries,

100 000 tons of micronutrients from process industries and 15 000 tons of lime products (Kankaanrinta, 2017).

Table 3. Nutrient recycling in Finland by Soilfood (2017).

Nitrogen (t)	Phosphorus (t)	Potassium (t)	Sulfur (t)	Total fertilization land area (ha)
280	80	60	100	10 300

The feasibility of nutrient recycling depends on the business environment. The information needed for calculating the waste streams is scarce, for example, information on biomasses is not yet openly available as the transportation of raw materials over long distances is not profitable. Since nutrients in waste are still seen as a cost rather than revenue, the profitability of nutrient recovery will be based mainly on gate fees or compensation for waste treatment. In many countries in the EU, landfilling of organic waste is banned or a fee is charged. The low price of nutrients is still the main hindrance for making nutrient recycling profitable. The strict environmental legislation and quality requirements for recycled fertilizers constrain the use of nutrient-rich waste as fertilizers. Thus, it is important to study other possibilities to make nutrient recycling techniques more sustainable globally and locally.

4.3 Market for ammonium sulfate, ammonium phosphate and ammonium nitrate

In Finland, many farmers apply commercial granular fertilizers and seed simultaneously. The farmers use a machine which is made to apply granular fertilizer and seeds close by at the same run (Figure 4). Therefore, granular fertilizers have a high demand, but the production of standard-sized granular ammonium sulfate might be expensive, so the production might not be feasible for small or medium-sized nutrients recycling companies. Liquid fertilizers (solid fertilizers mixed with water) are applied either under the soil surface or spread directly on the plant. NPHarvest can produce either water-soluble ammonium sulfate crystal or highly concentrated liquid ammonium sulfate (about 35% of ammonium sulfate solution) which can be used as liquid fertilizer.

Figure 4. Machine for seeding and granular mineral fertilization at the same drive.

Furthermore, a highly concentrated liquid fertilizer can be used in home gardens. For example, Biolan and Kekkilä sell liquid fertilizers in 1.2 L bottles. On the other hand, selenium is low in Finnish soil and sulfate is competing with selenium, which means that ammonium sulfate fertilizers (21% of nitrogen and 24% of sulfur) might have a lower demand in Finland. Evans (2007) reports that recently nitrogen stripping companies are changing from sulfuric acid to nitric acid as ammonium sulfate is too acidic for the Nordic soil. Therefore, it might be useful to look into other alternatives, such as ammonium phosphate, ammonium nitrate and ammonia water.

The most commonly used nitrogen fertilizers are ammonium nitrate or a mixture of ammonium and nitrate with other elements (Farmit, 2018, Mohammadi et al., 1991). Thus, the production of ammonium nitrate could be the second option. The production process is similar to ammonium sulfate. Production of ammonium phosphate (21% of nitrogen and 23% of phosphorus) can be the third alternative as ammonium sulfate and ammonium phosphate have similar properties. However, the use of phosphoric acid as raw material to produce ammonium phosphate is expensive. Plants need more nitrogen than phosphorus, so there will be less demand for ammonium phosphate. Ammonia water could be the fourth option. It is cheaper to produce as it does not need chemicals to capture ammonia. However, ammonia is highly volatile so it is difficult to produce highly concentrated ammonia water. There is also the risk of losing ammonia during storage.

Ammonium nitrate is mainly used as nitrogen fertilizers and/or mixed with other nutrients. This is the most commonly used nitrogen fertilizer in Finland (Mohammadi et al., 1991). Ammonium nitrate is also commonly used as a mining explosive: about 50 000 tons/year of ammonium nitrate is used for explosives in Finland (Jermakka, 2015). In 2001, about 90% of ammonium sulfate was used directly as a fertilizer and only 10% was used in the chemical industry or for producing metals (OECD SIDS, 2004).

4.4 Market for ammonia solution or ammonium hydroxide

Ammonia solution is not commonly used as a fertilizer but it is the main nitrogen component for industrial fertilizer producers. Ammonia solution is used in industry as a cleaning agent, food preservative and raw material for mineral fertilizer and NOx remover, among others. Energy producing companies use ammonia solution or urea for treating exhaust gases or NOx with Selective Non-Catalytic Reduction (SNCR) (Equations 5 and 6) and Selective Catalytic Reduction (SCR) technology (Equations 5 and 7).

$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$ Equation 5

$2\ NO + (NH_2)_2CO + 1/2\ O_2 \rightarrow 2\ N_2 + CO_2 + 2\ H_2O$ Equation 6

$2\ NO_2 + 4\ NH_3 + O_2 \rightarrow 3\ N_2 + 6\ H_2O$ Equation 7

In Finland, about 25% of industries use ammonia solution (19-29 % NH_4-N content) or about 290 tons/year (40 tons/plant/year) of ammonia solution is used. Energy companies in Finland are interested in purchasing ammonia solution (Moldakhovskaia, 2013). SNCR technology is not sensitive to impurities. Pulp and paper companies also use a similar technique to clean their exhaust air but they use mostly urea. However, it is possible to replace urea with an ammonia solution. An integrated pulp and paper mill consumes about 365 tons per year of ammonia solution. Valmet is one of the leading companies that treat exhaust air from energy and pulp and paper companies. The demand for ammonia water will increase as the Finnish environmental legislation is setting stricter restrictions to NOx emissions (personal communication with Finnish energy association, 2018).

Pulp and paper industries use ammonia also for their wastewater treatment processes. Unlike municipal sewage, pulp and paper mill wastewater contains high concentrations of carbohydrates but low concentrations of nitrogen. Therefore, nitrogen and phosphorus should be dosed prior to biological treatment (Moldakhovskaia, 2013). Some pulp and paper mills use urea, which can be easily replaced with ammonia solution. If an integrated pulp and paper mill consumes about 360 tons per year of ammonia solution (Moldakhovskaia, 2013), the consumption of ammonia solution in Finnish pulp and paper industries (17 paper and 19 pulp mills (Finnish Forest Industries Federation, 2017)) in Finland is estimated at 6500 tons per year.

4.5 Market for sediment phosphorus, calcium carbonate and sludge

In Finland, most of the recycled phosphorus is collected from animal manure (19 300 tons per year), which covers 74% of recyclable phosphorus in Finland (Marttinen et al., 2017). About 2600 tons of phosphorus is collected from sewage sludge (calculated from Kangas, 2017). Sewage sludge can be treated using lime stabilization, composting, anaerobic digestion, oxidative chemical treatment or thermal drying. Well-treated sludge such as compost (sewage sludge and other organic waste) can be used for cereal crops but not for root crops. There is no recycled phosphorus fertilizer production on a commercial scale using chemical precipitation in Finland. Ravita project in Viikinmäki wastewater treatment plant is piloting the recovery of phosphorus as phosphoric acid (HSY, 2017).

The price of calcium carbonate depends on quality. The price of powdered natural calcium carbonate (GCC) is 205 €/ton (ICIS) and the price of the cheapest precipitated calcium carbonate (PCC) in Finland is 120 €/ton (Teir et al., 2005). Calcium carbonate is used in different sectors such as pulp and paper industries and iron or metal industries. A large volume of calcium carbonate is used in pulp and paper industry: in Finland, 700 000 tons of calcium carbonate is used for coating and 300 000 tons as is used as paper filler per year. There are seven calcium carbonate plants in Finland, which produced about 420 thousand tons of calcium carbonate in 2001 (GSF2, 2004; Koppinen et al., 2003).

Sediment with a high concentration of calcium carbonate and a low concentration of impurities can be used in agriculture and wastewater treatment plants. Calcium carbonate and calcium phosphate in sludge (containing less than 10% of sewage) can be used in agriculture. Calcium produced in the NPHarvest process has similar properties as commercial agrilime (personal communication with Nordkalk, 2018) and contains also a small portion of phosphorus.

The costs of phosphorus recovery technologies range from 2 to 14 euros per kg of phosphorus (Sartorius, 2011). The most promising phosphorus recovery technologies economically are phosphorus recovery from wastewater sludge using enhanced biological phosphorus recovery (EBPR/EPBR) and recovery from the ashes of incinerated wastewater sludge. However, no recovery technology can yet compete with phosphate fertilizers made of rock phosphate which costs ca 1.8 €/kg of phosphorus.

The NPHarvest process uses a significant amount of calcium products to precipitate phosphorus as well as to remove suspended solids. Used calcium products are recovered as sediment with phosphorus and the quality of phosphorus and sediment depends on the type of the treated liquid waste. Liquid waste that contains high concentrations of suspended solids might need pre-treatment to improve the quality of the sediment. Recovering calcium carbonate and calcium phosphate which contain a low concentration of impurities has better market value compared to calcium and phosphorus sediment with a high concentration of suspended solids. The sediment recovered from urine is in the form of calcium carbonate and calcium phosphate which has a low level of impurities compared to sediment recovered from reject water without pre-treatment. Calcium phosphate is comparable to phosphate rock which makes it a valuable recovered chemical that can be used directly as a phosphorus fertilizer or in phosphate industry (Schipper et al., 2001).

However, there are some limitations to reusing sewage sludge in agriculture. It needs to be treated properly to meet the national requirements on hygienic quality and concentration of heavy metals. After the treatment, the use of sewage sludge is limited to arable land and only to specific crops (MOFA, 2013). Vapo Oy has also produced secondary fuel by co-combusting dried wastewater digestate (Hupponen, et al., 2012). Therefore, the co-combustion option could be studied further as digestate sludge has a calorific value of 15.8 GJ/ton (Figure 5). It can be used as energy for boilers similar to peat which is priced at 3.5 €/GJ (Karhunen et al., 2014).

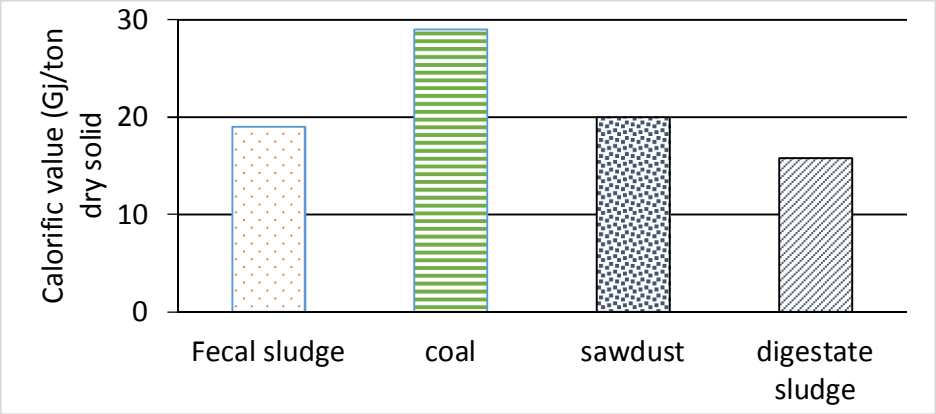

Figure 5. The calorific value of different recyclable waste types. (Muspratt et al., 2014; Kratzeisen et al., 2010).

4.6 Summary: market for NPHarvest end products

The market for NPHarvest end products is summarized in Table 4. The production costs of mineral fertilizers produced with the NPHarvest technique depend on several factors. Figure 6 shows that the production cost of mineral fertilizers (ammonium sulfate, ammonium phosphate and ammonium nitrate) produced with NPHarvest is higher than other mineral fertilizers. Therefore, some subsidies are required (Table 5). In general, fertilizer production costs decrease as the concentrations of nitrogen and phosphorus in source liquid waste increase. As the market price of ammonium water is not well known it is difficult to predict the price development in the future. However, it is possible to generate revenue from the treatment of reject water. In general, the treatment cost is 5 €/m^3 (i.e. 0.4 €/kg N) which will cover some of the production costs.

Table 4. The market for NPHarvest end products.

Nitrogen product	**Potential use**
Ammonium sulfate	Fertilizer, industrial use
Ammonium phosphate	Fertilizer, industrial use
Ammonium nitrate	Fertilizer, mining explosive
Ammonia solution	Raw material for fertilizer, NOx treatment, industrial use
sediments	
Calcium carbonate, calcium phosphate and sludge	Lime, Fertilizer, landscaping, composting with other organic waste,
Calcium carbonate, calcium phosphate	Fertilizer, landscaping, lime at wastewater treatment plants or composting, construction (as cement component or building material).
Skimmed sludge (pre-treatment-DAF)	Composting or Fuel for; boilers (central heating systems), cement clinkers (Lechtenberg, 2011), tire factories (e.g. Nokia)
Calcium carbonate, calcium phosphate, sludge and sand (Ballasted sediment)	lime, landscaping, composting with other organic waste,

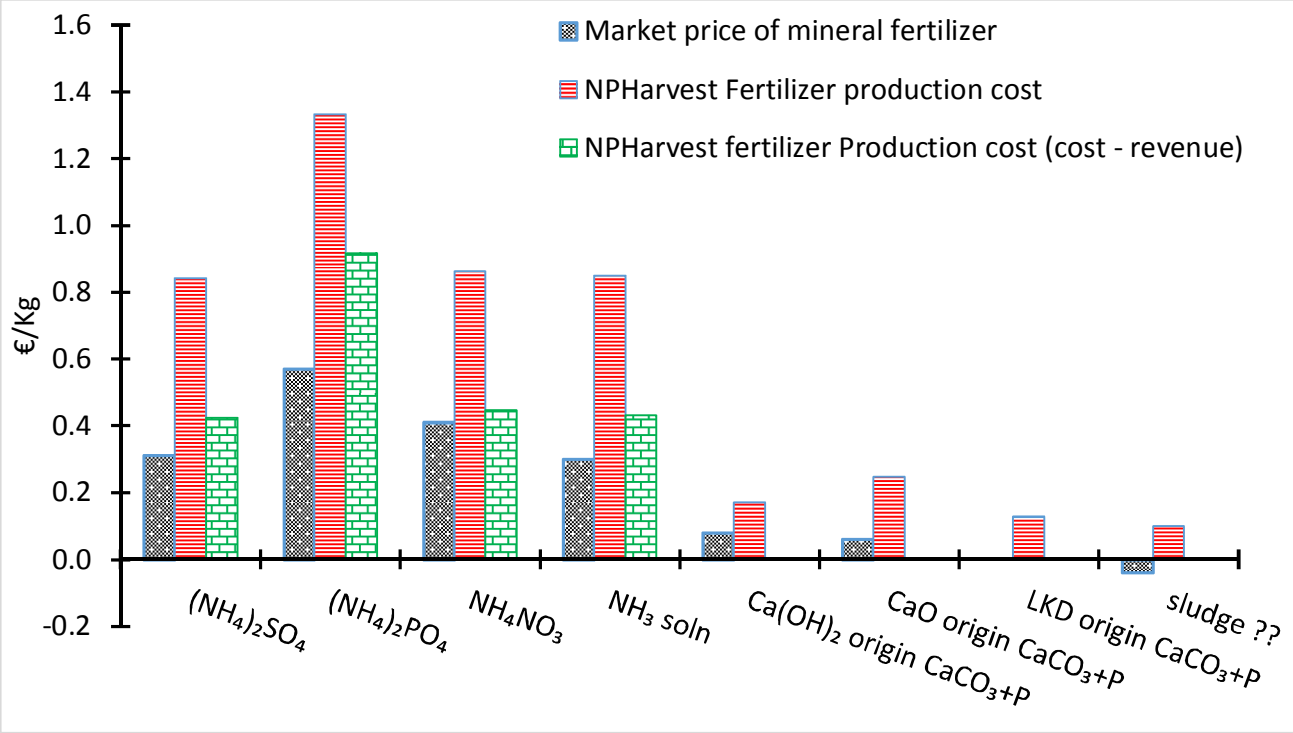

Figure 6. The production cost of recycled mineral fertilizers produced with NPHarvest compared to market prices of conventional mineral fertilizers.[4]

In Finland, liquid nitrogen and digestate produced by biogas plants meet the requirements of the Decree of the Ministry of Agriculture and Forestry (24/2011, amendments up to 7/2013 included) (Envor Oy, 2015). However, biogas digestate or reject water is restricted to the use of freshly eaten vegetables (Envor Oy, 2015). The sales price of liquid nitrogen or ammonium sulfate with about 9% of nitrogen content is 12 €/m^3 or 1.3 €/kg of nitrogen (SITRA, 2014). The digestate is priced based on the phosphorus content and it is estimated at 1.8 €/kg of phosphorus (SITRA, 2014). However, most of the biogas plants in Finland give digestate for free, and biogas plants even pay for the transport expenses (Ojala, 2017). In addition to the most common uses of digestate, Gasum is trying to find ways to create new products of reject water such as ammonium sulfate, biocoal and struvite.

[4] Calculated considering 1 kg NH_4-N/m^3 (nitrogen value similar to reject water from Viikinmäki wastewater treatment plant). Revenue from liquid waste treatment is calculated as 5 €/m^3 (5 €/3 kg N). The investment cost is 243 €/m^3/year. The production cost for sludge is included in the main products or mineral fertilizer (details in Annex 3 and Annex 4).

Table 5. The cost comparison to fertilize 1 ha of arable land in Finland using conventional fertilizers compared to using fertilizers and lime produced with NPHarvest.

	Nitrogen	Phosphorus	Calcium carbonate	Subsidies needed (€/ha)
Fertilizer/lime needed (kg/ha)	150	15	200*	
Cost for industrial ammonium sulfate (€/ha)	221			
Cost for industrial ammonium nitrate (€/ha)	176			
Cost for NPHarvest produced ammonium sulfate (€/ha)	601			380
Cost for NPHarvest produced ammonium nitrate (€/ha)	370			194
Cost for industrial ammonium phosphate €/ha	**	36		
Cost for NPHarvest produced ammonium phosphate (€/ha)	**	83		48
Cost for industrial lime (€/ha)			6	
Cost for lime produced with NPHarvest from LKD (€/ha)			26	20
Cost for lime produced with NPHarvest from calcium hydroxide (€/ha)			35	29

* liming is normally done once in a 3-5 years as 1 tons/ha (Niemi and Väre 2017). **13 kg NH_4-N includs with P.

In nutrient recycling, CAPEX, OPEX, the price of the end products and the price of the liquid waste treatment depend on several factors. Thus, the sustainability of the nutrient recovery technique is difficult to evaluate. For example, Vaneeckhaute et al. (2017) report that the operational cost to recover nutrients from digestate ranges between 4.5 and 8.6 €/m^3. The market value of ammonium sulfate ranges between 90 and 120 €/ton and struvite between 45 and 1393 €/ton (pure struvite contains 6% of nitrogen, 29% of P_2O_5 and 10% of magnesium) (Vaneeckhaute et al., 2017). The cost of sludge treatment by KemiCond is 35-80 €/ton of dry sludge (SITRA, 2014) and 20 €/ton by composting (Plana, 2014).

In Finland, a very small portion of organic waste is disposed to landfills. All waste containing more than 10% of organic matter is prohibited in landfills since 2016 (ministry of environment, 2016). The tax for landfilled waste is 70 €/ton starting from 2016. If a recycling company charges less than 70 €/ton as a gate fee, waste producers are likely to collaborate with them. The majority of biogas plants in Finland are using this disposal price as an income (waste charges and taxes, 2018). Therefore, the use of gate fee as revenue compensate the production cost of recycled fertilizers. For reject water, the disposal cost is

about 25 €/m^3 (transportation cost is 25 €/m^3/100 km) so if nutrient recycling companies can treat reject water for less, biogas companies will be interested in collaborating with them.

5. Conclusion

Mineral fertilizers that contain recycled nitrogen will be competing with conventional mineral fertilizers produced by multinational companies like Yara. Ammonium nitrate has a higher market potential compared to other products considering production costs and stability. Although the NPHarvest technique has not been developed in full-scale yet, calculations show that production costs are currently higher than the market price. In some circumstances, it is possible to generate additional revenue from gate fees or waste treatment fees. These fees will reduce (by compensating) the production cost of recycled mineral fertilizers (see Annex 3).

In general, the value of recycled mineral nutrients is unclear in Finland. Most of the recycled ammonium sulfate is in liquid form which is difficult (need more space) to store for a long time. The value of sediment also depends on its content and quality. Sediment with high calcium carbonate and phosphorus content can be used in agriculture or wastewater treatment plants. However, sediment containing several substances or high amount of suspended solids (SS) might have a lower value. Sediment with higher value can be produced by separating SS and organic matter first for incineration as dried digestate has a high calorific value. After the removal of suspended solids and organic matter, the rest can be treated with lime to produce calcium carbonate and calcium phosphate or phosphorus which is another valuable product. However, sediment quality depends on the treated liquid waste type. For example, sediment from urine might contain less organic matter than reject water.

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Annex 1. Nitrogen and phosphorus in reject water produced in different biogas plants managed by Gasum.

Producer	**tons/year**	**Total N Kg/m^3**	**Soluble N kg/m^3**	**Total P kg/m^3**	**Soluble P kg/m^3**	**Source**
Gasum Vehmaan Biokaasulaitos (Concentrated reject water)	xx		1.6%		0.14	Gasum 2018a
Gasum Perus Plus, Honkajoki		5.7	3.3	0.6	0.1	Gasum 2018b
Gasum Humusvoima, Honkajoki		5	1.6	5	0.05	,, ,,
Biotehtaan Maanparannuslannos, Honkajoki						,, ,,
Gasum Biotehtaan Maanparannuslannos, Honkajoki (Concentrated reject water)	xx	4.2	1.36	3.3	0.08	,, ,,
Kauppanimi Gasum Perus, Honkajoki	xx		3.3		0.07	,, ,,
Gasum Perus, Vampula	xx	6.2	3.2	1.4	0.02	,, ,,
Gasum Humusvoima, Vampula	xx	5.2	1.8	4.2	0.2	,, ,,
VamBion Maanparannuslannos	xx	6.2	1.6	5.1	0.05	,, ,,
Gasum Perus, Kuopio	xx	5.8	2.8	2.6	0.05	,, ,,
Gasum Humusvoima, Kuopio	xx	5.4	1.3	7.2	0.01	,, ,,
Gasum Perus, Oulu	xx	4.6	2.28	1.7	0.06	,, ,,
Gasum Humusvoima, Oulu	xx	7	0.93	7.3	0.03	,, ,,
Gasum Perus, Riihimäki	xx	5.7	2.7	1.2	0.02	,, ,,
Gasum Humusvoima, Riihimäki	xx	6.4	1.5	5.5	0.035	,, ,,
Gasum Humusvoima, Riihimäki	xx	6.4	1.5	5.5	0.035	,, ,,
Gasum Humusvoima, Turku	xx	13	0.9	10	0.08	,, ,,
Gasum Humusvoima, Vehmaa	xx	11	1.9	7	0.1	,, ,,
Total volume	500 000					Gasum, 2018c

Annex 2. Demand, use, source and recycling of nitrogen and phosphorus per year in Finnish agriculture.

Fertilizer		**Mineral**	**Organic**		
	Demand (tons)	Supply/used (tons)	Available (tons)	Supply/recycle (tons)	**Source**
N	261 400*	145000 **	128100***	100000 (from manure)	***Calculated from Järvenpää 2016 * (2 million ha land fertilized with 140kg N/ha), Salo et al 2013. (**Eurostat 2015)
				80.5	sewage sludge
			2957		fur animal manure
			2.66 kg/m^3 soluble N pig slurry	5914	Luostarinen et al., 2017
			1.46 kg of soluble N/m^3 Poultry deep litter		Luostarinen et al., 2017
				4096	12411000 total poultry (all commercial birds for 2016) Statistics Finland1, 2018. 0,33kg/hen/year soluble N for layers (Luostarinen et al., 2017
			500270 (food processing industry)		Helcom report, 2017
P	*33 000	**11 000	**36680	17000 (from manure)	* Niemi and Väre, 2017 **calculated from Kangas et al., 2017 + other available waste in the table.
				2624 (from sewage sludge)	Calculated from Kangas et al., 2017 (41% of 160000 tons/year DW of 4% P)
				3600 (Pig manure)	Luostarinen et al., 2017
			1800 (Fur animal manure)		Luostarinen et al., 2017
				1500 (Poultry manure)	Luostarinen et al., 2017

Annex 3. Economic calculation on the treatment of 1 m^3 of reject water (with 1 g/L of ammonium nitrogen). The investment cost is calculated as 243 €/m^3/year. The mineral fertilizer is assumed to be a pure product and the calcium carbonate and phosphorus are also assumed to contain low concentrations of impurities after pre-treatment.

Cost stream

	H_2SO_4 (kg)	H_3PO_4 (kg)	HNO_3 (kg)	*NH_4-N water	$Ca(OH)_2$ (Kg)	CaO (Kg)	LKD
Acid cost (€) (A)	0.9	2.9	1.5				
Alkali cost $Ca(OH)_2$ (€) (B)	0.6	0.6	0.6	0.6	0.6	0.8	1.6
Total chemical cost (€) (A+B)	1.4	3.5	2.1	0.6	0.6	0.8	1.6
Energy cost to dry only N fertilizer (€/m^3)	1.4	1.4	1.4	1.4			
Energy cost for sludge dewater (€/m^3)					0.7	0.5	4.8
Energy for pumping (€/m^3)	0.04	0.04	0.04	0.04			
H_2SO_4 for effluent neutralization (€/m^3)	0.4	0.4	0.4	0.4			
Investment cost €/m^3	0.2	0.2	0.2	0.2			
Total treatment cost (€/m^3) (C)	3.5	5.5	4.1	2.6	1.3	1.3	6.4

Revenue stream

Produced fertilizers	$(NH_4)_2SO_4$	$(NH_4)_2PO_4$	NH_4NO_3	*NH_4-N water	$CaCO_3$+P	$CaCO_3$+P	$CaCO_3$+P
End product produced from 1m^3 RW (Kg) (D)	4	4	5	3	7.5	5	50
Production cost (€/Kg) (C/D)	0.84	1.33	0.86	0.85	0.17	0.26	0.13
Revenue from Reject water treatment (€/m^3 or about 3 kgN/m3)	5	5	5	5			
Total Production cost (€/Kg)	0.42	0.92	0.45	0.43	0.17	0.26	0.13
Price of mineral fertilizer (€/Kg)	0.31	0.57	0.41		0.06	0.06	0.06

*Ammonia solution

Annex 4 Price of different types of fertilizers.

Technique	**Products**	**Production cost(€/kg)**	**Market Price (€/ton)**	**Market Price (€/kg)**	**reference**
Industrial	$(NH_4)_2SO_4$ (21%N)	NA	305	0.31	Cemagro, 2018
” ”	$(NH_4)_2PO_4$	NA	566	0.57	,, ,,
” ”	NH_4NO_3	NA	414	0.41	,, ,,
NPHarvest	$(NH_4)_2SO_4$	0.8			Details in Annex 3
Nordkalk (industrial)	$CaCO_3$	NA	105-205	0.08	Email from Nordkalk, 2018
Nordkalk (industrial)	CaCO3 (LKD	NA	55	0.06	Email from Nordkalk, 2018
Nutrient recovery (Phosnix)	Struvite	NA	250	0.25	Japan (Ueno and Fujii, 2001)
Nutrient recovery	Struvite	NA	251	0.25	Australia (Münch and Barr ,2001).
AirPrex	Struvite	NA	50-400		Ruotsalainen, 2011
Paques	Struvite	*1.31			The Netherland (Bakker, 2017)
Mining	Rock phosphate	NA	43	0.04	US geological survey, 2005
	Composted soil	NA	27/m^3		Wäänänen, 2010
	Compost	NA	4/m^3		Wäänänen, 2010
Sewage sludge, Finland	Sewage sludge	NA	-40		Huopana et al., 2012
Chemical used by NPHarvest process		NA			
	Sulfuric acid (98%)	NA	290		Rothrock, 2013
	Phosphoric acid (75%)	NA	730		Alibaba.com1
	Nitric acid (68%)	NA	283		Alibaba.com2
Nordkalk	$Ca(OH)_2$	NA	93		Email with Nordkalk, 2018
Nordkalk	CaO	NA	190		Email with Nordkalk, 2018

*operational cost

Reference for Annex

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Few words: -
Nutrients recycling is a very good idea for the sustainable environment and circular economy. Nevertheless, a very small amount of nutrients is recycled in agriculture. There are several constraints on nutrient recycling, for example (1) high transportation cost for bulky material (2) hygiene and heavy metal issues and (3) perception of reusing waste in agriculture. Recently, nutrient recovery and production of mineral fertilizers from waste are receiving more attention. Our NPHarvest technique has successfully produced ammonium sulfate, ammonium phosphate from reject water, bio-washer water from tunnel compost and urine. The next step was to identify the recycled fertilizer market in Finland for manufacturing high demand chemical fertilizers in Finland. This study found that ammonium nitrate has higher demand in Finland compared to other chemical fertilizers, although recycled ammonium sulfate is also used as fertilizer in Finland. This information will be useful for the stakeholders working in the nutrient recycling business.

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