Feasibility Study: Phosphorus Recovery from Household Solid Organic Waste

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ROYAL INSTITUTE OF TECHNOLOGY

Master of Science Thesis

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Abstract

Phosphorus is an essential source with significance use in agriculture. Phosphorus is lost in the human intensified global cycle and it is important to remove phosphorus from water body. However, important and potential sources for phosphorus product which is suitable and effective for fertilizer use may be ignored due to over emphasize on the pollution prevention. This work aims to identify the potential of phosphorus recovery from solid organic waste in Sweden. Based on the result of Material Flow Analysis of phosphorus, solid food waste is identified the main solid waste fractions containing phosphorus substances of phosphorus in Sweden. From the case study and comparison of three alternatives, the possibility of recovery of phosphorus from household solid food waste is analyzed. A SWOT analyst is applied to provide a best solution for phosphorus recovery from food waste. The key drivers, the system boundaries for the phosphorus recovery and collection, storage, transport and use of the phosphorus are also discussed.

Key words: Phosphorus recovery; Solid waste; Food waste

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Abbreviations

USGS: US Geological Survey
FAOSTAT: Food and Agriculture Organization of the United Stations
SEPA: Scottish Environment Protection Agency

1 Introduction

1.1. The significance of phosphorus

Phosphorus is essential resource for all life, including bacteria, plants and animals. Human beings and livestock get phosphorus from crops which in turns mainly come from phosphate fertilizers applied to agricultural soils to ensure high yields in modern human society. Phosphorus has no substitute in food production which depends on a large and continuous supply. This makes long-term availability and accessibility to phosphorus tied up with feeding 9 billion people by 2050 (Cordell et al., 2009). Today, the world's main source of phosphorus is phosphate rock, around 90% of which extracted globally is for food production while the remaining 10% is for industrial applications, for example, detergents (Prud'homme, M., 2010). However, It takes around 10-15 million years to form phosphate rock, which makes it a non-renewable resource. Furthermore, only a small fraction of rock has high-grade utilized phosphorus and among these rocks, much contains prohibitive levels of contaminants (such as cadmium), of which mining is constrained (Cordell, 2010). Report from USGS shows that current reserves at 16,000 million tones of phosphate rock (containing approximately 30% phosphoric acid) and 85% of these reserves are controlled by China, Morocco, the US, South Africa and Jordan control, make Sweden a phosphate importer vulnerable to geopolitical tensions in these countries, and to volatile prices (as demonstrated during the recent 800% spike in the price of phosphate rock in 2008). Import quantity of phosphorus and other nitrogen compounds has reached the peak of 6904 tons in 2005 (FAOSTAT, 2011). Figure1 shows the import quantity in nutrients of phosphate fertilizers in Sweden from 2002 to 2008 (FAOSTAT, 2011). From the figure, the demand of imported phosphate fertilizers in Sweden has been increased to 77,923 (tones of nutrients), almost five times as it was in 2002. Regardless uneven geological distribution of phosphate rock, the rate of production of economically available phosphate reserves will eventually reach a peak around 2034 (Cordell et al., 2009), which is in a similar way to oil and other non-renewable resources with the finite nature. Meanwhile, due to an increasing demand for food from a growing world population, the demand for phosphorus of fertilizers use is expected to increase globally and steadily with an annual growth rate of 2.7% (Heffer and Prud'homme, 2008). Concerning the significance of phosphorus resource, there is a need to look into the human intensified global cycling loop of phosphorus for sustainable governance of phosphorus resource.

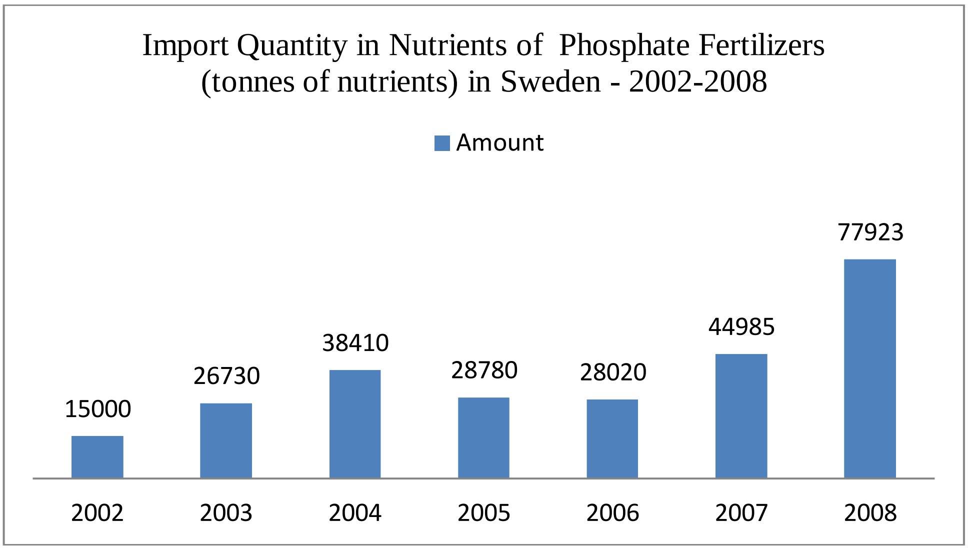

Figure1 Import quantity in nutrients of phosphate fertilizers (P_2O_5 total nutrients) in Sweden (Source: FAOSTAT, 2011)

1.2. The human intensified global cycling of phosphorous

Figure 2 (Liu et al., 2008) shows a simplified schematic of the human intensified global phosphorus flows. The natural cycle contains one inorganic cycle and two organic cycles. The inorganic cycle starts with tectonic uplift and exposure of phosphorus-bearing rocks to the forces of weathering, continued with physical erosion and chemical weathering of rocks forming soils which is gradually leaching to the rivers and sea where sedimentation and sink of insoluble calcium phosphate occur. When the uplift of sediments into the weathering rigime begins, the cycle also along with it starts again (Follmi 1996). The two organic cycles mainly serve as part of the food chain, moving phosphorus through living organisms. The land-based phosphorus cycle transfers phosphorus from soil to plants, to animals, and back to soil again while the water-based one circulates phosphorus among the creatures living in water bodies including rivers, lakes, and seas.

In the societal cycle, Phosphate rock is initially converted to phosphoric acid and further processed to produce fertilizers, food-grade and feed-grade additives, and detergents and other marginal applications include metal surface treatment, corrosion inhibition, flame retardants, water treatment, and ceramic production. Part of the phosphorus mined for fertilizer production enters human body through food chain showed in figure 2 and finally enters into land and water bodies as waste (Cordell et al., 2009). Losses of phosphorus include mining losses, losses due to soil erosion (phosphorus eventually ending up in the oceans sediments), crop losses as well as food losses. Furthermore, when phosphorus-rich materials end up in landfill or in sewage sludge, losses also happened.

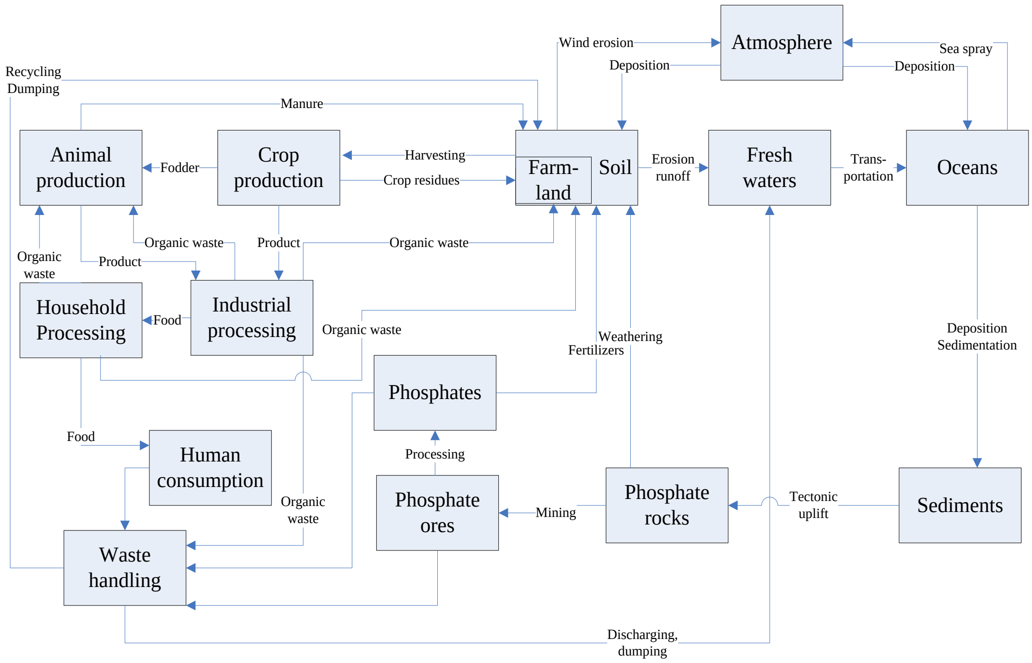

Figure 2 The human-intensified global phosphorus cycles (Source: Liu et al., 2008)

1.3. Sources of phosphorus for recovery and reuse

Phosphorus can be recovered from both mixed wastewater streams, and separate organic waste fractions, including: urine, faeces, greywater, animal manure excreted ex-farm animal carcasses and slaughterhouse waste (bones, blood, hooves etc), food waste, detergents (laundry, dishwashing), other industrial wastes, crop residues generated ex-farm (e.g. by the food processing industries). In addition to these 'used' sources, phosphorus can also be captured from new sources, such as mineral phosphate, algae, seaweed, aquatic sediments and even seawater (Cordell et al., 2011). The total amount of available phosphorus (in thousands of tones of P per year) in each source will vary from country to country depending on a number of factors. Table 1 shows concentrations of phosphorus and recovery approaches from different sources. High concentration of phosphorus in organic fractions is crucial, which is linked with total phosphorus available for recovery from a source and the viability of phosphorus recovery, storage and transport.

Table1 the concentrations of phosphorus and recovery approach from different sources (Source: Cordell et al., 2011)

Phosphorus sources	P (% P by weight)	Phosphorus recovery and reuse process
Human urine	0.02-0.07	Storage and direct use
Human Faces	0.52	Composted/dry faeces
Human excreta	0.35	Incinerating toilet (EPA, 1999)
Activated sewage sludge	1.4	Recovery from wastewater treatment plant
Sludge(from bigas digester)	0.48-0.77	Composted
Struvite	13-14	
Cow dung	0.04	Directly application
Poultry manure	1.27	Directly application
Farm Yard Manure(FYM)	0.07-0.88	Directly application
Rural organic matter	0.09	
Vermi compost	0.65	
Crop residues	0.04-0.33	Ploughed into field; ashes from burning
Urban composted material	0.44	
Oil cake	0.39-1.27	
Meatmeal	1.09	Composted
Bonemeal	8.73-10.91	Composted

1.4. The significance of seeking potential source for phosphorus recovery

Animal manure as well as human excreta and urine is widely used as a natural source of phosphorus fertilizer in most regions of the world, especially in parts of Asia (Matsui, S., 1997). In Sweden, animal manure occupied more than 50% of the total phosphorus fertilizer in 2011 (European Commission, 2011). However, unlike those developing countries, all human excreta and urine enters into sewage water through city down-flow pipe. Driven by the concerning of eutrophication problems caused by phosphorus entering waterways (Driver, 1998), recovering phosphorus in wastewater sludge and related numerous phosphorus recovery technologies and processes (Rittmann and Carty, 2001) are the main research directions. On the other hand, application of sludge in agriculture is still a considering source due to concerns of contamination especially the risk of heavy metals (Driver, 1998). According to SEPA (2002), only 21% of the sewerage sludge was reused in agriculture in 2000. Considering the main use of phosphorus is in fertilizer production, the quality of the recovered phosphorus and its effectiveness as a fertilizer would be the first concern. This means some important and potential sources for phosphorus product which is suitable and effective for fertilizer use may be ignored due to over emphasize on the pollution prevention. In other words, there is a need to look into other points rather than to focus on the “end-of-pipe” in the cycling of phosphorus system.

1.5. Phosphorus recovery from solid waste

As societal use of phosphorus is mainly for food production, substantial flows of phosphorus occur both upstream and downstream of the field. Though distributions vary significantly by country or region (Schröder et al., 2010), global-scale of phosphorus loss trend in all processes of food production has been identified by scientists (Liu et al., 2008; Cordell et al., 2009; Schröder et al., 2010). Based on Cordell's analysis (2009), approximately 3 Mt/a of P is consumed in the food eaten by the global population, which is only one-fifth of those mined in phosphate rock specifically for food production. On the other hand, in 2011, a total of 4,349,910 tonnes of household waste was generated in Sweden. Only 14.9% of the household waste went to biological treatment while 51.4% of it was treated by incineration (Avfall Sverige, 2012). The large quantity of waste not only indicates the effort needs to put into the solid waste management system but also shows the potential of phosphorus recovery quantitively.

Driven by huge loss of phosphorus in food production and solid waste management in Sweden, identifying the potential source for phosphorus recovery from the solid waste streams is critical and essential.

1.6. Aims and Objectives

This work aims to identify the potential of phosphorus recovery from solid waste in Sweden. More specifically, objectives to realize this aim are:

- Identify the state of research of phosphorus recovery from solid waste
- Identify the main solid waste fractions containing phosphorus substances of phosphorus in Sweden.
- Analyze the possibility of recovery of phosphorus from potential sources.
- Suggest a method for recovery of phosphorus from solid waste and analysis the feasibility.

2. Methodology and Scope

The main research method of this study was literature review and study visit. The literature source includes peer reviewed papers and reports from authoritative data sources, published books, investigation report of the statistics authority and government. Documents and records were taken from organizations working on the related subjects. The first hand data was collected through the study visit to Svenskt Fågelkött AB. Interviews carried out at Fågelkött AB plants along with a field visit enabled insight into plant operations and waste planning. A face-to-face interview was carried out by the aid of questionnaires. Email contact with the company was also used to discuss about some details of the working process of the company.

The criteria used for preparing this thesis could be summarized as below. The main rationale behind this study is looking for practical and implementable data both from others work in the research field and relate companies. Therefore, the accuracy of some data used in this study is reliant on the figures given in the literature. The need for more factual and measured data can be fulfilled when actual working plan carried out based on the study result. The details for all purposes in this study have been maintained only to the practical use and purpose of this study. Further work need to be done in order to use the study result as project appraisal.

Methodology used for material flow analysis

Material flow analysis (MFA) is an analytical method of quantifying flows and stocks of materials or substances in a well-defined system. In this study, MFA is used to identify the main solid waste fractions containing phosphorus substances of phosphorus in Sweden. As phosphorus is a reactive element and tends to diffuse into the environment, it is difficult to achieve accurate material-flow accounting. To simplify matters, this paper evaluated the total phosphorus flow by considering seven systems. The inputs and outputs for each sector were estimated and were taken into account the total mass balance. The method will be described in more detail in chapter 3.

Methodology used for scenarios

In Sweden, biological treatment and incineration are most important treatments for household organic waste including food waste. Biological treatment is implemented through anaerobic digestion or composting. Anaerobic digestion produces biogas and phosphorus-contained-digestate is an excellent nutrient for the soil. Composting produces long-lasting phosphorus fertilizer which contained various kinds of nutrients used as soil improver in gardens and parks. Incineration is an effective method for producing energy including heat and electricity from waste. With proper technology, phosphorus can be also possible recovered from the incineration ash.

In order to analysis the possibility of recovery of phosphorus from potential sources, three different scenarios based on the different treatment methods including incineration, composting and anaerobic treatment were created to identify the best treatment plan for the phosphorus recovery. Also, the alternatives are established under the framework for Swedish waste management. Related target proposed by Swedish Environmental Objectives is:" By 2015, at least 40 percent of food waste from households, caterers, retail premises and restaurants will be biologically treated to provide fertilizer and energy". (Avfall Sverige, 2011)

Recovery rate of phosphorus is directly linked with the quantity of phosphorus from different treatment. While whether the final product from different treatment methods can be used on agriculture land is determined by P-content in the final product and its substitution to chemical fertilizer. Thus, the study takes into recovery rate of phosphorus, P-content in the final product and substitution to the chemical fertilizer of final product into consideration during evaluation. The method will be described in more detail in chapter 5.

2.1. System boundary

For the review of phosphorus loss and different phosphorus sources, this report takes the whole world's situation into consideration in order to obtain an overall understanding about phosphorus loss. When suggesting the new potential source in the scenario cases, this report just considers the Swedish circumstance. So results just adapt to Swedish situation. If apply the results into other country, further research should be done.

2.2. The progress of the report

This paper provides a three-step work to study the feasibility of phosphorus recovery from household solid food waste rather than focusing on a specific technology or process. Firstly, MFA is used to identify the main solid waste fractions containing phosphorus substances of phosphorus in Sweden. Secondly, the case study which introduced an industrial model is implemented to check the possibility to use the potential source identified by MFA for phosphorus recovery. Thirdly, three scenarios are made to identify if the industrial model can be used for phosphorus recovery from household solid food waste.

3. MFA of phosphorus in food production

The research system includes seven different processes that include the production of food (soil, animal and crop production), the processing of food (household and industrial processing) and human consumption and waste handling. There are many flow streams included in this system, but only the main flows, for example, the flow of fodder, fertilizer, manure and food products, are shown in the figure 3. The research aims and objectives are reflected from the system and the system border includes the processes related to the consumption and production of food. Extraction of fertilizer from phosphates and the fate of phosphorus in both inland and coastal water bodies are beyond the system border. In order to compare Swedish situation with global situation, the food products consumed are assumed to be produced and processed in the region. Thus, food imported from outer systems is not included. The surplus flow refers the remaining phosphorus not exported as animal product to the consumer or reused as manure fertilizer in agriculture and phosphorus in bone and slaughter waste or dead animals.
In this study, the phosphorus entering into the soil as the form of fertilizer is defined as 100% P. Because of phosphorus recycling of internal system and land released phosphorus, total out flow might exceed 100%. “%P” is based on the quantity of the P.

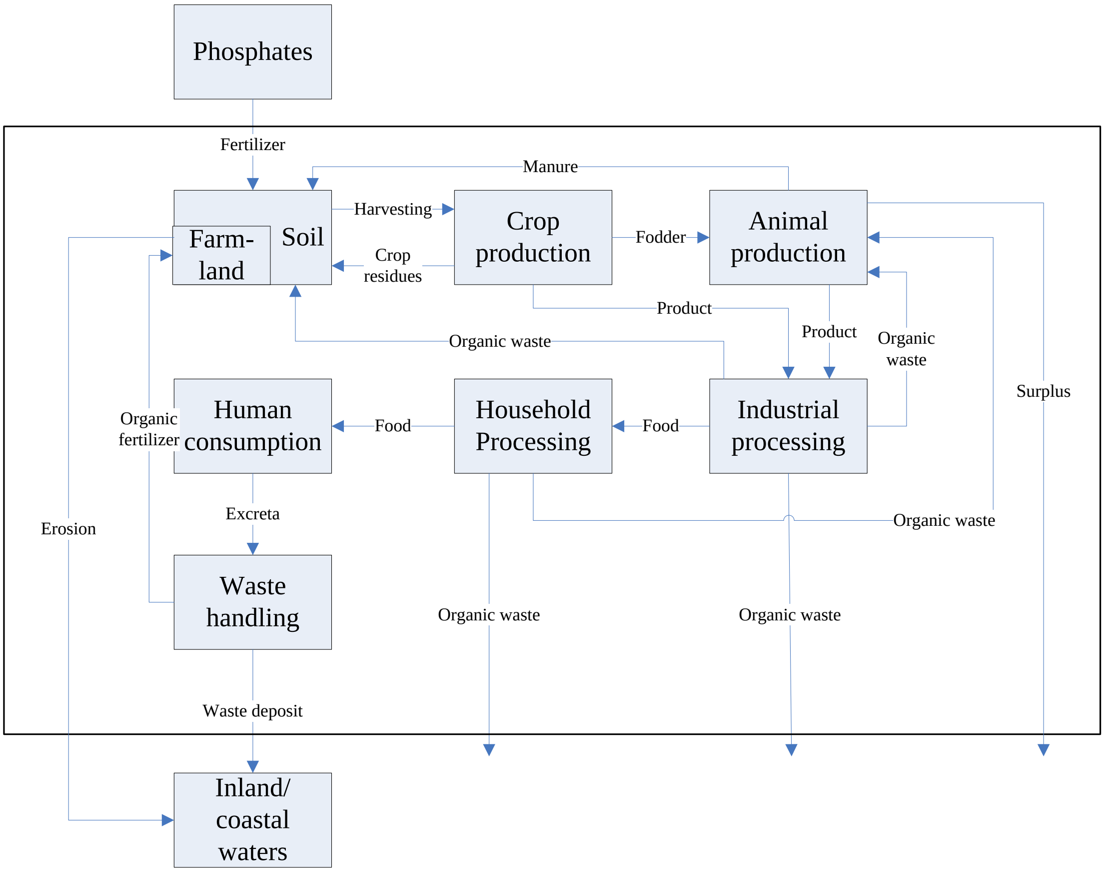

Figure 3 the system for the food production and consumption (developed from Tina-Simone Schmid Neset et.al., 2000)

3.1. Global situation

Figure 4 summarizes key findings based on Cordell et al. (2009). It indicated that the two largest flows of lost P are soil erosion and runoff (57% of mined P) and surplus (50%). The P flow from erosion and runoff usually are identified as a ''non-point source,'' for example, agricultural drainage ditches or surface storm-water flow, which are not easily captured before they reach a natural stream or river. Much of the P in runoff is associated with particulate matter that can settle out in wetlands, rivers, reservoirs, and lakes. Therefore, quickly capturing P from water flows with large quantity and low P concentration is a big challenge to today's technology. While The P flows in manure is quite the opposite which has a small flow rate and a high concentration. Similarly, to collect small streams of animal waste is not practical either from the global aspect.

The P discharged into human sewage treatment system and finally lost in the water body and sludge is 19% combined. In Figure 4, the flow of lost P from the processing of food is about 9%. The distribution of the lost P in the household processing and industrial processing has not been identified clearly.

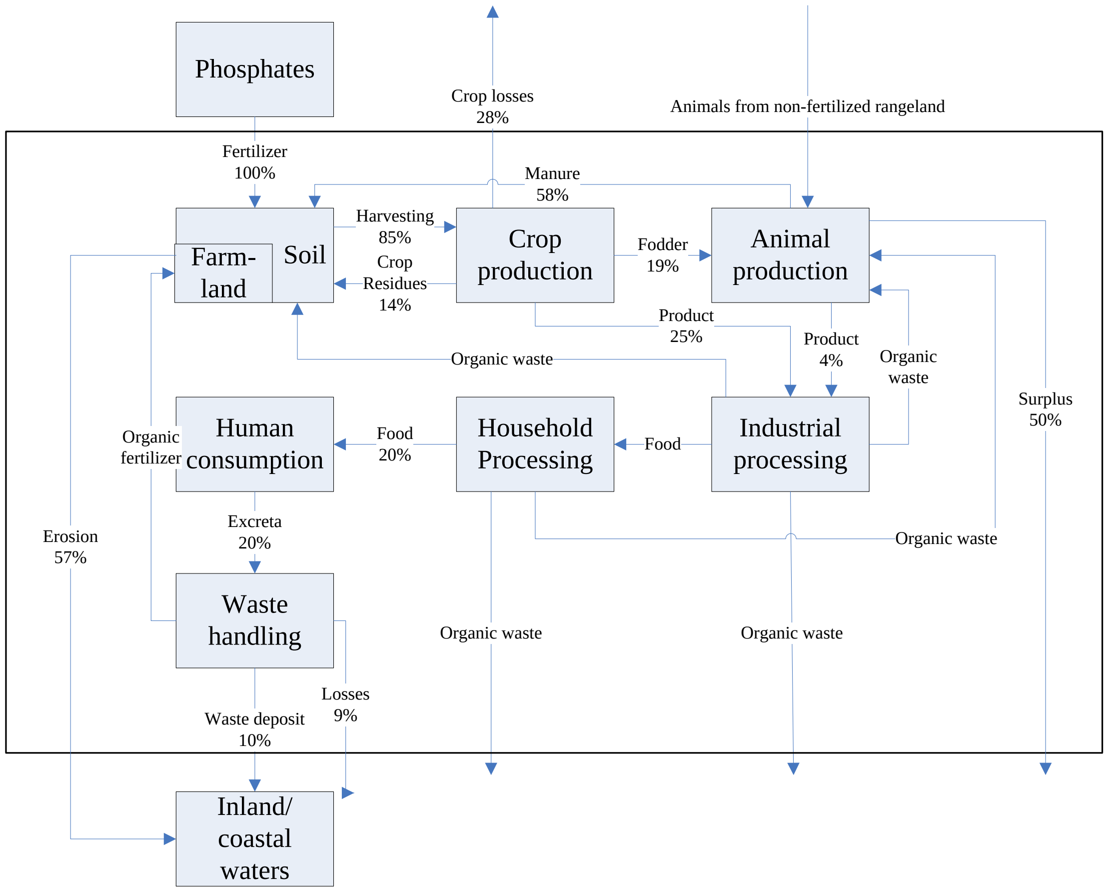

Figure 4 global P flow (Source: Cordell et al., 2009)

This global phosphorus flow picture gave a general picture of how and how much phosphorus flew and lost in every section of food production, processing and consumption. Since the number would be different according the food production and consumption in every country, there is a need to narrow the space scales to identify every streams in the research system. In order to answer how the phosphorus flows, which are the main flows, and how changes in consumption, agricultural production and waste handling influence the flow of this resource, more specific data was needed. In this paper, the study result of the flow of phosphorus in food production and consumption in Linköping (Tina-Simone Schmid Neset et.al., 2000) has been adopted.

3.2. A Linköping case

Figure 5 shows the flow of phosphorus for the food consumption and production of Linköping (Tina-Simone Schmid Neset et.al., 2000), which is situated in southern middle Sweden. Once a centre of old culture region, it has today risen to be the fifth largest city in the country and is known for known for its university and its high-technology industry. The number of inhabitants is 104,232 in 2010 (Linköping Kommun, 2011).

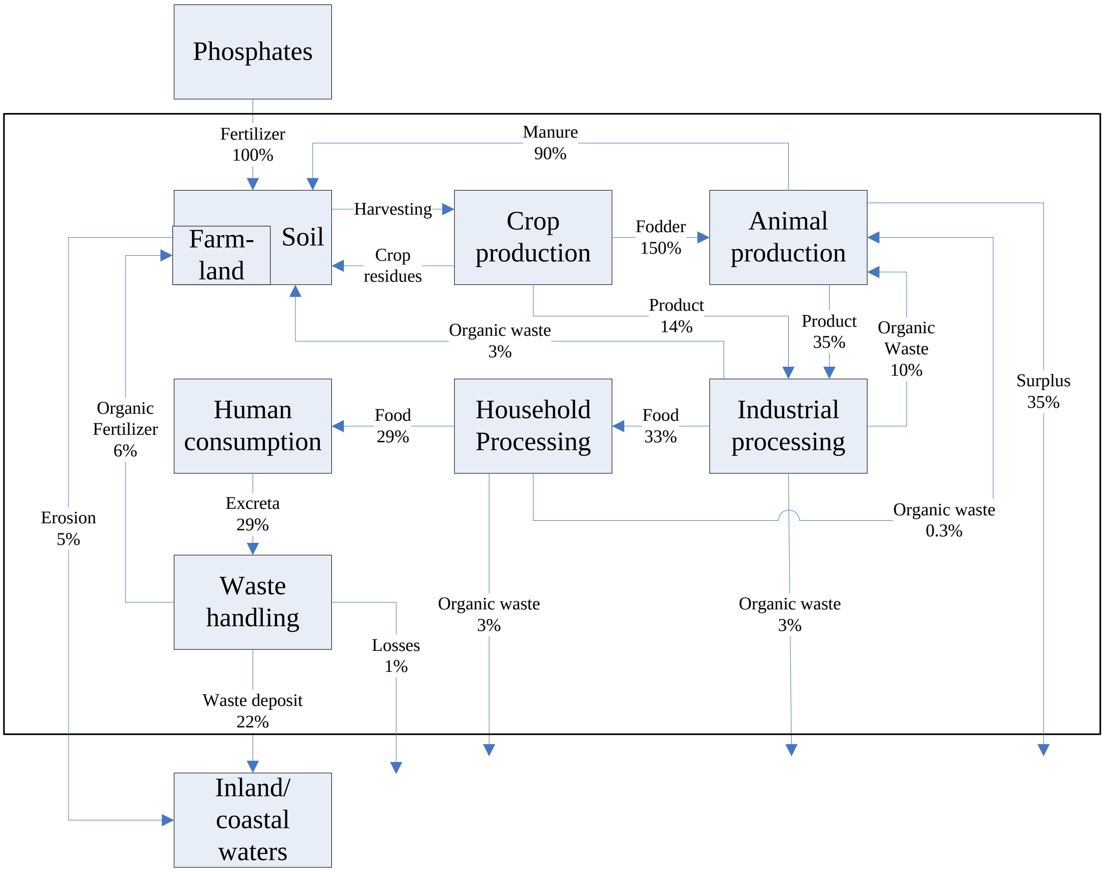

Figure 5 Linköping P flow (developed from Tina-Simone Schmid Neset et.al., 2000)

Compared to the global P flows through the food production and consumption system, the lost P from the whole system is smaller, which is 42%. The surplus is still the largest stream of lost P (35%) while lost of P due to erosion is considerable smaller, which is only 5%. Crop loss is insignificant compared to other flows and not showed in the figure. The deposit P from human excreta is 22%. Loss of P from organic waste from both household processing and industrial processing is clear and significant (3%, respectively). Organic waste from industrial processing reused for agriculture and animal production is 3% and 10% respectivelywhile only 0.3% of food waste from household processing has been reused for animal production. Compared to the global P flow, manure used for agriculture in Linköping has increased to 90%, which shows a relatively high P recovery ratio in this area. Generally, the biggest difference of P flow between global situation and Linköping case occurs in the food production process. In order to identify the phosphorus recovery situation in whole Sweden, specific data about input and output of phosphorus for agriculture land of whole Sweden is needed.

3.3. Input and Output of phosphorus for agriculture land in Sweden

Figure 6 shows the input and output of phosphorus for agriculture in 2009 in Sweden (statistiska centralbyrån, 2011). It can be concluded that the major input of phosphorus stream is manure (25,080 tones) instead of chemical fertilizer (9,060 tones), which shows the reuse ratio of the manure in the research system is already very high in the whole Sweden in 2009. Loss of phosphorus due to erosion is considerable small, only 2% of the total input. This makes manure and runoff in the agriculture field not ideal sources for capturing the lost P in Sweden.

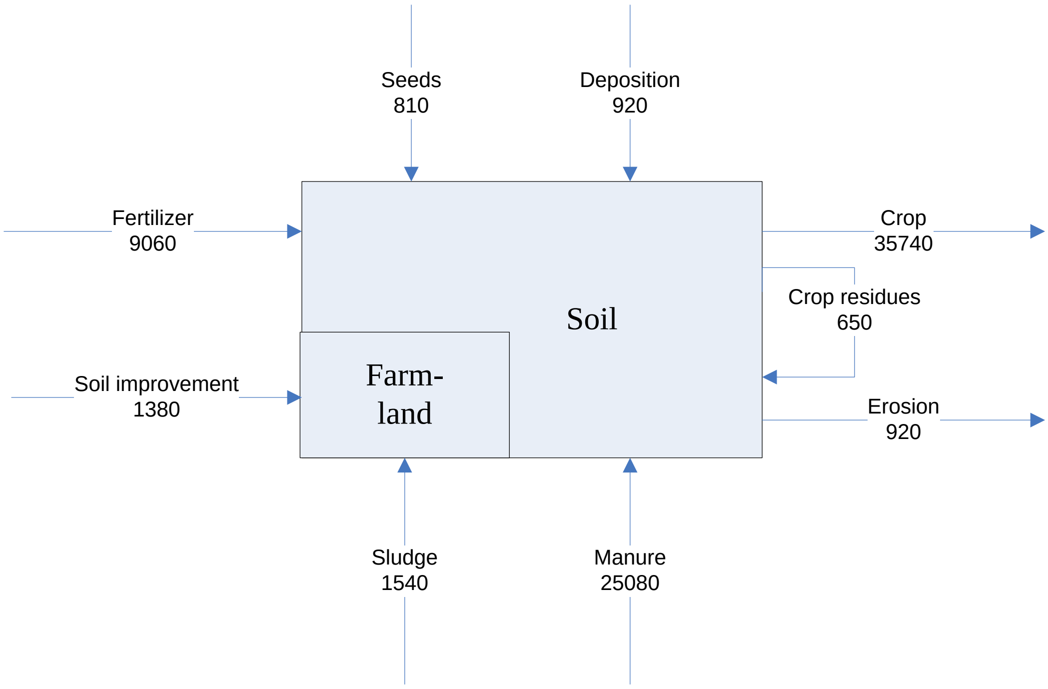

Figure 6 Input and output of phosphorus for agricultural land by source in 2009. Tones (source: statistiska centralbyrån, 2011)

Look back into the system for the food production and consumption (figure 5): phosphorus recovery from organic food waste from the industrial food processing has already been used for agriculture. While the P loss from household food processing has not been recovered yet, this part of P loss might be a potential source in Sweden. To check the possibility of P recovery from this source, this study looked into the industrial model with specific data about how and how much phosphorus can be recovered for organic food waste.

4. Case studies

Svenskt Fågelkött AB is a small meat processing company and their major products are hen and chicken, lamb and sheep that are cut into specified pieces and as whole piece. As the organic waste from the company are mixture of mostly intestine and bones, the phosphorus concentration in the mixture waste can be assumed as 5% according to the findings in literature (Cordell et al., 2009; Bernstad, 2011). The company sold the animal waste to the biogas company named Falkenbergs Biogas AB. Mixed with food waste from the community, manure, energy crops and miscellaneous, biogas was produced from the waste during anaerobic digestion. The sludge is by-product of anaerobic digestion and used as biofertilizer to be applied into agriculture land again (Falkenbergs Biogas AB, 2011).

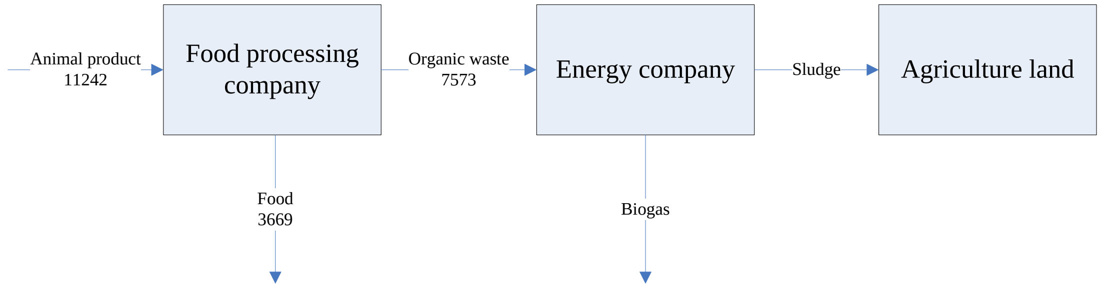

Figure 7 Waste flow in tonnes from the food processing company to the energy company. (Svenskt Fågelkött AB, 2011)

4.1. Phosphorus from the sludge of the biogas company

Svenskt Fågelkött AB sold 7,573 tons animal waste to the biogas company in the year 2010 (Figure7). The phosphorus content of the sludge will vary with what is digested. However, in practical, the company does not separate the sources, which means sources such as manure, residues from the food, energy crops and other wastes are mixed together. The raw material required for the production of biogas is based on 90,000 tonnes of manure, 10,000 tons of residues from the food, 10,000 tons of energy crops and 10,000 tons of other per year. The digestate after digesting is around 40%-60% of the raw material and the calculated average of the phosphorus in the digestate is 1 kg per ton (Falkenbergs Biogas AB, 2011). It means the animal waste from Svenskt Fågelkött AB contributed to around 3,029 kg-4,544 kg phosphorus actually recycled in the year 2010. From these figures, it can be concluded that there is great potential to recovery phosphorus from organic food waste

Though the potential of organic food waste for P recovery has been approved in this case study, the composition of household organic food waste is different from industrial food waste. Whether this treatment method can be also applied to household organic food waste for P recovery needs further study through comparison of different scenario treatment methods in chapter 5.

5. Scenarios for the phosphorus recovery from food waste

In this chapter, in order to figure out whether the above industrial model for the phosphorus recovery from the organic food waste applied to the household organic waste, three treatment alternatives for household organic waste including centralized anaerobic treatment (industrial model), decentralized composting and incineration are compared.

5.1. Study area and background information

The comparison between different treatment methods for the foods waste is based on the statistical result of Swedish waste management. The quantity of treated household waste was 4,363,880 tons in 2010 in Sweden (Avfall Sverige, 2011). There was 587,170 tons of household waste biologically recycled through anaerobic digestion or composting, accounting for 13.5% of the total quantity of treated household waste and 47.7% of total biologic treatment waste. Digestate can be applied to the agriculture land is 582,750 tons. It is showed in a survey carried out by Avfall Sverige – Swedish Waste Management (Avfall Sverige, 2011) that 163 municipalities collect source-separated food waste. About 20 of them only collect food waste from restaurants and large-scale kitchens, while the remaining municipalities have systems for households as well. According to the survey, an additional 70 municipalities are planning to introduce systems for source-separation of food waste. According to Avfall Sverige – Swedish Waste Management's calculations, 214,230 tons of food waste (an estimated 24% of total food waste) was biologically treated in 2010. This means if all the cities in Sweden introduced the systems for source-separation of food waste, 892,625 tons food waste in 2010 would be treated through biological treatment. Accordingly, the digestate can be used for agriculture as fertilizer would incease greatly. (Avfall Sverige, 2011)

Table 2 the Waste treated biologically in 2010 in Sweden (Avfall Sverige, 2011)

Item	Tons
Total waste treated through anaerobic digestion	661,620
Total waste treated through composting	566,210
Total food waste treated biologically	214,230
Total quantity of household waste treated biologically	587,170
Digestate	582,750

5.2. Description of scenarios

According to Avfall Sverige (2011), around 892,625 tons household food waste produced in 2010, which is assumed the amount of organic waste source-separating considering incineration, composting and anaerobic digestion are used in the whole Sweden in different cities in the scenarios. The waste characterization method used in this study was assumed same between vegetable and animal food waste and the division between the two was assumed 24:76 (Petersen and Domela, 2003).

Table 3 shows the P-content in the waste in the Southern Sweden. Since the food structure varies little in the whole Sweden (Petersen and Domela, 2003), the waste fraction of the scenarios in this study were based on the results showed in Table 3. The P capacity in the food waste would be around 1,200 tons.

Table 3 Waste composition and P-content of the waste (Source: Bernstad, 2011)

Type of waste	% of source-separated waste	DS(%)	P-content (% of DS)
Vegetable food waste	64.6	23.0	0.23
Animal food waste	20.4	42.9	0.996
Other organic waste	12.8	51.8	0.198
Plastic	0.8	85.9	0.02
Paper/cardboard	0.8	77.7	0.013
Combustables	0.3	90.5	0.015
Mixed metals	0.1	91.7	0.025
Inert	0.2	92.7	0.012

Scenario A: Food waste and other organic waste are not separated and are incinerated together with residual waste in a waste incineration plant.

In this scenario, food waste is disposed together with residual household waste, collected and transported to an incineration plant. The methods used to extract phosphorus from ashes include electro-kinetic, thermo-chemical, bioleaching and accumulation, and wet chemical methods (Kalmykova and Karlfeldt Fedje., 2013). The achieved P recovery can vary from 1%-70%.

Since the final quantity of phosphorus recovered would be decided by the extraction technology (Kalmykova and Karlfeldt Fedje, 2013), this study adopt theoretical value of phosphorus can be recovery from this treatment based on the wet chemical method from the research result (Kalmykova and Karlfeldt Fedje, 2013), which have higher efficiency and shorter processing time required compared to other method. The final product of this scenario is incineration fly ash with acidic leaching and precipitation. The chemical form of P in this final product is $Ca_3\ (PO4)_2$. In the study, the ash sample was collected from a mass burn combustor for incineration of municipal and industrial solid waste in Sweden. The P-content in the fly ash is 5.9 kg (ton^{-1} fly ash) and 70% of the P content of the ash can be recovered. The detailed technology and cost is not into consideration. According to the Swedish Waste Management Report carried out by Avfall Sverige (2011), 239,050 tons fly ash generated by incinerating 5,100,370 tons of waste in 2010. Ignored the co-effect of incineration of different wastes, 892,625 tons food waste contributes to 41,836 tons fly ash.

Scenario B: Food waste together with other organic waste is source-separated by households and treated in decentralized compost reactors on the level of residential area.

In this scenario, food waste is source-separated, collected and transported to the compost site. Composts are assumed emptied twice a year. Soil produced is collected and transported to a storage factory, and finally packed in 50 kg-bag. Phosphorus exists in both organic (Po) and inorganic (Pi) forms. Data regarding phosphorus content is based on a site-specific value (Grahamn, 2003). Weight reduction is 50% and the dry substance after composting is around 57%. P-content in the compost is 3.2 kg ton^{-1} DS.

Scenario C: Food waste is source-separated in paper bags by households.

In this scenario, food waste is source-separeted, collected and transported to a biogas company. The organic fraction is assumed to be treated under mesophilic conditions. Phosphorus exists in both organic (Po) and inorganic (Pi) forms. The fraction is assumed to be co-digested with other waste, such as manure, energy crops and residues from production industry. Co-digestion of these organic wastes can result in higher or lower phosphorus content in the digestate. However, except the lost due to rejected food, there is no loss of P during the treatment. Theoretical recovered P in this scenario, which is calculated according the P content in the food waste before treatment (see appendix) is not affected by the co-digestion. Data regarding rejected food waste, P-content in the digestate and P-content in the final product are collected from the actual biogas plant. Based on the figures from Falkenbergs Biogas AB (2011), the reject is assumed to be 18wt% due to incorrectly waste sorting by residents. P-content in the digestate and DS are 1kg (ton^{-1} digestate) and 25 kg (ton^{-1}DS) respectively. Since there is no loss of macronutrients in the treatment chain, 892625 tons food waste contributes to 981 tons P.

Table 4 P-content in the residues after three treatments

Scenarios	Item	P-content of source	Theoretical recovered P	P-content of final product	Reference
A	41,836 tons fly ash	5.9 kg ton^{-1} fly ash	172 tons	30 kg ton^{-1}DS	Kalmykova and Karlfeldt Fedje, 2013
B	254,398 DS	3.2 kg ton^{-1} DS	814 tons	3.2 kg ton^{-1}DS	Graham,2003
C	-	1 kg ton^{-1} digestate	981 tons	25 kg ton^{-1}DS	Falkenbergs Biogas AB,2011

5.3. Comparison of the three scenarios

Table 4 shows the available P-content in the residues after treatment under the three scenarios. P recovered efficiency and application of final product are analyzed as below.

5.3.1 Scenario A: P recovered from incineration fly ash

Based on the 70% P recovery efficiency obtained in this scenario, theoretical recovered P from incineration fly ash is 172 tons, which accounts only 14.3% of the total P in the food waste and other organic waste. Apart from efficiency of extraction method, P lost in the incineration process and buried in the bottom ash would also contribute to the low recovery rate. P loss varies from 28%-47% during incineration process, which is affected by different incineration temperature. (Zhang et.al, 2000)

In this scenario, the P accounts for 3w % (dry weight) of the final phosphorus product from incineration fly ash with acidic leaching and precipitation (Kalmykova and Karlfeldt Fedje, 2013), which content is around 5 times compared to the fly ash. When compared to commercial NPK mineral fertilizer which contains about 2.7% P, the obtained P product contains similar P. However, the high content of trace element in the final product prevents its application to agricultural land. Trace elements including Cd, Cr, Cu and Pb exceed the Swedish limits for metal load through sludge application. (Kalmykova and Karlfeldt Fedje, 2013) In order to avoid any contamination of agricultural land with trace metals, the final P product cannot be used as first P source and applied directly.

5.3.2 Scenario B: P recovered from compost

Scenario B is the treatment where phosphorus can be recovered most in the form of compost which contains 814 tons P and the recovery rate is as high as 68%. Compost can be used to replace peat and commercial NPK mineral fertilizer directly. Studies of the availability of N, P and K in compost show that percent of uptake of P amongst plants fertilized with compost compared to uptake in plants where mineral fertilizers were used is 100% while substitution ratio of N vary from 30%-50% (Dalemo et al., 1998; Patyk and Reinhardt, 1997). A simplified model for replacement of chemical fertilizers has been carried out by Bernstad and Jansen (2011). In the model, 81% of N has been lost in the treatment chain due to emissions of NH_3 during the aerobic degradation process. The loss of N decreases the possibility to substitute commercial NPK fertilizer on farmland.
The P accounts for only 0.3w% of the compost, which is far lower than P in the low-grade phosphate ores (2.2-2.4wt% P). It is not preferable for the P product to be used as a secondary source and substitute virgin phosphate ore in the conventional mineral fertilizer production.

5.3.3 Scenario C: P recovered from digestate

Due to rejection of food waste and other organic waste (18wt% of incoming waste and 50% DS in rejected material) in the pre-treatment in Scenario C (Falkenbergs Biogas AB, 2011), the recovery rate is 82%. The digestate contains 2.5% P, which is in the same level as commercial NPK mineral fertilizer. The digestate can be applied to substitute the NPK fertilizer directly. Many studies have examined the availability of N, P and K in digestate compared to use of commercial NPK mineral fertilizer. (Bernstad and Jansen, 2011; Möller et al., 2009; Krogstad et al., 2004) According to Haraldsen et al. (2010), when applied at equal amount, digestate gave the same yield of spring as NPK chemical fertilizer. Meanwhile, in the case of P, the uptake of P from digestate was also same as from NPK. (Möller et al., 2009; Krogstad et al., 2004)

5.3.4 Summary

Same criteria factors including P-content of final product, the recovery rate of P, and substitution ratio of nutrients to chemical fertilizer in this study are needed to compare the three scenarios. The number of "+" is used to show the level of favored of the scenarios in this study. (Table 5)

Table 5 the comparison of Scenario A, B and C

Criteria	Scenario A	Scenario B	Scenario C
P-content of final product (in %)	+++	+	+++
Recovery rate of P	+	++	+++
Substitution possibility of nutrients to chemical fertilizer	+	++	+++

Due to the extraction method, the P-content would be a reference figure for further study and research in Sweden. Scenario A enabled the phosphorus in the food waste concentrated in the incineration sludge. It is the same as wastewater treatment sludge, application of incineration sludge in agriculture is still a considering source due to concerns of contamination especially the risk of heavy metals. However, unlike numerous phosphorus recovery technologies and processes for wastewater sludge, research for incineration sludge is still on the beginning. From the both perspectives of phosphorus recovery technology and present waste management goals in Sweden (Avfall Sverige, 2011), Scenario A is not an idea option for phosphorus recovery. Within the development of technology and driven force of energy, Scenario A may be supported by some incineration companies. However the details of such a scenario in the future time are outside the ambit of this study and need in-depth study to visualize the actual outcome of this approach.

Scenario B is the treatment where phosphorus can be recovered in the form of compost and compost can be applied as garden soil. However, this scenario takes the period of two years without any energy recovery. The stakeholders will need to take a back seat in planning and will have to critically identify returns under this scenario. Since compared to 2009, composting is declining due to the interests of branches and large twigs turning to incineration instead of to composting (Avfall Sverige, 2011).

Scenarios C is most favored in this thesis as part of implementation strategy (Table 5). Phosphorus can be recovered most in this scenario (981 ton) and P content in the digestate and the availability of P to crops are on the same level as commercial NPK mineral fertilizer. This scenario is also in line with the waste treatment situation and development trend in Sweden (Avfall Sverige, 2011). The biogas companies are willing to work with government to get more sources for biogas products under this scenario (Falkenbergs Biogas AB, 2011). The Swedish government policy on targeting environment objective" By 2015, at least 40 percent of food waste from households, caterers, retail premises and restaurants will be biologically treated to provide fertilizer and energy" finds a scenario can be implemented in some typical cities (Avfall Sverige, 2011). The cost effectiveness could be ideally tabulated if more concrete actual parameters are given which remain out of the scope of this study.

6. SWOT of phosphorus recovery from food waste under Scenario C

Based on the analysis in Chapter 5, solid food waste is identified a potential source for phosphorus recovery and reuse and this source has already applied (though not aimed at phosphorus recovery and reuse) in some area in Sweden. However, many barriers need to be crossed to make phosphorus recovery and reuse as mainstream practice due to the gaps between science and policy, policy, economic, society and technology. For example, a quality based phosphorus recovery technology may be energy consuming; new recovery technology may not be accepted by small company due to high cost. To address such conflicts, a system thinking of the approach is needed to achieve the ambition goals of phosphorus recovery in this study. This SWOT analysis under Scenario C is from the government perspective and the objective of the SWOT is providing a best solution for phosphorus recovery from food waste.

STRENGTHS: • Source-separating of the food waste is needed and acceptable in Sweden •phosphorus recovery is definitely needed at national level • phosphorus recovery from food waste is an obvious recovery solution with a lifelong policy base	OPPORTUNITIES: • Gives another dimension to facilities that produce digestate •Business opportunities for biogas companies • Research inputs can be an add on for a futuristic setup • Bioenergy setup for the commune • Good fertilizer product for farmers • Better image for inhabitant
WEAKNESS: • Existing source-separating system is driven by waste management instead of recovery of phosphorus • It relies on government support for setup • Depending on inhabitant interests	THREATS: • Long term to realize source-separating of the food in whole Sweden • Risk of waste rejection by the biogas companies due to misclassification by inhabitant. • Risk of changing stakeholders' interests in phosphorus recovery

STRENGTHS:

From the survey carried out by Avfall Sverige (2011), source-separating of food waste has been implemented by several cities and are welcomed by most of other cities. In 2010, Total food waste treated biologically is 214,230 tons (Avfall Sverige, 2011), which accounts only 24% of total food waste. Under Scenario C, all food waste will be treated biologically and the quantity of digestate will increase a lot. From figure 6, we can see that soil improvement which is made of digestate is important and used in agriculture, which can partly decrease the use of chemical fertilizer. It also served as an energy solution for Sweden which has a history of green energy practices. Food waste is separated by family and collected by biogas companies can prevent the odor from the mixture waste in the collect points, which has manifold environmental benefit. Food waste treated by biological measures can decrease the sludge which generated from incineration and minimize the waste treated by landfill.

WEAKNESSES:

Though many cities in Sweden have introduced source-separating system for food waste and they are treated through biological treatment, from which biogas is produced and the digestate is used on farmland to replace commercial fertilizers. Collecting and reusing household organic waste actually is driven by the need of waste management or Swedish Environmental Objectives (Avfall Sverige, 2011). Reuse the digestate in the agriculture to recover phosphorus is a secondary driver. This means separating organic waste is mainly for the biogas production, the digestate product which contains phosphorus is “by-product” in Sweden at present. If the fertilizer value of phosphorus in digestate used as the primary driver, the quality of the recovered phosphorus and its effectiveness as replacement of commercial fertilizers will be turned to the key. The existing model for collecting the waste and biogas production might go though series of revolution because of change of the driver. Relevant research and technology should also focus more on the phosphorus recovery other than biogas production. The government may spend a lot of effort discussing and comparing cost and benefit. People will be tired of discussions/ planning and ignore the big benefit of phosphorus recovery.

OPPORTUNITIES:

According Falkenbergs Biogas AB (2011), the major source for biogas produce is manure. Increasing food waste source may give another dimension to those biogas companies that produce digestate. Since composting treatment is declining due to the energy recovery concern (Avfall Sverige, 2011), source-separating of food waste could transfer some portion of waste to anaerobic treatment. If businesses with varied competencies can identify themselves in this movement with a larger goal of bioenergy production and phosphorus recovery, it can provide jobs and even evolve to a model setup. Research into phosphorus recovery systems is advancing at a fast pace in Sweden. Though the system boundary has been drawn clearly and under scenario C the theoretical phosphorus can be recovered from the food waste has been given in Chapter 5 (981 tons), the potential phosphorus can be recovered is affected by the key driver and corresponding biological treatment technology a lot. Using inputs from the latest research the government could build an interesting model for a showcase of phosphorus recovery for other countries. Importantly, compared with other recovered source (sludge, waste water), the quality of the recovered phosphorus as a fertilizer is proved in some studies (Möller et al., 2009; Krogstad et al., 2004). The farmer's dependence on chemical fertilizers is reduced. According Avfall Sverige (2011), certificated quality labels can be used on the product by the facilities that produce digestate from food waste.The energy input, emissions and phosphorus loss associated with artificial fertilizers producing processes is avoided. The inhabitant's effort and contribution will win their good reputation.

THREATS:

Even with policy support, it still takes time for the inhabitant to adapt the new household waste classification. Misclassification will result in much waste being rejected for anaerobic treatment by biogas companies. The figure in this research is 18wt%, which is the main reason for phosphorus loss under Scenario C. Driven by the fertilizer value of phosphorus-contained digestate, phosphorus recovery under scenario C is still most favored for combined fertilizer and energy provision. However, in this case, reuse of digestate is not just individual company's behavior, but a solution for phosphorus recovery from potential source and a socio-technical system including collecting, storage, treatment and reuse. The institutional arrangements, regulations and policies need to be changed and appropriate policy instruments to facilitate this option are needed. Therefore, under scenario C, the system boundary for phosphorus recovery solution is clarified as country in this study. Further, government, householders, biogas companies, fertilizer manufacturers and distributors, farmers, food producers, distributors and retailers, dieticians and nutritionists, consumers are important stakeholders who can affect or be affected by the system. In this study, the government, biogas companies and the householders are identified the key stakeholders. The government will manage and finance elements and overall coordination of the system and the householders and biogas companies are major participants and performers of the system. The decision of source-separating of the waste is subject to environmental policies. Political parties can make or break incentives to inhabitant and related companies.

7. Discussions

The feasibility of recovery of P from solid food waste was investigated in this study. MFA method is used to identify the main solid waste fractions containing substances of phosphorus in Sweden. A Linköping case is analysed in this study. In this case, the food products consumed are assumed to be produced and processed in the region while food imported from outer systems is not included. This assumption is consistent with assumption made by previous study (Tina-Simone Schmid Neset, 2000). The total loss of P in food process is 6% based on this assumption. However, 8.75% of food in Sweden is imported from other countries in 2010 according to a World Bank report published in 2012 (Trading Economics, 2013). This means the total loss of P in food process accounts more than 6%. On the other hand, loss of phosphorus due to erosion is considerable small, only 2% of the total input in whole Sweden (Figure 6).Consequently, recovery P from solid food waste is more crucial in Sweden compared to other country which relied much on agriculture.

In order to check the possibility of P recovery from solid food waste, this study looked into the industrial model with specific data about how and how much phosphorus can be recovered from this identified waste fraction. As the large-scale, centralized recovery system is preferred in this study, the spatial distribution of the solid food waste (phosphorus recovery source) and the distance between the source and the farmland (end users) are important for the feasibility of the project as well as the cost and benefit. The energy consumption and the effect to the environment during transportation are determined by the distance. Generally, large city with high population density is the source of food waste containing phosphorus, which comes from the farm products. Theoretically, returning the phosphorus from the city to the farm land will create a close loop named "cradle to cradle". However, the quantity of collected food waste, the production of the digestate used as fertilizer of the biogas companies, the demand of fertilizer of the farmland need to be considered when planning the project. Hence, the life cycle costs of the projects associated with the collection, storage, transport, treatment and reuse are determined by those factors. The life cycle costs of the whole recovery and reuse system need to be compared with the life cycle costs of mineral phosphate fertilizer from mine to farm land.

In this study, Scenarios Analysis are used to figure out whether the industrial model for the phosphorus recovery from the organic food waste applied to the household organic waste, three treatment alternatives for household organic waste including centralized anaerobic treatment (industrial model), decentralized composting and incineration are compared. Although the results from this study show a clear rank between compared treatment methods (Table 5), the results are very sensitive to assumptions and the rank can be changed depending on these assumptions. In Scenario A, the co-effect of incineration food waste with other municipal solid waste has been ignored in this study. Thus, the capacity of calculated fly ash contributed by incineration of food waste is controversial. In Scenario C, digestate is used on sandy soils to replace commercial fertilizers. If digestate is used on loamy soil, the total loss of nitrogen is larger than that in Scenario B (Bernstad and Jansen, 2011). Compared to the assumed plant up-taken loss in Scenario C and majority loss due to emission during composting phase in scenario B. this loss is due to large nitrate runoff from clay soils and would results in a large contribution to nutrient enrichment. It is also assumed that the produced digestate substitute all use chemical fertilizer. Previous study (Lantz et al., 2009) shows that digestate and chemical fertilizer are often used on the same field, but spreading in different seasons. The leakage from the applied fertilizers and up-taken of P would be affected in reality.

The results would also be affected by factors as technology development, future policy, etc. Table 4 shows the P-content in the final product in three scenarios. The extraction method and P-content in the final product in this study is based on the experimental result from previous study on P recovery from MSWI fly ash (Kalmykova and Fedje, 2013). The method will be modified to yield more P than this study and P in the final product may increase. The most important issue in this scenario is that the application of P to the agriculture is prevented by its heavy metal content. In the future method development, P recovery can be complemented with extraction of metals, which makes Scenario A be a considerable option. It should also be pointed out that the composting system simulated in this study is low tech while high tech systems are being looked into and some are on the market. The material loss during composting in Scenario B may decrease. Similarly, with improvement of anaerobic treatment system, the recovered P from digestate in Scenario C can increase

SWOT is used to analysis the feasibility of recovering P from solid food waste under scenario C in this study. The result of this analysis directed towards households whose participation is important to source-separation system of food waste for P recovery. As food rejection occurs during pre-treatment process of anaerobic treatment. The rejected food is treated by incineration and in the LCA study of the household food waste of similar treatment system, around 18% P is lost in this pre-treatment (Bernstad and Jansen, 2011). Therefore, households' active participation can greatly increase the feasibility of the strategy for P recovery in this study.

The SWOT of phosphorus recovery from food waste provides a clear picture of phosphorus recovery under Scenario C, appropriate recovery scale and system to address the key goals need to be discussed under Scenario C. Small-scale biological treatment system has been used by some cities in southern Sweden (Bernstad, 2011). However, the key objectives are the reduction of the solid waste and protection of the environment, generated digestates in the treatment is a by-product and applying the digestates into agriculture to reduce the mineral fertilizer use including phosphorus is not the key driver. Considering the present waste separating and collecting system in Sweden, centralized phosphorus recovery and reuse system has the advantage of economy of scale compared to the household or community-scale retrofits. However, centralized system needs decreased costs, energy and resource costs of networks, technology costs which need to be considered by stakeholders.

8. Conclusion

The feasibility of phosphorus recovery from organic solid waste (mainly food waste) is studied in this paper. Three different scenarios are made to indentify the best way to recover phosphorus and Scenario C in which food waste is source-separated in paper bags by households is most favored in this study.

The result of this study will be affected by technology development, future policy, householders' participation, etc. It indicates that phosphorus recovery from the solid waste needs different stakeholders to be involved and work together to achieve the goal.

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Appendix

Fly ash: 239050*892625/5100370=41836

Theoretical recovered P in A: 41836*5.9=172

Theoretical recovered P in B: 254398*3.2=814

Theoretical recovered P in C:

(1-18%)*892625*(0.23*23%*64.6%+0.996*42.9%*20.4%+0.198*51.8%*12.8%) =981