Sustainable Phosphorus Management in Sweden

A Study of Phosphorus Recycling from Wastewater Sludge in Several Municipalities of the Östergötland County

Henok D. Haile

Master’s Programme in Science for Sustainable Development

Master’s Thesis, 30 ECTS credits
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Supervisors: Tina-Simone Schmid Neset and Birgitta Rydhagen

2015
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Abstract

The Swedish Environmental Agency (SEPA) proposed a national target to increase the rate of phosphorus recycling from wastewater sludge in 2013. Reusing phosphorus from wastewater sludge by spreading it on arable lands raises the risk of contamination and substance deposition in soils. In addition to quantifying the targeted rate of recycling, the proposal has also introduced new thresholds that limit the concentrations of undesired substances in wastewater sludge. This thesis assesses the potential challenges and opportunities in implementing the proposed measure in the Swedish municipality settings. Both qualitative and quantitative data have been gathered from three selected mid-sized Swedish municipalities in the Östergötland County and other data sources. The analytical framework of the thesis is based on the Systems Framework for Phosphorus Recovery and Reuse. Several discrepancies between the national goal to increase phosphorus recycling and local circumstances that affect local decision-making have been identified in this thesis. Reducing the flow of undesired substances into the wastewater stream raises goal conflict and is an enormous challenge which requires regulating the way chemicals are consumed in society. From the policy perspective, the national environmental objectives framework is ambiguous with regards to how local decisions should be directed in line with the national goals. The proposed measure should hierarchically be unequivocal and its implementation needs to be coordinated across all geographical scales. The thesis also highlights that there are significant local opportunities for addressing other sustainability goals through phosphorus recycling measures. Sweden’s commitment to creating a resource-efficient phosphorus cycle affirms that the key for a sustainable phosphorus management is the transformation of path-dependent social and technical systems.

Keywords: phosphorus recycling, phosphorus scarcity, sustainable phosphorus management, environmental quality objectives, systems approach, wastewater sludge
### Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP</td>
<td>Adenosine Triphosphate</td>
</tr>
<tr>
<td>Ag</td>
<td>Silver</td>
</tr>
<tr>
<td>BAU</td>
<td>Business as Usual</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CaO</td>
<td>Calcium oxide (Quick Lime)</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost-Benefit Analysis</td>
</tr>
<tr>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>DAP</td>
<td>Di-ammonium Phosphates</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic Acid</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EQO</td>
<td>Environmental Quality Objectives</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>g</td>
<td>Gram (SI)</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
</tr>
<tr>
<td>H</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>ha</td>
<td>Hactare (SI)</td>
</tr>
<tr>
<td>Hg</td>
<td>Mercury</td>
</tr>
<tr>
<td>K</td>
<td>Potassium</td>
</tr>
<tr>
<td>Kg</td>
<td>Kilogram (SI)</td>
</tr>
<tr>
<td>km</td>
<td>Kilometer (SI)</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LRF</td>
<td>Lantbrukarnas Riksförbund (Federation of Swedish Farmers)</td>
</tr>
<tr>
<td>MAP</td>
<td>Mono-ammonium Phosphates</td>
</tr>
<tr>
<td>mg</td>
<td>Milligram (SI)</td>
</tr>
<tr>
<td>Mt</td>
<td>Mega tonne (SI)</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>N/A</td>
<td>Not Available</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>O</td>
<td>Oxygen</td>
</tr>
<tr>
<td>P</td>
<td>Phosphorus</td>
</tr>
<tr>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>PCB</td>
<td>Polychlorinated Biphenyls</td>
</tr>
<tr>
<td>REVAQ</td>
<td>Ren växtnäring från avlopp (Pure Plant Nutrients from Sewage)</td>
</tr>
<tr>
<td>RNA</td>
<td>Ribonucleic Acid</td>
</tr>
<tr>
<td>SCB</td>
<td>Statistiska centralbyråns (Swedish Statistical Bureau)</td>
</tr>
<tr>
<td>SEK</td>
<td>Swedish Krona</td>
</tr>
<tr>
<td>SEPA</td>
<td>Swedish Environmental Protection Agency (Naturvårdsverket)</td>
</tr>
<tr>
<td>SWWA</td>
<td>Swedish Water and Wastewater Association</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>t</td>
<td>Tonne (SI)</td>
</tr>
<tr>
<td>USD</td>
<td>United States Dollar</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WWTP</td>
<td>Waste Water Treatment Plant</td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
</tr>
</tbody>
</table>
1. Introduction

Phosphorus (P) scarcity is an emergent global environmental challenge which has recently grabbed the attention of the international scientific community (Cordell, 2010; Schnug et al., 2013). The peak of the crisis in the international fertilizer market that took place in 2008 sparked the awareness of the looming scarcity problems. Between 2009 and 2012 alone a total of 40 scientific publications have been published on P-scarcity in different parts of the world (Schnug et al., 2013); but the predominant focus has been the global aspect of this challenge. Addressing the scarcity challenge requires the design and implementation of various measures in the international, national and local scales (Cordell, 2009; Cordell and White, 2013, Neset and Cordell, 2013). The relevance of this thesis is that it relates to the P-scarcity challenge from the global scale to a localized aspect of the responsive actions that can be taken to address it.

In 2013 SEPA (Swedish Environmental Protection Agency) came up with its latest target proposal to increase the national P-recycling rate to 40% by the year 2018. The estimated available amount of P from wastewater in Sweden is 5,800t, but currently 25% of this is being recovered and reused as fertilizer (SEPA, 2013). Furthermore, the proposed target not only aims for an interim increase of P-recycling, but also lays down successive regulations by which a sustainable recycling of P from wastewater is to be guided in the long-run. The target has been proposed at the national level and its goal is to attain a resource-efficient utilization of the domestic P resources. Sweden is administered in a self-governance system which divides the country into 21 counties and 290 municipalities. Swedish municipalities have the autonomy of making local decisions concerning a broad range of public services including wastewater treatment and sanitation. The Swedish municipal WWTPs (Waste Water Treatment Plants) are overseen by municipal administrative councils and operate through fees collected from residents. The municipal WWTPs will be responsible in implementing the nationally proposed target.

The implementation of nationally envisioned environmental policy measures at the local level often ends up being contradictory to the original policy intentions (Blake, 1999; Edvardson, 2004; Nilsson et al., 2008). With respect to the implementation of the proposed national measure for P-recycling, it would be necessary to analyze the relevant circumstances at the local scale. By assessing the local circumstances, the potential tensions between the goals at the national level and the relevant circumstances at the local scale can be identified. Therefore, the overall aim of this thesis is to understand the local circumstances in relation to implementing the nationally proposed-recycling measure at the Swedish municipalities. This thesis attempts to address the following two questions: what are the local circumstances in terms of the challenges and prospects for the effective implementation of the proposed measure at the local level; and what are the lessons that could be learned from Sweden’s local circumstances with regards to implementing measures that address P-scarcity? Thus, the findings of this thesis are expected to identify potential challenges or opportunities and the role of local decision-making in implementing the proposed measure.
Conceptually, the thesis departs from the Ecological Economics perspective to sustainable development to analyze the significance of recycling as an appropriate measure in addressing the P-scarcity challenge. The data analysis in this thesis has used certain components of the Systems Framework for Phosphorus Recovery and Reuse (SFPRR) as an analytical framework. These conceptual frameworks have been used to analyze the local circumstances through a study conducted in three mid-sized municipalities from the Östergötland County in East Sweden. In such a way, the analysis in this thesis alternately relates to the policy goals at the national level and the associated local circumstances for the effective implementation of the proposed measure.
2. Background

2.1. Phosphorus as an Essential Element

The human civilization is advancing at an unprecedented pace, but with the consequent imposing challenges to sustainable development. These challenges have been profoundly exacerbated by climate change, exhaustion of natural resources, poverty and environmental degradation. At a time of heightened awareness of global climate change, the focus is more often associated with finding sustainable energy sources or the availability of water resources (Cordell et al., 2009). Yet another equally alarming environmental challenge is unfolding behind the global limelight – the scarcity of an essential element. Phosphorus (P) is an essential element which plays a vital role in the formation of the molecular structures and storage of energy in the cells of living organisms. P compounds build up cell membranes, the genetic materials in DNA/RNA (Deoxyribonucleic Acid/ Ribonucleic Acid) and serve as energy storage units in ATP (Adenosine Triphosphate), a bond containing three phosphate groups (Smit et al., 2009; Cordell, 2010; Elser, 2012). Plants draw macronutrients such as N (Nitrogen), P (Phosphorus) and K (Potassium) from soils to maintain continuous growth. In the natural cycle, animals obtain P by feeding on plants or other animals and thereafter release P compounds through excreta back to the environment. Plants are also sources of P, as their decomposed matter enriches soils with nutrients and organic matter. Although there are different sources of P in the natural cycle, this element cannot be substituted by any other element or compound (Smit et al., 2009, Cordell, 2010; Elser, 2012).

P is also an essential input for agricultural productivity and it will be challenging to maintain food security with eventual shortages of phosphates fertilizers, eventually when the global demand for food is expected to rise at an alarming rate (Cordell and Neset, 2014). Although a limited amount of P is present in various types of soils, P stocks in soils deplete due to plant uptake or leaching. The limiting factor to crop yield is that P is continuously taken up by crops that external addition of P fertilizers on agricultural soils is required. P does not have atmospheric cycle unlike the other abundant elements such as H (Hydrogen), O (Oxygen), N or C (Carbon). Plants can only uptake from soils those P compounds which are soluble and the availability of P for plant uptake also depends on soil chemistry. In order for plants to absorb P from soils, it has to be readily available in a soluble form. Since P is chemically a highly reactive element, P compounds are not freely available but can be found in a mineral form bonded with other elements. This means that although P is the 11th most abundant element in the lithosphere, its occurrence as a readily available plant nutrient is limited (Smit et al., 2009; Cordell, 2011).

2.2. The Global Phosphorus Resources

The P used in the manufacturing of artificial fertilizers is mined from inorganic mineral phosphate rock. Then the mined phosphate is upgraded to a quality level required for the manufacturing of phosphate fertilizers. Geographically, the global distribution of phosphate
reserves is limited to few locations on earth and according to recent estimates by the USGS 75% of these reserves are found in Morocco (USGS, 2014). P is an important agricultural input which is required for increased agricultural productivity that is required to maintain global food security. For centuries, agriculture has depended on traditional P sources such as manure and human excreta (Fig. 1). The Green Revolution that started during the mid-1940s was mainly driven by the extensive use of industrially manufactured fertilizers along with other agricultural innovations. During the Green Revolution, extensive application of mineral fertilizers has made it possible to raise agricultural productivity and feed the growing world population (Heckenmüller et al., 2014; Scholz et al., 2014). Consumption of phosphates-based fertilizers increased dramatically right after the end of the Second World War by five-folds in a matter of few decades (see Fig. 1). The use of phosphates in agriculture has significantly reduced the potential impacts of starvation that would otherwise have been caused by the pressures of rapidly growing populations in developing countries (Scholz et al., 2014). In the developed world, phosphates have played an important role in keeping up with the growing food consumption that was driven by rapid economic growth in the decades following the end of the Second World War (ibid).

Currently, food production constitutes around 90% of the global mineral phosphates consumption either in the form of fertilizers or animal feed (Cordell et al., 2012). Although, as to how long the global P reserves could last is controversial among different researchers, the fact remains that P is an in-substitutable and scarce non-renewable resource (Weikard and Seyhan, 2009; Cordell and White, 2013). Scholz and Wellmer (2011) explain that P resources are non-renewable in the human time-scale since they take relatively longer time to mineralize in the earth’s crust. The world’s P resources are based on phosphate reserves which have been formed through a geological process that takes up to 10-15 million years (Cordell, 2010). The laws of thermodynamics dictate that the P compounds that form phosphate rocks are not destroyed after leaving the human cycle as they are displaced from one form into another. Temporally speaking, it takes them much longer time to return and be renewed into their previous mineralized state.
Currently, there are no scientifically proven estimations of the actual global P reserves as new reserves are being reported from time to time (Clift and Shaw, 2012 and Edixhoven et al., 2013). Edixhoven et al. (2013) argue that inconsistencies in the classification of P resources by the concerned international organizations have greatly influenced the uncertainties of estimating the actual global P resources. One instance mentioned by these authors is the Iraqi P reserves which had not been reported before and which were later reported in 2012 by USGS as being 5,800 Mt. With this reporting Iraq’s P resources suddenly became the second largest in the world before being revised again to only 430 Mt in the 2013 USGS report (Edixhoven et al., 2013; USGS, 2013). Nevertheless, new discoveries of P reserves do not change the fact that P is a scarce non-renewable resource. Cordell and White (2013) maintain that new discoveries would only push ‘Peak Phosphorus’ further by few decades. Another factor that limits the estimation of the longevity of the world phosphate reserves is the difficulty in predicting the rates at which future P demands will grow (Weikard and Seyhan, 2009). As the global population is expected to reach around 9.4 billion in 2050 (Keyzer, 2010), the future trends in the demand for food and thereby for phosphates is also expected to grow substantially in the next few decades.

2.3. The Phosphorus Scarcity Discourse

Leading researchers anticipate that there is an impending likelihood for yet another global fertilizer prices hike, similar to the one that occurred during 2007/2008 (Cordell and White, 2011). During the 2007/2008 period, world fertilizer and phosphate rock prices dramatically escalated by 800%, coinciding with a simultaneous global food market crisis. Ulrich and
Schnug (2013) maintain that the P-scarcity challenge began to gain awareness around 2007 from the realization that the market crises are reminding signals that indicate P is a scarce resource. These authors regard this period as a departure point for the emergence of the global P-scarcity awareness, which they term as ‘the modern phosphorus sustainability movement’ (ibid).

One of the conceptual models used to explain the dynamics of P resources is ‘Peak Phosphorus’, a point in time when demand peaks to surpass supply, while reserves begin to deplete at a faster rate. Déry and Anderson (2007) followed by Cordell et al. (2009) applied a similar model previously used to analyze ‘Peak Oil’ and concluded that P like crude oil will soon reach its peak production point before the reserves begin to be depleted towards the end of this century. Various estimations predict ‘Peak Phosphorous’ would take place sometime within few decades to a few centuries’ time (Cordell, 2009, Cordell and White, 2011, Cordell et al., 2012; and Linderholm et al., 2012b). It is difficult to accurately estimate when ‘Peak Phosphorus’ will take effect in time as ‘actual estimates of phosphate depletion or peak phosphorus vary widely, from the critical point occurring in 30-40 years to 300-400 years’ (Cordell et al., 2012:839). However, scarcity does not necessarily imply that there is a limited supply of phosphate products in the international market today. Regardless of the uncertainties in estimating how long the global phosphate rock reserves could actually last, the present consumption trend is unsustainable (Cordell, 2010).

Even though the global phosphates market is demand-driven, P is categorized as a ‘low cost commodity’; on average costing each human being around 6.14 USD per year (Scholz and Wellmer, 2013:14). The world’s major phosphate ores are accessible for mining and require relatively low extraction costs (Heckenmüller et al., 2014). As a result, there is an adequate production of phosphates for the international market. This suggests that the notion of scarcity should not be taken at its simplest context, as if P is already physically a scarce resource. A closer study of the current price trends in the world phosphate market suggests that the recent fluctuations were not caused by the physical scarcity of phosphates (ibid). The price fluctuations were rather the results of compounded effects of the dramatic price hikes in other commodity markets such as, the food and natural oil markets (ibid). Cordell (2010) identifies five broader contexts of P-scarcity: physical, economic, managerial; institutional and geo-political. In the future, if the current global P consumption trends continue unsustainably, the P-reserves with minable grades that are economically viable for extraction become depleted and the problem of physical scarcity takes effect (Scholz and Wellmar, 2013).

The global P-reserves are concentrated in few countries, making the global supply of phosphates susceptible to the geo-political factors in these countries. On top of the limited distribution of the global phosphate resources, the strategic policies pursued by countries and political instabilities in the regions where these resources are concentrated; interplay to intensify global vulnerabilities to the scarcity challenge. For instance, Morocco’s occupation of Western Sahara has been controversial internationally, as the territory is known to have substantial phosphates reserves (Cordell, 2010; Neset and Cordell, 2011). Recent upheavals in North Africa and the Middle East with the ensuing conflicts (in Syria and Iraq) have made the
region unstable, disrupting the production and export of phosphate rock (HCSS, 2012; Heckenmüller et al., 2014). In response to the recent global price escalations of phosphate fertilizers, countries such as China have pursued protectionist policies to limit their phosphates exports. China’s recent imposition of high export tariff on phosphates is aimed to ensure that its growing demand for phosphates is domestically met (Cordell, 2010; HCSS, 2012).

2.4. Closing the Phosphorus Cycle

One of the sustainable P management strategies suggested by experts in the field is the recovery of P from the human cycle to minimize the dependence on mineral phosphates (Cordell, 2010; Neset and Cordell, 2011; Childers et al., 2011; Clift and Shaw, 2011; Cordell and White, 2013, Seyhan et al, 2012; Weikard and Seyhan, 2009). Addressing the scarcity challenge involves a combination of efficiency and recycling measures that are expected to reduce the demand for phosphate rock (Fig. 2). If such measures are rigorously adapted, they have the potential to shift the business-as-usual (BAU) trend of total dependence on phosphate rock to a sustainable pathway that constitutes alternative phosphorus resources. As depicted in Fig. 2, one of the sustainable measures that potentially change the BAU trend in P consumption towards a sustainable pathway is the recycling of P from human excreta. Cordell et al. (2012), through their studies carried out using Substance Flow Analysis (SFA) suggest that hotspots in the human phosphorus cycle should be identified in order to reduce P losses and recover it for reuse in agriculture. P-losses in the human cycle are everywhere all the way from extracting the mineral P to the P in the food on our plates. Childers et al. (2011) and Cordell et al. (2011) estimate that it is only about 20% of the P in the human cycle that gets consumed by the human body while the rest 80% is lost at different stages of the cycle. Wastewater is one of the important hotspots where a substantial amount of P can be recovered from the human waste. Closing the human P-cycle by recovering P through the sanitation system is pivotal in both the prevention of environmental degradation and recovering of this scarce resource. According to Cordell and White (2011) globally the average human releases 1.0-1.5 g P in excreta every day, while 90% of this amount is lost mainly into the hydrosphere. The world’s total P in human excreta is estimated to correspond to around 22% of the global P-demand (Mihelcic et al., 2011).

The amount of P-concentrations in wastewater is variable across the world due to socio-economic factors and dietary habits (Mihelcic et al., 2011). In Sweden, it is estimated that 64% of the P released from the human body is found in urine while the remaining 36% is released through faeces (SEPA, 2013). On the global scale only 10% of the total amount of P from human waste is recovered and used as fertilizer on arable lands (Mihelcic et al., 2011). Cohen et al. (2011) estimate that 95% of the P in wastewater flowing into the Swedish WWTPs (Waste Water Treatment Plants) can be recovered, while P accounts for 3% of the dry matter of dewatered wastewater sludge. Moreover, Cordell et al. (2011) explain that P concentrations in wastewater sludge vary depending on the extent that the sludge is either slurry or dry. The P in wastewater is mainly derived from human excreta and some amount from other sources such as household detergents. Closing the human P-cycle requires increasing efficiency in various human systems (e.g. mining, logistics, and agriculture) in combination with the
sustainable recycling of phosphorus resources from different sources. More importantly, recycling of phosphorus resources is a sustainable measure that closes the loopholes in the human P-cycle (Fig. 2), while preventing environmental degradation from nutrient pollution (Cordell et al. 2011; Cordell et al. 2012).

**Figure 2: Future Pathways of Different Sustainable Phosphorus Measures**  
*Source: Cordell et al., 2009*

Recovering P from wastewater poses significant challenges, since sewage sludge contains not only nutrients, but also undesired substances such as heavy metals, pathogenic agents and other persistent organic substances such as Polychlorinated Biphenyls (PCB) (Lundin et al., 2004). These undesired substances are partly chemicals that are ingested into the human body along with food and pharmaceutical products that eventually end up being released in excrement. Other sources of these substances in wastewater include ordinary household chemicals found in detergents, construction materials, paints, rinsing of paint brushes, car washing, construction materials and run-off from asphalt roads. Hence, most of these substances are released into wastewater and finally remain in wastewater sludge. Therefore, a sustainable P-recycling measure involves reusing the recovered P from wastewater sludge, while making sure that the long-term accumulation of these substances in the environment does not cause environmental hazard.

### 2.5. Phosphorus as an Environmental Pollutant

As any other non-renewable minerals, P is a resource which deserves well to be closely scrutinized through the telescopic angle of sustainability (Elser, 2011). As a resource, P is strategic to human survival, since its scarcity is a limiting factor in the production of food. On the other hand, P is a pollutant element as its release into the hydrosphere mainly due to anthropogenic causes has negative environmental impacts. In fact, as an element, its chemical volatility limits its mineral occurrence and geographical distribution. Through the mining of phosphate rock, mineralized P stocks end up being relocated from the sediment layers under the earth’s surface to different components in the human P-cycle. Excess P leaks from
industrial processes, agricultural activities and the waste management system by flowing into the natural environment. The disruption of the aquatic ecological balance due to the release of excess concentration levels of nutrients such as P and N into the hydrosphere is known as eutrophication. Eutrophication destabilizes the aquatic biodiversity as micro-organisms (phytoplankton and algae) proliferate due to the availability of excess nutrients and compete with the population of other aquatic species through the depletion of O in aquatic bodies. From an environmental perspective, P has been predominantly associated with eutrophication rather than its scarcity.

2.6. Developments in Phosphorus Recycling from Wastewater in Sweden

In Sweden, the on-going public debates on the usage of wastewater sludge as fertilizer can be traced back at least as far as the late 1960s (Bengtsson and Tillman, 2004). In fact, the issue started to be publicly discussed as early as the 1900s when modern toilets became mandatory in Sweden (Linderholm et al., 2012b). Obligatory wastewater treatment was instituted in 1969 to prevent Sweden’s public sanitation problems and nutrient pollution, but until 1990 ‘phosphorus in wastewater was seen as a problem, not a resource’ (Linderholm et al., 2012a:883). The emergence of the sustainable development concept that emerged globally with the publication of the renowned Bruntland Commission’s Report in 1987 has influenced the new perspective of the need to create a resource-efficient society (Linderholm et al., 2012a). Moreover, in the beginning of the 1990s, concerns over the impacts of nutrient pollution in the Baltic Sea were heightened and recovering P from wastewater was re-emphasized as one of the preventative measures against eutrophication (Linderholm et al., 2012b). Mandatory nutrient recovery measures levitated the opportunity for sustainable P-recycling, while concerns over the potential environmental hazards of spreading wastewater sludge on arable lands equally arose among various stakeholders.

By 1994 two significant milestones with regards to reusing wastewater sludge as fertilizer were reached in Sweden. To encourage the use of wastewater sludge, the prominent Swedish actors involved in wastewater treatment and wastewater sludge [LRF (Federation of Swedish Farmers), SWWA (Swedish Water and Wastewater Association) and SEPA (Swedish Environmental Protection Agency)] reached at a voluntary agreement to cooperate for the safer use of waste water sludge on arable lands. However, maintaining cooperation among different stakeholders involved in the Swedish waste water sludge has already proven to be difficult since the 1980s. Particularly, the food industry and retailers were cautious of supplying consumers with agricultural products that have been grown on arable lands that use wastewater sludge as fertilizer. Simultaneously, the Swedish government took a step forward in introducing a regulation to ensure the safety of using wastewater sludge on agricultural lands in 1994. SNFS 1994:2 is a regulation which was promulgated in 1994 to regulate the use of wastewater sludge on agricultural soils (SEPA, 1994). This regulation was further reinforced by the ordinance SFS 1998:944, to restrict the concentration of substances in a range of products including wastewater sludge and commercial fertilizers (SEPA, 1998).
2.6.1. Phosphorus Recovery and Scarcity in the European Context

In Sweden and Europe in general, the use of wastewater sludge on agricultural lands as fertilizer has been in practice for decades. Initially, the motive behind recovering nutrients other than the need to use them as fertilizers was to prevent nutrient pollution (Linderholm et al., 2012a). After becoming an EU member state in 1995, Sweden integrated its wastewater treatment regulations with EU directives for wastewater treatment. At the EU level, regulations for the safe agricultural use of wastewater sludge with recommended levels of undesired substances have been in implementation as early as 1986. EU directives such as 86/278/EEC and 91/271/EEC have paved the way for a safer recycling of P and other nutrients from wastewater sludge within the region. These directives require the removal of nutrients from wastewater and regulate the safety of using wastewater sludge as an agricultural fertilizer. The regulations serve as the framework for nutrient recycling measures in EU member states. Presently, in view of the need to reduce vulnerabilities to the global P-scarcity, these directives become the basis for the overall policy guideline concerning the sustainable recycling of P resources from wastewater.

The EU offers a regional platform for defining the policy framework for concerted measures that address P-scarcity regionally. However, at the moment there is no consolidated EU policy framework designed to guide the sustainable management of P resources, but there are different policy measures already in place in several member states (EC, 2013). In July 2013 EU released its report on the sustainable use of P resources entitled: ‘Consultative Communication on the Sustainable Use of Phosphorus – COM (2013)517’. COM (2013)517 aims to ‘draw attention to the sustainability of phosphorus use and to initiate a debate on the state of play and the actions that should be considered’ (ibid). The report also assesses the EU’s situation in relation to the global P-scarcity and concludes that the region is highly dependent on the net imports of P fertilizers by as much as 92% in 2011 (ibid). Therefore, EU envisions the creation of a policy framework in which individual member states can set their own goals for sustainable P management appropriate to their own socio-economic conditions (ibid).

2.6.2. Phosphorus Recycling Action-Plans in Sweden

The current regulations which were developed in the 1990s are intended to allow a safer reusing of P and other nutrients from wastewater sludge. These regulations make it mandatory for wastewater sludge to have restricted levels of undesired substances before being spread over arable lands (Kvarnström and Nilsson, 1999). Although such regulations were already put in place to ensure for a safer recycling of P from wastewater by mid-1990s, the debate over using wastewater sludge as an agricultural fertilizer has remained to be a key environmental issue until now. In 1999 the debate intensified in Sweden as LRF broke-off the agreement previously reached in 1994 and recommended its members to stop using sludge. LRF cited an increase in the concentration of certain undesirable substances in Swedish sludge (Bengtsson and Tillman, 2004; Lundin et al., 2004). Eventually, this led to a significant reduction in the use of wastewater sludge in the following years (Bengtsson and Tillman, 2004). Consequently, farmers became less willing to use sludge on their lands and the municipal WWTPs ran out of options for disposing of sludge, as the ban on disposing sludge in landfills followed in 2000.
This created a conflict between the goal for resource-efficiency and the goal for creating a toxic-free environment. Eventually, continuous discussions to resolve the problem by the major stakeholders (LRF, SEPA and SWWA) led to the inception of a wastewater sludge certification system known as REVAQ (‘Pure Plant Nutrients from Sewage’ - in English) in 2002. REVAQ became fully operational in 2008. Although REVAQ is administered by SWWA, it was launched with the cooperation of various stakeholders from the agriculture, food and retail industries. As a result, the major players in the Swedish food industry currently accept agricultural products that have only been produced through the use of REVAQ-certified sludge. The certification system involves a series of test analyses that enable the detection of up to 60 trace elements including some of the hazardous pathogens in wastewater sludge (Mattson et al., 2012). Currently, the number of WWTPs joining REVAQ is gradually increasing as WWTPs voluntarily join the certification system.

By the end of 2002, SEPA released its proposal for a P-recycling target which aimed to increase the recycling of P from wastewater by 60% by 2015. This made Sweden to be the leading country to come up with a P-recycling target (EC, 2013). According to this proposal, at least 30% of the recovered P would be spread as fertilizer over arable lands, while the remaining half would be used on other productive lands. The 2002 target aimed at increasing the rate of P-recycling from wastewater on arable lands ‘without jeopardizing health and the environment’ (SEPA, 2002:22). Nevertheless, the 2002 proposal did not come up with new stringent regulations to further reduce the concentration levels of undesired substances in wastewater sludge. Perhaps, it would be important to note that the 2002 proposal did prioritize the primary purpose of recovering P is to prevent environmental problems and increase the availability of fertilizers due to ‘the limited amount of minable phosphate minerals in the natural world’ (ibid: 23). The 2002 target was expected to be implemented by 2003, but in the years ahead it met strong criticisms from different sections of the Swedish society and did not get the approval need for implementation. The 2002 target was among others, criticized for not clearly indicating how the target was to be achieved with a parallel reduction of undesired substances (SEPA, 2013). Another criticism pointed to the fact that the term ‘productive lands’ was ambiguous and needed clarifications (ibid).

In 2012, the Swedish Government commissioned SEPA to propose a new target for P-recycling and SEPA released its report for the proposal of a new target in September 2013. SEPA’s 2013 proposed target is expected to be introduced sometime in 2015 and aims for achieving the recycling of at least 40% of P from waste on arable lands by the year 2018. In the following two phases which are proposed to begin by 2023 and 2030 respectively (Table 2), the goal is to continuously lower the contents of undesired substances in wastewater sludge. The proposal for the 2013 target assesses that the potential of recovering P from different sources such as manure, sea-floor sediments, mining waste, wastewater sludge and human urine by source-separation. Urine has higher concentration of P with lesser contents of the undesirable substances and the 2013 proposal estimates that the total recoverable P from urine in Sweden could annually amount to 2,350 t. However, urine diversion requires modifications to the existing sewer infrastructure, and its potential for P-recycling in the short-run is limited (SEPA, 2013). Today recycling of nutrients through urine diversion involves a relatively small number
of Swedish households that are fitted with urine sorting utilities. For the interim period the recycling of phosphorus from wastewater sludge has been given emphasis over other sources.

Table 1: Proposed Thresholds of Maximum Concentration Levels of Heavy Metals to be Annually Added on Agricultural Lands (g/ha/year)

<table>
<thead>
<tr>
<th></th>
<th>Year 2015 g/ha per year</th>
<th>Year 2023 g/ha per year</th>
<th>Year 2030 g/ha per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>25</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.55</td>
<td>0.45</td>
<td>0.35</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>300</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>40</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.8</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>0.8</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>3.5</td>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Source: SEPA (2013)*

Table 2: Proposed Concentration Thresholds for Different Undesired Substances under the Proposed Phases (mg/kg)

<table>
<thead>
<tr>
<th></th>
<th>2015 mg/kg DSW*</th>
<th>2023 mg/kg DSW</th>
<th>2030 mg/kg DSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>35</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>1</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>600</td>
<td>550</td>
<td>475</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>60</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>40</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>800</td>
<td>750</td>
<td>700</td>
</tr>
<tr>
<td>Dioxin</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>PFOS</td>
<td>0.07</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Chlorinated Parafins</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>PCB 7</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>BDE-209</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Source: SEPA (2013); * Dry Substance Weight
What makes the 2013 target different from the 2002 target is that the first clearly lays down the means by which P-recycling will increase sustainably over a long-term period. To allow consistent reductions of the undesired substances so that P-recycling increases overtime, the new regulation sets thresholds in three phases (Table 1). The idea behind establishing stringent limits to the undesired substance contents of wastewater sludge is to encourage the use of sludge as fertilizer gradually. In light of this, the 2013 target is more robust than the 2002 target, since it has introduced stringent regulations which are the pre-condition for sustainable P-recycling. Tables 1 and 2 show the consistently lowered thresholds for the undesirable substances in wastewater sludge (Table 2) including their deposition on arable lands (Table 1) over the three phases. The proposed target has also introduced the limits for additional substances such as Silver (Ag) and other organic compounds which have not previously been included in the current regulation (Table 2). Due to the relatively higher concentrations of undesired substances in wastewater today, the intended rate of P-recycling could decline in the interim phase.
3. Conceptual Framework

3.1. Phosphorus Scarcity in the Context of Sustainable Development

Discussing P-scarcity and P-recycling outside the context of sustainability would be virtually impossible. Today we live in a world where the awareness of human impacts on the environment has considerably grown globally and ‘sustainability’ often sounds as the buzzword of our times. The term ‘Sustainable Development’ first emerged at the global arena with the Brundtland Commission’s Report, ‘Our Common Future’ in 1987 (WCED, 1987). According to Quental et al. (2011) and Redclift (2005), the concept of sustainable development has significantly expanded in scientific thinking since 1987. Sustainable development is a broad multidisciplinary concept linked with different connotations and perspectives. The common approach defines sustainable development as the harmonious balance among the three dimensions of development: economy, society and environment. However, Giddings et al. (2002) maintain that this approach portrays the relationships that exist among these converging three dimensions, as if each one is independent of the other. Instead, these authors propose an approach that considers sustainable development as being a ‘multi-faceted and multi-layered’ (Giddings et al., 2002:192) interdependency in which economy and society are superimposed as the integral parts of the environment. The environment serves as the space upon which all human systems are built on and the source of natural resources that are required to drive these systems. From its extraction to its consumption and its release into the environment through various waste streams, P is a resource which is linked with sustainable development in various aspects.

3.1.1. The Ecological Economics Approach

Quental et al. (2011) identify and describe the prominent contemporary conceptual approaches of sustainability. One of the main scientific roots to the concept of sustainable development is the Ecological Economics approach (ibid). The Ecological Economics approach defines the environment as a source of natural capital, which includes various amenities such as the supply of natural resources (Zilberman, 2013). The approach regards economy and society as being interdependent on the environment (Greenwood and Holt, 2008) and maintains that there is a threshold of boundaries in the environment that limit the human utilization of natural capital. Ecological Economics regards sustainable development as an approach that opts to minimize environmental impacts through the redistribution of wealth (Greenwood and Holt, 2008; Quental et al., 2008). However, according to the conventional Neoclassical thinking, society’s prime economic goal is to sustain growth, while markets and technology can work together to compensate for the resultant economic impacts or losses of natural capital (Giddings et al., 2002).

The divergence in these two perspectives is epitomized by their definition of sustainable development as being either weak or strong (Quental, et al., 2011). Weak sustainability is advocated by the neoclassical approach, which emphasizes on the development path in which economic growth is sustained through the losses of natural capital which are assumed to be
substitutable with human-made capital (Ayres, 2007; Quental, et al., 2011). Conversely, the Ecological Economics perspective maintains that since the human economy is embedded within the environment, the latter has limited natural sinks to absorb the resultant impacts and supplies limited stocks of natural capital. This approach emphasizes that development cannot be sustainable unless the interdependency between human economic activities and the environment is recognized. Strong sustainability is maintained when development needs are met within the limits of the natural capital. Therefore, according to the Ecological Economics approach, sustainability is defined as being strong, as the development needs should be met within the limits of the environment’s capacity; human-made capital has limited capacity to replace natural capital (Quental et al., 2011).

When it comes to non-renewable resources, the Ecological Economics approach presents an interesting perspective with respect to mineral resources such as P. The central concept of this perspective is that sustainable development can only be achieved if utilization of natural resources continues in such a way that dependence on non-renewable resources is minimized over time. Zilberman (2013) suggests that efficiency in the recycling of non-renewable natural resources reduces consumption of the resource base over time and extends the longevity of renewable resources. With respect to non-renewable resources:

An operationally important measure of renewable resource stocks is known reserves. Some of the mined resources can be re-captured through recycling. Thus, for many resources that are considered nonrenewable, the equation of motion that matters depicts changes in known reserves over time, which is equal to new discoveries plus recycled amounts, minus consumption. This suggests that in the long-run, once all the reserves are known, if a certain percentage of a stock can be recycled, one can sustain consumption that is equal to the recycled amount (ibid: 389-390).

Thus, Zilberman’s (2013) analysis on the longevity of reserves of non-renewable resources overtime can be summarized as:

\[ \Delta R_t = R_n + R_r - C \]

Where:
- \( \Delta R_t \) (‘Known Reserves over time’)
- \( R_n \) (‘Newly Discovered Reserves’)
- \( R_r \) (Recycled Resources)
- \( C \) (Consumption)

Assuming that the rate of recycled phosphorus resources approaches the rate of consumption, theoretically the depletion rate for the known reserves of rock phosphates would decline. This means that the change in the known reserves (\( \Delta R_t \)) of rock phosphates depends on the rate at which new reserves are discovered (\( R_n \)) and the changes in the consumption patterns (\( C \)) for the resources. In addition to increased recycling of phosphorus resources, the discovery of new reserves could theoretically extend the longevity of the global phosphorus resources. However,
this reasoning depends on how the consumption patterns for phosphate rocks change over time, in terms of consumption of fertilizers to produce competing agricultural products such as biofuels, cereals or animal products. Moreover, the increasing difficulties in accessing these reserves and the associated high extraction costs would not make it economically viable to continue mining the remaining reserves over time (Cordell and White, 2011). To offset the impacts of an increasing consumption trend resulting from population pressure or changes in the consumption patterns, recycling ($R_r$) and efficiency in consumption should proportionally increase. The implication of Zilberman’s analysis with regards to phosphorus resources is that recycling in combination with the efficient use of phosphorus resources extends the longevity of the known global phosphorus reserves over time. However, it should be noted that beyond extending the longevity of non-renewable resources, the effects of recycling itself are subject to limitations and do not completely reverse the finiteness of natural resources (Grosse, 2010).

### 3.1.2. Phosphorus Recycling as a Strong Sustainability Measure

Zatzman (2012) suggests that the principles of sustainable development are fundamentally concerned with whether certain pathways or processes are sustainable or not, rather than the scarcity or availability of natural resources. This has also been duly addressed by Cordell (2010), who broke down the multiple dimensions of phosphorus scarcity. Childers et al. (2011) stress that sustainable measures aimed at addressing the P-scarcity challenge require pathways that follow the ‘strong sustainability’ approach. This approach is termed as ‘strong’ due to its emphasis that the sustainability in a system or process (e.g. increased agricultural productivity) should not result in the unsustainability of another (e.g. depletion of the global mineral stocks) (Cordell et al., 2011). The criteria for sustainability should harmoniously be met across each of the sustainable development dimensions. Otherwise, the application of measures that primarily rely on human capital such as technological solutions cannot sustainably address the scarcity challenge, as the gain in one aspect would result in losses on the other. The strong sustainability perspective of addressing P-scarcity challenges means that sustainable solutions are required in every system and process involved. This also applies to how recycling measures are sustainable in terms of their resultant impacts on the environment (e.g. GHG (Greenhouse Gases) emissions or environmental hazards) or if their social benefits outweigh the costs.

As a resource, P is not only un-substitutable and non-renewable but is strongly linked to food security. Ayres (2007) maintains that generally, non-renewable mineral resources are subject to the limits of substitutability and argues for the strong sustainability approach to tackle the P-scarcity challenges. Hence, the relevance of recycling and efficiency as measures of the ‘strong sustainability’ approach to address the P-scarcity challenges (see Fig. 2) is evidently emphasized. Sweden’s P-recycling target is one of the milestone targets designed to facilitate the achievement of the ‘Environmental Quality Objectives’ (EQO). The national EQOs have been adopted by the Swedish Parliament in 1999 to guide the country into a sustainable development path (SEPA, 2012). These objectives embody Sweden’s environmental policy and they have been formulated to create an environmentally sustainable society. Sweden’s EQOs constitute a total of 16 objectives in the areas of ‘recovery of ecosystems, conserving biodiversity and the natural and cultural environment, good human health, efficient material
cycles free from dangerous substances, sustainable use of natural resources, efficient energy use, and patterns of consumption’ (ibid:2). In this respect, the proposed target is not an independent measure by itself, but it is an integral part of an overall policy framework that is meant to guide Sweden along a sustainable development path.

The relevance of the Ecological Economics approach in this thesis is to streamline the overall conceptual perspective of the thesis within the concept of sustainability. Firstly, the purpose is to conceptually highlight the significance of P-recycling as an appropriate sustainable measure in addressing the P-scarcity challenge. The Ecological Economics approach to sustainable development has been adopted in this thesis as a perspective that highlights recycling as one of the sustainable measures to address the P-scarcity challenge. Thereon, secondly, the purpose is also to highlight on the rationale behind Sweden’s P-recycling target as being one of the national milestone targets designed to contribute to the overarching attainment of sustainable development. Sweden’s P-recycling target, as a national policy measure has been nationally envisioned and formulated with a sustainable development mindset (SEPA, 2012).

Since the national target is to be implemented at the local level, the achievement of the intended outcomes of the target should also be assessed with the same mindset. The ‘strong sustainability’ argument as advocated by the Ecological Economics approach leverages a key perspective in which how implementing the proposed target should be linked with other sustainable development goals. This argument links the need to recycle the scarce P resources with simultaneously protecting the environment from harmful deposition of substances and the associated social costs or benefits affecting local communities.

The Ecological Economics approach clearly depicts the inter-dependent relationship that exists between each of the sustainable development dimensions. According to this perspective, P-recycling is an appropriate responsive measure that recognizes the limitations of the environment both as a supply of P-resources and the sink for P outflows into the environment. Furthermore, it is important that P-recycling measures can be linked with other systems to address sustainable development goals (Neset and Cordell, 2012). On the basis of this perspective, those sustainability criteria which are linked to P-recycling can be identified by tracing them from the national sustainability objectives (EQOs) with their implications to the local setting. Hence, the sustainability criteria that are closely linked to implementing the proposed target under each sustainability dimension can be categorized as follows:

i. **Social**: health safety, institutional arrangements, systems or processes and the chemical consumption patterns in society

ii. **Economic**: resource efficiency, reduced imports/use of mineral fertilizers, cost-efficiency and agricultural productivity

iii. **Environmental**: nutrient pollution prevention, ecological balance, GHG emission reduction, deposition of substances and sustainable waste management

To gain an insight into the relevance of various sustainability criteria in relation to measures intended to address the P-scarcity challenge, it would also be worth mentioning several related studies. Molinos-Senante et al. (2010) conducted a study on the economic feasibility of P-
recovery on 20 WWTPs in Spain using the Cost-Benefit Analysis (CBA) method. Their study shows that such analysis must put into account not only the operational costs at WWTPs, but also the social and environmental externalities of P-recovery. According to the findings of the above-mentioned study, P-recovery at WWTPs induces benefits for the environment not only because it removes nutrients from wastewater, but because it also recovers a scarce non-renewable resource for further use. The authors maintain that internal cost factors at WWTPs should not solely be considered to evaluate the feasibility of P-recovery projects. Although these authors underscore that the CBA of P-recovery processes at WWTPs should be undertaken with a broader perspective, their analysis does not specifically put into account how the undesired substances (heavy metals and persistent organic substances) in wastewater sludge should be considered in such analyses. On the other hand, Linderholm et al. (2012b) conducted a life cycle assessment (LCA) to study the P flows in Swedish agriculture and the environmental impacts of various P-recovery options. Although the analyses in the study (ibid) were based on the criteria of energy consumption, GHG emissions and deposition of undesired substances, the authors have not taken a holistic approach that encompasses the broader sustainability perspectives. Most importantly, in terms of GHG emissions and energy consumption, results from the LCA indicate that spreading of wastewater sludge is the most efficient recovery option. Nevertheless, as far as addressing the P-scarcity challenges from a ‘strong sustainability’ perspective is concerned, Cordell et al. (2011) propose a broader systems framework approach to analyze the sustainability of P-recovery in every system or process involved. Because of its broader perspective, the systems framework approach is relevant to serve as an analytical tool in this thesis.

3.2. An Overview of the Systems Framework for Phosphorus Recovery and Reuse

Since P-recycling involves the recovery of P resources from various loopholes in the human system, understanding the associated challenges and potentials requires a systems approach. Cordell et al. (2011) propose a systems approach framework to develop responsive strategies or measures across various systems or processes, as illustrated in Fig. 3. The systems approach involves an eight steps framework: ‘designed to facilitate research and decision-making towards the most cost-effective and energy-efficient means of recovering and reusing the most phosphorus to achieve multiple goals of food security, environmental protection, sustainable sanitation and possibly energy generation’ (Cordell et al., 2011:748). To highlight on the applicability of the systems framework to diverse socio-economic, technical and geographical settings, the authors take various P-recovery cases from around the globe and analyze them through the framework. The Systems Framework for Phosphorus Recovery and Reuse (SFPRR) is not designed to be rigorously applied in a sense that it ‘is intended as a flexible and iterative guide only and should not be taken as a rigid step-by-step process’ (ibid). Thus, the analysis in this thesis does not need to necessarily go through each of the framework’s steps, as they require much broader studies. Instead those steps which are most relevant to the Swedish setting and to the objectives of this thesis will be analyzed.

First and foremost, the importance of this approach is that it is designed to analyze P-recycling across various institutional settings, systems or processes such as sanitation, food production
and logistics. According to Cordell et al. (2011), in guiding P-recycling measures a systems approach is required so that such measures would simultaneously result the most attainable sustainable outcomes in those systems or processes involved. For instance, various P-recovery options enhance resource efficiency by recovering the scarce nutrient from waste streams, while preventing nutrient outflow into the environment. Nevertheless, by the same token, recovery processes should not result negative effects in the form of GHG emissions, higher costs of energy consumption or environmental hazards. Secondly, the systems framework is designed to guide both research and policies in all geographical scales. These authors (ibid) cite that the purpose of developing the systems framework approach is due to the lack of a conceptual framework with a broader systems approach to direct P-recycling measures across all geographical scales. Hence, with respect to the research aim of this thesis, this framework is an appropriate tool in analyzing the goals behind the national target and the associated circumstances at the local setting.

With regards to analyzing the national aspects of P-recycling through the eight steps of the framework (see Fig.3) the 2013 proposed target already consists of information corresponding to several steps of the framework. In connection to the first step of the framework, the 2013 proposed target identifies achieving the goal of resource-efficiency as the main driving factor for initiating the target. With regards to Step 2 and 3 of the systems framework (see Fig.3), the proposed target has identified the different P-recovery points in Sweden and has assessed that wastewater as the most effective source of recovery in the interim period. Accordingly, various sources of recovery such as manure, food waste and biological wastes have also been assessed, while wastewater has been identified to be the most effective source with annual unrecovered amounts of 4,300 t P (SEPA, 2013). With regards to defining the system boundary, the mining industry, chemical industry, agriculture, retail industry, households and the sanitary system are generically related to P-recycling (Linderholm et al., 2012b). The proposal also makes reference to several recovery technologies that are available today (Step 4) and deems spreading wastewater sludge on arable lands as the most feasible option. Regarding Steps 5 and 6, there are several studies which have already been carried out in the Swedish setting with regards to the logistics and costs of various recovery options (see Appendix III). Moreover, the proposal assesses that the presence of undesirable substances in wastewater as a major challenge in the recycling process (Step 7) and lays down the technical limits to allow the sustainable recycling of nutrients (see Tables1 and 2).
Figure 3: Steps in a Systems Framework for Phosphorus Recovery and Reuse (SFPRR)
Source: Cordell et al. (2011)

For this thesis, the SFPRR will be relevant in analyzing two aspects of Sweden’s P-recycling target in relevance to the research aim of this thesis. The framework will be used to analyze the policy aspect of the target with respect to the national goal which the target is intended to deliver. For this purpose, Steps 1 and 7 of the framework have been considered to be relevant, as they are concerned with the identification of the driving forces for the target and the potential conflicts or synergies that it potentially creates. Additionally, in relation to the implementation of the target, it would be necessary to analyze the associated circumstances at the local settings. Steps 3, 6, 7 and 8 of the SFPRR are also relevant for analyzing circumstances at the local settings which potentially interact as the opportunities and challenges of implementing the target. Ultimately, the SFPRR will be used to guide the analysis in this thesis into assessing
the local circumstances in relation to implementing the proposed national goal of increasing P-recycling.
4. Methods

4.1. Selection of the Study Area

The county of Östergötland is one of Sweden’s agricultural regions and is situated on the southeastern parts of the country. Östergötland constitutes 13 municipalities and ranks as the fourth largest populated Swedish county. Norrköping and Linköping are the largest urban centers in the region with a population of 133,749 and 150,202, respectively (SCB, 2014b).

There are several reasons for selecting Östergötland as the study area. I, as the researcher, am a resident of Östergötland and selecting the county as a study area was advantageous to this thesis in several ways. Firstly, two of the experts selected as interviewees for the study are leading experts who are based in the county. Secondly, since Östergötland is an agricultural region, it offers a good opportunity to study the agricultural use of wastewater sludge. Thirdly, being in proximity to many parts of the county meant that traveling to the selected municipalities would reduce travel time and cost.

Population was the main criterion for selecting the municipalities that would be included in the study. The Swedish municipalities which have relatively large population sizes have better financial resources and implementing capacity. Whereas, the smaller municipalities are relatively less-resourced than the larger municipalities and generate smaller sums of taxation incomes from their residents. Although, municipal WWTPs operate through fees collected from residents, undertaking major investments requires considerable financial resources which are beyond the means of WWTPs. However, population is not evenly distributed across the 13 Östergötland municipalities (see Annex IV). There is significant variation of population sizes among the 13 municipalities. Norrköping and Linköping are the largest urban centers in the county and each of them have more than 100,000 residents. On the other hand, 6 of these 13 municipalities have population sizes which are less than 10,000 (SCB, 2014). Eventually, there is significant variation among population sizes of Östergötland’s municipalities and it was necessary to determine a homogenous group of municipalities. Both extremities in the population sizes of the larger and smaller municipalities may not represent the situation in the majority of Swedish municipalities. Selecting a group of municipalities with an optimal population size would ideally simplify the analysis in understanding the circumstances within a relatively homogenous group. By Swedish standards, the mid-sized municipality has a population size roughly in the range of 20,000 to 40,000 residents (Karlsson, 2013). Therefore, Finspång (Population: 20,903), Mjölby (Population: 26,313), and Motala (Population: 42,187) have been selected to be included in the study (SCB, 2014).

4.2. Methodological Triangulation

The triangulation method in research can be described as the use of multiple methods to obtain more accurate data on a given subject matter (Jick, 1979). Hussein (2009) mentions that there are two main aspects of applying the triangulation method in research. Some regard the method as a means of drawing a broader and deeper perspective of a research problem, while others
view it as a strong means of validating data for more accurate analysis. The benefit of using the triangulation method in a relatively new field is that besides validating data, it broadens data capturing by compensating for the lack of sufficient scientific knowledge concerning a research problem. According to Jick (1979:608), ‘[t]he effectiveness of triangulation rests on the premise that the weaknesses in each single method will be compensated by the counter-balancing strength’. Since the P-scarcity challenge various dimensions, its study requires a multi-disciplinary approach with multiple methods. Cordell (2010) has used the triangulation method by combining ‘multiple theories and perspectives to better understand areas of convergence and divergence’ in a formative multidisciplinary research concerning the global P-scarcity challenge (Cordell, 2010:16).

There are two reasons for selecting the triangulation method in this thesis, in line with the research aim. Firstly, the method has been used to steer the study in this thesis in such a way that the multiple methods used could serve as explorative means in lieu of the apparent information gap. The insights gained by probing into the research problem could compensate for the lack of sufficient scientific knowledge on the local setting conditions and the subject matter in general. Secondly, combining different methods is effective since it is possible to benefit from the advantage of each type of method used. The use of multiple methods improves the versatility to gather data that probe into the different aspects of the research problem. Particularly, the purpose of including the qualitative method in this thesis has been to obtain data which could not have been otherwise captured by the quantitative method.

4.3. Data Types

Identifying the quantity and quality of the recoverable P contents in wastewater is the third step of the systems framework discussed in the previous chapter (see Fig.3). Assessing the local settings which are relevant to P-recycling at the selected municipalities requires quantitative data with regards to how much sludge is produced at the WWTPs, the quality of the sludge produced; and the extent to which the sludge is reused. The purpose of quantifying the recyclable amount of P from wastewater at the studied municipalities is to assess the potentials or the challenges of implementing the proposed target locally. In particular, quantifying the amount of wastewater sludge reuse in the studied municipalities gives insights into the local settings that potentially enable or hinder reusing P from wastewater sludge. Furthermore, analyzing the quality of wastewater sludge in terms of its contents of undesired substances or P fractionations is one of the key undertakings of this thesis, since sludge must meet the proposed new thresholds for substances if P-recycling is expected to increase. These data are later analyzed to gain insights into the potentials or challenges of implementing the proposed target at the municipalities.

4.4. Data Sources and Data Gathering

This thesis draws data from both primary and secondary sources. The primary sources of data include wastewater treatment engineers from WWTPs in the selected municipalities, Environmental Officers from the Municipality or County environmental bureaus, and experts
from the scientific community whose specialization is related to P-recycling. A total of seven semi-structured interviews were conducted with the concerned interviewees to collect the required qualitative data (Table 3). Moreover, personal communication via e-mail was also used to obtain an expert’s opinion on the technological aspects of P-recycling from an expert representing a Swedish nutrient recovery innovation company which is currently engaged with developing P-recovery technologies. As for the secondary data sources, internal documents and records from the studied WWTPs, official statistical data from the Swedish Statistics Bureau (SCB), published books, peer-reviewed scientific literature, official public websites and policy documents were used. The qualitative data gathering method initially involved designing the relevant semi-structured questions with the corresponding theme areas relevant to the respondents’ areas of specialization. The interviews were designed to be semi-structured in the sense that the questions would be explorative and whenever it is appropriate the interviewees would be asked follow-up questions so as to obtain different perspectives of the research problem.

4.4.1. Relevance of the Interview Method

Quantitative data alone cannot sufficiently give the overall picture of the research problem. Probing into the local aspect of the research problem requires obtaining qualitative data to better understand the local setting and fill the information gap. In connection to the appropriateness of using a qualitative method in this thesis, it is important to consider two factors that are relevant to the research problem. The research problem is ultimately linked to the emergent field of P-scarcity and the SEPA target is currently just at its proposal stage. There is insufficiently available relevant information, particularly regarding the situation at the Swedish municipality level. Therefore, under the circumstances, the interview method has been selected as the appropriate method of gathering qualitative data in this thesis.

Without the qualitative inputs, the ability to probe into the research problem would be limited. Firstly, the use of interview as a qualitative method could broaden the possibility of gathering sufficient data to overcome the aforementioned lack of relevant data. Interviewing respondents from the different actors linked with P-recycling at the local level could effectively provide insights into the different perspective of the research problem. Another advantage of the interview method in relation to the research aim of this thesis is that it allows for interpreting the contexts of the quantitative data by triangulating them with the qualitative data.

4.4.2. Designing and Conducting Interviews

The potential interviewees were initially selected on the basis of their role in relation to P-recycling from wastewater. This involved dividing the role of the potential respondents into two categories (see Table 3). The first category represents actors who operate and coordinate wastewater treatment at the municipal or regional level. Those who fall in this category are technical staff at the municipal WWTPs or environmental officers from the municipal or regional administrative councils. The other category includes respondents from the scientific community whose specializations are related to wastewater and nutrient recovery. Upon the
recommendation of the thesis advisors, *Experts 1 and 2* were selected for the interviews as they represent the scientific community and their area of work is within urban wastewater and nutrient recycling. The inputs of these two interviewees have been profound for this thesis. Moreover, *Expert 3* not only represents the Swedish companies engaged in innovating nutrient recovery technologies, but also represents the scientific community; with several published scientific articles concerning nutrient recycling. *Expert 3* has published several scientific articles and was identified through one of these articles. Unfortunately, this expert lives in another part of Sweden and personal correspondence was used as the alternative means of acquiring information. The occupational roles of the respondents who participated in the qualitative methods used in the study and the respective methods used to gather data are hereby summarized in Table 3.

**Table 3: List of Respondents and the Qualitative Methods Used in the Study**

<table>
<thead>
<tr>
<th>Designated Name*</th>
<th>Occupation</th>
<th>Organization</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineer 1</td>
<td>Chief WWTP Engineer</td>
<td>Finspång WWTP</td>
<td>Interview</td>
</tr>
<tr>
<td>Officer 1</td>
<td>Head of Environmental Bureau</td>
<td>Mjölby Municipality</td>
<td>Interview</td>
</tr>
<tr>
<td>Engineer 2</td>
<td>WWTP Engineer</td>
<td>Motala WWTP</td>
<td>Interview</td>
</tr>
<tr>
<td>Engineer 3</td>
<td>WWTP Environmental Coordinator</td>
<td>Motala WWTP</td>
<td>Interview</td>
</tr>
<tr>
<td>Officer 2</td>
<td>Environmental Coordinator</td>
<td>Östergötland County Administrative Board</td>
<td>Interview</td>
</tr>
<tr>
<td>Expert 1</td>
<td>Consultant</td>
<td>A Swedish Urban Water Consulting Firm</td>
<td>Interview</td>
</tr>
<tr>
<td>Expert 2</td>
<td>Consultant</td>
<td>Swedish Rural Economy and Agricultural Societies</td>
<td>Interview</td>
</tr>
<tr>
<td>Expert 3</td>
<td>CEO</td>
<td>A Swedish nutrient recovery technology innovation firm</td>
<td>E-mail Correspondence</td>
</tr>
</tbody>
</table>

*For the sake of anonymity and simplicity, the names of all respondents have been replaced with designated identification according to their respective occupational roles.*

In designing the interview guide, caution was taken to present the questions as clear and unambiguous as possible. During the course of conducting the interviews, there were several instances where several interviewees would go on by briefly responding to the questions they had been asked. In such cases, the interviewees were asked again with follow-up questions to make sure that they respond thoroughly to the questions. Nevertheless, the interview sessions were all conducted in a relaxed atmosphere, while the interviewees actively participated in responding to the questions. With the consent and full cooperation of the interviewees, each interview session was recorded and transcribed before being analyzed later. The method of
analysis used was to assemble the transcribed material into the three theme areas and summarize the data accordingly. In some instances, the materials were compared with the quantitative data to verify and interpret their contexts.

4.5. Scope and Limitations

The research problem of this thesis is ultimately linked to the P-scarcity challenge and a specific measure which aims to address this challenge in a specific geographical setting. Hence, the main points related to the scope and limitations of this thesis are briefly summarized as follows:

i. **P-recycling as recovery and reuse**: From a systems perspective, P recycling can be broken-down into recovery and reuse (Cordell et al., 2009; Cordell and White, 2013). Recovery is the process of extracting P from different leakage points in the human system and making it available for further use in other systems. On the other hand, reusing is a process in which the recovered P is reintroduced back to the human system for further consumption (see Table 2). Recovery of P is a part-and-parcel process of P-recycling, while efficiency deals with utilizing P resources so as to minimize wastage at every level of the human P-cycle. However, at times it would be ostensibly difficult to distinguish between recovery and reuse.

ii. **P-recycling from wastewater**: From the short term perspective as outlined in the 2013 SEPA recycling proposal, the strategy to increase P-recycling in Sweden gives priority to P-recovery from wastewater. Therefore, this thesis excludes other sources of P-recovery such as biomass or food waste.

iii. **The Swedish debate on the use of wastewater sludge as agricultural fertilizer**: The point of reference for this thesis is the 2013 SEPA proposal for P-recycling target and the associated conditions at the local level. The sludge use debate has a formidable influence over the agricultural use of wastewater sludge in Sweden (Bengtsson and Tillman, 2004). Nevertheless, this debate is a much broader research problem that needs to be examined with broader perspectives. Therefore, the debate has been briefly covered in this thesis without the need to deeply analyze its dynamics.

iv. **Heavy metals as undesired substances**: The 2013 proposed target has included the thresholds for Ag and other persistent organic substances for the first time (Table 2). In practice there is limited knowledge and experiences of controlling the impacts of these persistent organic substances on the environment. For this reason, this thesis will only focus on the eight heavy metals, including Ag.

v. **Possible revisions of the proposed regulations**: this thesis is written prior to the approval and implementation of the proposed target, the possible revisions that could be made to the proposed target or how it will end up being implemented at
the municipal WWTPs cannot be anticipated at this point. However, this thesis assumes that the proposed target will soon (2015-2016) go into implementation without significant moderations.

vi. **An apparent knowledge-gap:** P-scarcity has been termed as a ‘newly emergent’ environmental challenge which has notable knowledge gap concerning its diverse aspects (Cordell, 2010; and Ulrich and Schnug, 2013). Moreover, P-recycling has not yet been fully developed into becoming a ‘mainstream’ process (Cordell, 2011:748). The available scientific studies focus on the global aspect of P-scarcity rather than the local perspective (Ulrich and Schnug, 2013). Otherwise, the analysis in this thesis would have benefited from a broader accumulated scientific knowledge.

vii. **Time limitations:** On several occasions, several interviews had to be rescheduled due to the heavy workloads which several interviewees encountered. As a result of repeated postponements, a considerable backlog was created on the thesis schedule.

viii. **Language barrier:** Although most Swedes do speak English, my lack in the command of the Swedish language has also been a limitation to some extent. There were several occasions where it was difficult for several of the interviewees to comfortably respond in English.

ix. **Harmonizing data:** Each of the studied WWTP uses different units of measurement to quantify sludge. Harmonizing sludge data into a common unit of measurement has proven to be time-consuming. Moreover, due to inconsistent record keeping methods used by different personnel at WWTPs over the years, it was not possible to obtain long-term data.
5. Results

5.1. Wastewater Sludge Output and Use

Identifying the quality and quantity of the recoverable P from the sanitary system is one of the essential steps in the systems approach framework for recovering P from the sanitary system (see ‘Step 3’ in Fig. 3). In this sub-section, the quantitative data with the amount of wastewater sludge produced by the studied WWTPs and the amount used as fertilizer on agricultural lands are presented. The produced quantities of wastewater sludge do not indicate the actual extent to which wastewater sludge from the studied municipalities has been used as fertilizer on arable lands. Therefore, the sludge output data have also been supplemented by quantities of wastewater sludge that have been used in agriculture. Here, the aim is to assess each municipality’s current situation in terms of the extent to which P is being recycled from wastewater. From these data, it would be possible to assess the potential challenges or opportunities of implementing the proposed P-recycling target. The quantities of wastewater sludge used as fertilizers on arable lands indicate each municipality’s situation in terms of P-recycling. By analyzing the sludge use data in each municipality, the potential for P-recycling in the municipalities can be assessed.

Table 4: Wastewater Sludge Output and Use in the Selected Three Municipalities from 2007-2013 (t) (Dry Weight)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motala</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>802</td>
<td>810.6</td>
<td>874</td>
<td>837</td>
<td>930</td>
<td>887</td>
<td>N/A</td>
</tr>
<tr>
<td>S&lt;sub&gt;agr&lt;/sub&gt;</td>
<td>596</td>
<td>816.7</td>
<td>769.1</td>
<td>754</td>
<td>770</td>
<td>880</td>
<td>N/A</td>
</tr>
<tr>
<td>Finspång</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>473</td>
<td>452</td>
<td>222</td>
<td>520</td>
<td>490</td>
<td>466</td>
<td>260</td>
</tr>
<tr>
<td>S&lt;sub&gt;agr&lt;/sub&gt;</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mjölby</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>915*</td>
<td>934*</td>
<td>768.5</td>
<td>734.2</td>
<td>828.2</td>
<td>850.7</td>
<td>747.5</td>
</tr>
<tr>
<td>S&lt;sub&gt;agr&lt;/sub&gt;</td>
<td>716*</td>
<td>710*</td>
<td>522.3</td>
<td>0</td>
<td>0</td>
<td>226.4</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Finspång, Mjölby and Motala WWTPs, 2014.
*Obtained from the Swedish Rural Economy and Agricultural Societies in Östergötland

NB:-
1. S<sub>tot</sub> stands for the total amount of sludge produced and S<sub>agr</sub> stands for the total amount of sludge used in agricultural lands.
2. N/A stands for not available data.

Based on the data presented in the above table, in Motala a high proportion (89.2%) of the sludge produced has been used on agricultural lands over the six-year period (Table 4). Table 4 also shows that in 2008 the amount of sludge used for agriculture exceeded the annual sludge output in Motala by about 6.1t. This amount is the carryover from the previous year (2007) which remained in stock in 2008 in order to undergo the mandatory 6 months of sludge sterilization phase. Contrastingly, in Mjölby only 35.5% of the recovered wastewater sludge has been used for agriculture (2007-2013), while no sludge has been used at all in Finspång.
The sludge which is not used for agricultural purposes is currently used for other purposes such as covering material on landfills and soil conditioner on non-agricultural urban landscapes.

Hypothetically one can assume that the larger the number of inhabitants that live in an urban area, more quantities of sludge which can be extracted out of the inflowing wastewater at WWTPs. Nevertheless, the amount of sludge produced in WWTPs also varies on the methods and processes used in separating the suspended particles from wastewater. A comparison of data in Table 4 indicates that although Mjölby has a population size which is 62% of Motala’s population, the quantities of sludge produced in Mjölby was at times more than Motala’s for several years. Similarly, Mjölby’s average concentration of the P in wastewater sludge is the least of the three municipalities (see Table 4). The reason for the higher sludge weight and density in Mjölby is that lime (CaO) is added to stabilize the wastewater sludge. Although the addition of lime is effective in sterilizing wastewater sludge against pathogenic agents, it raises the alkalinity and volume of sludge (Arthurson, 2008). Moreover, the use of lime as sludge stabilizer does not result in the release of biogases as by-products. Contrarily, the WWTPs in Motala and Finspång use anaerobic digestion for the stabilization of the separated sludge. Anaerobic digestion further breaks down the organic material in sludge in the form of methane (CH₄) and little quantities of carbon dioxide (CO₂) which are released as by-products (ibid).

5.2. Wastewater Substance Contents

The quantity of the P that can potentially be recovered from wastewater sludge without the analysis of the quality of wastewater sludge cannot sufficiently indicate the potentials for P-recycling. The quality of wastewater sludge mainly refers to the concentration levels of undesired substances it has and its content of P-fractionations. Using the average P concentration of wastewater sludge data from each of the studied WWTPs, it can be possible to estimate the amount of P which is recovered and which can potentially be recycled. In a generic sense, the average P-fractionation data are important because they imply the impacts which the proposed target would have in terms of increasing the quantities of recycled P.

Another important content of wastewater sludge is various undesired substances. In the intermediate period, the proposed target foresees the continuation of spreading wastewater sludge on arable lands as the viable P-recycling method. Reduced concentration levels of the undesired substances in wastewater sludge encourage the spreading of the sludge on arable lands with minimized risks for the long-term deposition of such substances. On the other hand, higher concentration levels of undesired substances in wastewater sludge not only inhibit recycling nutrients on arable lands, but they enhance dependence on the use of imported fertilizers. Therefore, the data presented under this sub-section are concerned with the contents of heavy metals the wastewater sludge produced in the studied WWTPs. These quantitative data in conjunction with the related qualitative data will be used to analyze the potential constraints or opportunities which each of the studied municipalities will encounter in implementing the proposed target.
In Table 5 the P-contents of the dry weight wastewater sludge from the studied WWTPs have been presented. Originally, such data are recorded in terms of monthly averages at the WWTPs and have been later reported as annual average values. Analyzing the amount of wastewater sludge produced at the WWTPs does not indicate the amount of P that could be recovered. Instead, the P fractionations in wastewater sludge can be used in estimating the potential quantities of P contents that could potentially be recovered and reused on arable lands. The P fractionations in wastewater sludge can give indications on how rich the sludge from each WWTP is in terms of its P contents. The amount of sludge output is not directly related to the total amount of potentially recoverable P from the sludge. Therefore, in addition to the quantities of wastewater sludge produced in the studied WWTPs, the P concentration

Table 5: Average Dry Weight Phosphorus Fractionations in Wastewater Sludge 2007-2013 (g/kg)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mjölby</td>
<td>N/A</td>
<td>14</td>
<td>12.2</td>
<td>12.7</td>
<td>12.1</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Motala</td>
<td>30</td>
<td>29</td>
<td>33.1</td>
<td>31.5</td>
<td>36.3</td>
<td>33.8</td>
<td>36.8</td>
</tr>
<tr>
<td>Finspång</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>21.3</td>
<td>22.3</td>
<td>24.8</td>
<td>25.5</td>
</tr>
</tbody>
</table>

Source: Mjölby, Finspång and Motala WWTPs, 2014

In addition to the P fractionations that are found in wastewater sludge, the concentrations of undesired substances determine if the sludge is safe enough to be spread as fertilizer on arable lands. Tables 6, 7, and 8 compare the average concentration of heavy metals in the studied WWTPs with the current and the proposed recommended threshold levels. These data will be later used to assess the quality of sludge from each of the studied WWTPs vis-à-vis the current and the proposed recommended threshold for the undesired substances. The purpose of comparing the heavy metals concentration data from the studied municipalities with the proposed thresholds is to show how each municipality is currently positioned with respect to the long term reduction of these substances. Moreover, such comparisons can help identify which particular substances require to be further reduced so that the P-recycling rate can sustainably increase in the municipalities. Although, SEPA’s latest target includes the thresholds for a range of substances that have not been included in the current regulation (see Table 2), the collected data in this thesis includes only eight heavy metals. The current regulation does not include Silver (Ag), but since the studied WWTPs monitor its concentration in wastewater, the data presented in the commencing tables include Ag as well.
Table 6: Average Heavy Metal Concentrations of Wastewater Sludge at the Studied WWTPs under the Current Regulation (mg/kg by Dry Weight)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Motala*</th>
<th>Mjölby**</th>
<th>Finspång***</th>
<th>Current Regulation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>16.4</td>
<td>7.3</td>
<td>15.1</td>
<td>100</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.8</td>
<td>0.5</td>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>365.9</td>
<td>310.4</td>
<td>401.1</td>
<td>600</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>24.9</td>
<td>14.5</td>
<td>27.3</td>
<td>100</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.7</td>
<td>0.3</td>
<td>0.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>15.7</td>
<td>9.6</td>
<td>18.5</td>
<td>50</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>598.9</td>
<td>285.4</td>
<td>541.8</td>
<td>800</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>5.1</td>
<td>0.9</td>
<td>2.1</td>
<td>-</td>
</tr>
</tbody>
</table>


Table 7: Comparison of the Current Regulation for Heavy Metal Concentrations with the Thresholds for the Proposed Phases (mg/kg by Dry Weight)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Current Regulation*</th>
<th>2015</th>
<th>2023</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>100</td>
<td>35,0</td>
<td>30,0</td>
<td>25,0</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>2</td>
<td>1,0</td>
<td>0,9</td>
<td>0,8</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>600</td>
<td>600,0</td>
<td>550,0</td>
<td>475,0</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>100</td>
<td>60,0</td>
<td>45,0</td>
<td>35,0</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>2,5</td>
<td>1,0</td>
<td>0,8</td>
<td>0,6</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>50</td>
<td>40,0</td>
<td>35,0</td>
<td>30,0</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>800</td>
<td>800,0</td>
<td>750,0</td>
<td>700,0</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>-</td>
<td>5,0</td>
<td>4,0</td>
<td>3,0</td>
</tr>
</tbody>
</table>

Table: 8 Comparison of Average Substance Concentration Levels at the Studied WWTPs Against the Proposed Threshold Levels (mg/kg by Dry Weight)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Motala</th>
<th>Mjölby</th>
<th>Finspång</th>
<th>2015</th>
<th>2023</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>16.4</td>
<td>7.3</td>
<td>15.1</td>
<td>35.0</td>
<td>30.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.8</td>
<td>0.5</td>
<td>1.2</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>365.9</td>
<td>310.4</td>
<td>401.1</td>
<td>600.0</td>
<td>550.0</td>
<td>475.0</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>24.9</td>
<td>14.5</td>
<td>27.3</td>
<td>60.0</td>
<td>45.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.7</td>
<td>0.3</td>
<td>0.6</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>15.7</td>
<td>9.6</td>
<td>18.5</td>
<td>40.0</td>
<td>35.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>598.9</td>
<td>285.4</td>
<td>541.8</td>
<td>800.0</td>
<td>750.0</td>
<td>700.0</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>5.1</td>
<td>0.9</td>
<td>2.1</td>
<td>5.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Source: Motala, Mjölby and Finspång WWTPs (2014); SEPA, 2013

The data in Table 5 have been presented graphically below in order to show the trend in the contents of P fractionations of wastewater sludge. Although the figures presented in Table 5 are not sufficient enough to assess their long-term trend. However, as it can be observed from Graph 1, the available data show that there is an increasing trend in Motala and Finspång, while in Mjölby the trend is somewhat constant. The average P fractionations at the studied WWTPs fluctuate through the years. There are many factors that affect the variations in P fractionation levels from one location to another. It can be noted from Table 5 and Graph 1, that the average P fractionation is much lower in Mjölby than the other two municipalities. Among other things, the variation can be attributed to the different types of P-removal methods used at the WWTPs.

Graph 1: Average Phosphorus Fractionations from Wastewater Sludge by Dry Weight 2007-2013 (g/kg)

Source: Mjölby, Finspång and Motala WWTPs, 2014
The following graphs show the heavy metals contents of wastewater sludge in the three Östergötland municipalities. The values are the yearly average sample values. Notice that Motala’s data is from 2007-2013 while Mjölby’s start from 2008 and Finspång’s data are only from 2010-2013 (see Tables 1-3 in Appendix). These data will be analyzed in the following chapter in which they are compared with the current and proposed thresholds. In the current standards of sludge quality Ag is not included as one of the heavy metals which are measured to indicate sludge quality. However, in the proposed target Ag will be added as one of the heavy metals contents of sludge to be restricted. The graphs below show that although the Ag content in Motala is following a declining trend over the years, it is much higher than the other WWTPs (Graph 1a). With regards to Cd and Hg, the trend is stable in the case of Motala while in Mjölby the trend fluctuates moderately. Nevertheless, even though Motala and Mjölby’s Cd content is relatively low, Finspång’s values are relatively higher with a notable rise between 2012 and 2013 (Graph 3a).

**Graphs 2a and 2b: Average Concentrations of Heavy Metal Contents in Wastewater Sludge in Motala 2007-2013 (mg/kg)**

![Graph 2a](image1.png)

![Graph 2b](image2.png)
Source: Motala WWTP, 2014

Graphs 3a and 3b: Average Concentrations of Heavy Metal Contents in Wastewater Sludge in Mjölby 2008-2013 (mg/kg)

Source: Mjölby WWTP, 2014
5.3. Sweden’s Policy Direction for Phosphorus Recycling

In the commencing sub-sections, the qualitative data obtained from the interviews conducted with the respondents who participated in the study are presented. The theme of the interview results discussed in this sub-section focuses on Sweden’s overall strategy towards a sustainable P management. With regards to the 2013 proposed target, Expert-1 and Expert-2 consider the target as a step forward in setting a sustainable P recovery pathway in Sweden. Both experts stress that reusing of P from wastewater sludge on arable lands is the most feasible recovery option. According to the opinions of the majority of the interviewees, as long as wastewater sludge meets the acceptable recommended quality standards, it should be used as a fertilizer.
on agricultural lands. Most of the interviewees agreed that the phosphorus recycling rate from wastewater sludge should be increased in view of the global P scarcity and Sweden’s pathway should continue to follow this direction. In particular, Expert-1 reflected on the historical experiences of recovering P, mentioning that Sweden was one of the first countries to install phosphorus removal technologies in WWTPs at least since the 1980s. Expert-1 mentioned that the debate on the usage of wastewater sludge on arable lands has been around in Sweden at least since the 1970s and both pointed out that the highlight came in the 1990s when the eutrophication problem became a major environmental concern. Although the recovery of phosphorus from the environmental protection perspective has been the main focus, the intention for nutrient recovery was already there. Several of the interviewees also made mention of the recent crises in the international fertilizer markets and noted that these crises have influenced the rise in the awareness of global phosphorus scarcity.

Both experts have pointed out that the approach to address the P-scarcity challenge in Sweden should mainly focus on the recovery of phosphorus from wastewater sludge at least during the interim period. Their opinions reflect concerns about the high fertilizer prices and the Cadmium (Cd) contents of the commercial fertilizers available at the international markets. Expert-1 in particular emphasized that although today Sweden imports phosphate fertilizers of good quality that have low Cd content, it is important to consider that phosphates-based commercial fertilizers are not entirely Cadmium-free. This expert also added further that compared to the substance content in the wastewater sludge from most of Sweden’s WWTPs, the Cd content of the commercial phosphate at the international markets is often higher.

The majority of the interviewees agreed that recycling of wastewater sludge by reusing it on agricultural lands is currently the most viable option. However, their arguments for the key drivers of using wastewater sludge as fertilizer depart from two perspectives. Expert-1 took a systems analysis approach to assess the viability of the direct application of wastewater sludge on agricultural lands as opposed to other options. According to this argument, cost factors in the P-recovery system are the guiding criteria in determining the means to be used in achieving the proposed target. Economic factors will be influential in setting the path that Sweden will follow until viable technological solutions are developed in the long-run. Regardless of the limitation posed by the presence of undesired substances in wastewater sludge, spreading sludge on arable lands is so far a cost-efficient method of recycling P from wastewater. Nevertheless, with the stringent recommended thresholds for undesired substances in wastewater sludge, implementing the 2013 SEPA target proposal will potentially hinder the intended outcome of increasing the P-recycling level. Hence, the challenge would be to find balance between controlling the long-term deposition of substances on soils and the need to optimize the allocation of resources including social costs.

Expert-2 regards spreading of wastewater sludge on farmlands as the most effective P-recycling method due to the multiple ecological advantages that sludge has in enhancing soil fertility and its potential effects of reducing dependence on commercial fertilizers. This view emphasizes that wastewater sludge contains not only P but also other valuable components such as organic matter contents. Expert-2 did not only emphasize on the ecological benefits
of wastewater sludge but also explained that the P balance in Swedish agricultural lands still requires additions of more P. *Expert-2* further pointed out that today crops growing on Swedish agricultural lands require on average 20-22 kg P/ha per year, but the net addition is less than what is required. In addition to the ecological benefits of using wastewater sludge as a biofertilizer, it augments the requirement for mineral P-fertilizers in Swedish agriculture. In view of the high prices of commercial fertilizers, wastewater sludge is also a cost-effective option to increasing the P stocks in Swedish agricultural soils. *Expert-2* emphasized that the P stocks in Swedish agricultural soils have been mined for many years and that wastewater sludge would be a less expensive-alternative source of P.

Concerning SEPA’s P-recycling proposal, most of the interviewees generally see it as an important step in taking actions in response to the phosphorus scarcity challenge. Both experts regard the proposed target as a realistic and balanced approach which considers the prevailing circumstances in Sweden. On the other hand, the other respondents think that the proposed target will likely face strong challenges that may undermine its effectiveness. *Officer-3* has the opinion that since Sweden is a developed country, it would be less affected by the rising fertilizer prices than the developing countries. Hence, this could diminish the driving force to increase P-recycling. Moreover, *Officer-3* expressed the opinion that if the quality of Swedish sludge does not improve, Sweden’s vast open areas such as abandoned mines and forests could tend to encourage the continuation of depositing sludge in these areas.

From another angle, one of the WWTP engineers thinks that the proposed target comes with stringent wastewater sludge quality standards and doubted that the proposed target is realistic enough to consider the local circumstances in Swedish municipalities. According to the opinion of *Officer-1*, the idea of P-scarcity should basically not be the only driving force behind the recycling target, because this creates unnecessary social costs. This interviewee explained that although the world P resources are limited, the focus should rather be on finding the balance between the resources that are required to be allocated to achieve the P-recycling target and the overall benefits to be gained by the society today. *Expert-2* expects that the proposed target would likely undergo through the approval process at the Swedish Parliament with no significant modifications, before it will finally be ratified as a national law sometime between 2015 and 2016. With regards to facilitating the effective implementation of the proposed target, *Expert-1* commented that there should be an exchange of information among the local, regional and national levels, well ahead before enforcing the proposed target. This would allow the Swedish WTTPs to transit into the new regulation in a coordinated manner.

The interviewees from the municipalities and the County Administrative Board of Östergötland indicated that although there is a general awareness of phosphorus scarcity at the regional and municipal environmental departments, it has not yet resulted in affecting local policies. The County Administrative Board in Östergötland as well as the municipalities do not have concrete strategies for increased P-recycling incorporated with their environmental plans. So far discussions on SEPA’s proposed target have been conducted at the Environmental Protection Department of the County Administrative Board in Östergötland and the Environmental and Health Protection Unit of Motala Municipality. The aim of these
discussions was to critically assess and comment on the proposed target. According to the respective respondents, themes of the opinions expressed at these meetings were also similar to some of the important issues raised during the interview sessions. In the remaining municipalities, such discussions have not taken place by the time this thesis was being written, but there are plans to eventually assess the feasibility of different recovery options. For instance, the municipality of Finspång has a plan which is on pipeline to evaluate the various P-recovery options in the municipality’s medium-term waste management plan (Finspång Municipality, 2014). According to the interviewees’ responses, the municipalities rather seek to wait for further guidelines concerning the implementation of the proposed target from the national government. However, there is a political goal particularly in Motala and Mjölby that aims to return 100% of the wastewater sludge on arable lands. Although P-recycling is implicitly incorporated with the municipal waste management plans, the emphasis given is on the sustainable waste management perspective rather than responding to the impacts of the global P-scarcity challenge.

5.3.1. Undesired Substance Concentrations in Wastewater Sludge

All of the interviewees agreed that the main challenge in achieving the targeted goal is the technical requirements to meet the quality standards for using wastewater sludge on agricultural lands. The experts highlighted that today there is sufficient scientific knowledge about the effect of heavy metals and already the concentration levels have significantly been reduced over the years. In relation to this, the concern of the experts is that there is little knowledge about the long-term effects of the micro-organic pollutants that are present in wastewater sludge. One example cited by Expert-2 is the persistent substances such as PCB which are difficult to accurately detect their concentration in wastewater sludge. Expert-2 further explained that although their use has been restricted in Sweden, they can still be found in wastewater. With the current state of scientific knowledge regarding these substances, further research is needed on advanced analysis methods and their long-term effects on soils. Expert-1 remarked that current knowledge on the organic pollutants found in wastewater sludge cannot determine whether these substances degrade in the soil with time or whether they affect plants or micro-organisms in soils. Furthermore, both experts explained that although the amount of organic pollutants found in a range of products is today much lower than it was several decades ago, these substances are persistent, difficult to trace; and their long-term effect still needs to be researched.

The experts explained that the presence of hormones and pharmaceutical residues in wastewater sludge is very insignificant and they potentially threaten the aquatic ecology when released to the environment along with effluents from WWTPs. Studies concerning the environmental impacts of such substances need to be deepened in order to accumulate adequate knowledge concerning them. The experts also emphasized that as long as the sludge meets the standard levels for the undesired substances it should be safe to be used in agricultural lands. Both of them cited the long-term experiments that are being carried out in Southern Sweden to investigate the effect of wastewater sludge on soils. The experts mentioned that results from a long-term Swedish study which has been going on since 1981, so far indicate no evidence
suggesting that wastewater sludge has long-term negative effects neither on the agricultural lands or the agricultural products produced using it. **Expert-2** further explained that often the arguments against using wastewater sludge on agricultural lands are not based on facts but rather on individual opinions.

The interviewees from the studied municipalities and the regional government remarked that wastewater sludge is highly valued by farmers in Östergötland as a source of nutrients and organic matter. However, one of the WWTP engineers mentioned that regardless of the local farmers’ preferences to using good sludge with acceptable concentration of undesired substances, the local food industry in that particular municipality does not accept grains produced using wastewater sludge as fertilizer from these farmers. For one of the studied municipalities, the implementation of REVAQ certification system bears high costs compared to the relatively smaller amounts of sludge produced at the WWTP. An interesting opinion also expressed by the engineer from this particular WWTP is that their decision for not joining the REVAQ certification system is that in the cases when the heavy metal content becomes high, the Swedish environmental protection system does not offer other options in dealing with the sludge. According to the opinion of this engineer, the remaining option for the WWTP is to incinerate the sludge and keep the ashes until other alternative solutions to extracting the P or using the ash become available. Currently, this particular WWTP has obtained from the regional government a temporary permit to use wastewater sludge as landfill covering material.

**5.3.2. The Proposed Recycling Target and Thresholds for Undesired Substances**

With regards to the new thresholds for the undesired substances proposed by SEPA, the majority of the interviewees remarked that the proposed thresholds for heavy metals could be challenging in achieving the proposed target. Especially, the interviewees from the WWTPs anticipate that implementing these standards would be technically and financially challenging, once the target comes into force. They gave two reasons as to why meeting the new standards would be challenging. The first reason was that although the concentration of heavy metals in the sludge has been declining over the years; the WWTPs find that often due to unknown reasons the contents of one or two of the metals in the sludge suddenly become higher than the recommended level. This is due to the fact that the WWTPs have no control over the in-flow from the sources. **Officer-3** also concurred that the municipalities do experience problems of frequent increases in the level of one or two of the heavy metals higher than the recommended levels due to unknown reasons. The interviewees in Motala explained that they do conduct test analyses to trace the sources for the frequent rises of the concentration levels of heavy metals in wastewater sludge. According to them, the sources for these fluctuations in the heavy metals content of the sludge occur mostly in residential areas, as the heavy industries in the municipalities have their own wastewater treatment facilities. The interviewees from the WWTPs also think that the sudden influx of high concentration of heavy metals in the sewage system comes from chemicals used in ordinary households. For that matter, an engineer from one of the studied WWTPs explained that because of the difficulty in controlling the sources for the occasional fluctuations of heavy metal concentrations, the only viable option left for the WWTP is to incinerate the sludge. This engineer further commented that incinerating the
sludge would not be a long-term solution as special permits are required to incinerate it only for a limited time.

Another challenge mentioned by the interviewees from the WWTPs regarding meeting the requirements of the proposed regulations is that the new proposal comes with stringent wastewater sludge sanitization requirements. This has increased cost implications to WWTPs to undertake a series of additional energy-intensive sanitization procedures required by the proposed regulation. According to the interviewees from the WWTPs, the current sanitization standards are still effective in making sure that the sludge is sanitized against pathogenic threats. Their opinion is that the current sludge sanitization processes applied by the municipal WWTPs are effective enough in preventing pathogenic infections. Replacing the current procedures with the proposed regulations would only unnecessarily increases the operating costs. The WWTP engineers mention that their quality control reports actually show that with the current standards, their sludge is normally free of pathogenic infections. According to them, presence of pathogens such as salmonella on wastewater sludge is extremely rare since the sludge goes through a series of sanitation processes before it is stored for a minimum of six months. Expert-2 also concurred that for a number of reasons within those six months of the drying phase any pathogenic agents that could have survived the sanitization processes are destroyed. This expert mentioned an example of tests carried out in the development of the REVAQ project where only one of a total of more than 700 samples was found to contain salmonella due to unexplained reasons. Accordingly, Expert-2 commented that the requirement for further sludge sanitization process has been included too early considering the sharply increasing costs of implementing such requirements that would need to be sustained by the WWTPs. With regards to the quality standards for the undesired substances that would become effective in the second phase of the target (by 2023), Expert-2 suggested that it would be too early to incorporate them in the proposed target a decade ahead before they are to be effectively implemented. According to this expert’s opinion, at the moment the scientific knowledge concerning the long-term impacts of organic substances is very limited. Moreover, the expert remarked that towards the end of the current decade, it would be possible to develop adequate scientific knowledge regarding these substances to introduce effective regulations.

5.4. Options for the Sustainable Recycling of Phosphorus

Some of the issues raised by the experts pertain to the role of technological options in the recovery of phosphorus from wastewater sludge (see Appendix III). Expert-1 in particular expressed the opinion that the main constraint in recovering phosphorus from wastewater sludge is that currently commercially viable technologies are not available in Sweden or elsewhere. According to the opinion of this expert, from a systems perspective the logistical costs involved in putting wastewater sludge on agricultural lands are still low enough to allow increased recovery rate from this option. Nevertheless, Expert-1 remarked that future technological advancements will allow the extraction of P-fractionations from wastewater sludge to be economically viable in the long-run. With regards to the different recovery methods that are being developed around the world, the agricultural expert is rather skeptical about the technical and economic feasibility of these methods in becoming effective...
phosphorus recovery options. Firstly, thermal methods waste other nutrients (K and N) and the carbon contents of wastewater sludge including microbes which play an important role in improving soil fertility. According to Expert 2, other chemical recovery methods such as struvite can only recover on average 20%-25% of P, with a maximum capability of about 50%; while with the direct application of wastewater sludge on soils, it would be possible to recover more than 95% of the P in the sludge. Secondly, the environmental impacts associated with the high cost of energy consumption, the use of chemicals and the resulting greenhouse gases emissions from the incineration process are not sustainable. However, Expert-3 who represents the technological stakeholders in P-recovery regards the thermal recovery that is currently under development as important means in achieving the proposed recovery target. The advantage of using thermal technologies to recover P, cited by Expert-3 is the high inefficiency in recovering P-fractions from sludge and separating the undesired substances. In the contrary, according to Expert-3, technologies that use incineration methods of P-recovery reduce the logistical costs associated with transporting dewatered sludge since this process reduces the sludge weight by 90%. Moreover, Expert-3 remarks that the development of a full-scale plant that will use the incineration method of recovering P from wastewater sludge is already in progress.

5.5. Institutional Aspects of Phosphorus Recovery

The qualitative data gathered through the interviews had several themes that pertain to the institutional aspects of reusing wastewater sludge as fertilizer. The first aspect is concerned with the parallel implementation of REVAQ as a voluntary sludge certification system versus the anticipated mandatory enforcement of the proposed regulation. Another important issue raised by the interviewees is concerned with the institutional arrangements which are related to the agricultural use of wastewater sludge. Hence, under this section, the qualitative data concerning the management aspect of REVAQ and several of the key stakeholders which are involved in the reuse of P from wastewater sludge are presented.

5.5.1. The Role of REVAQ

In relevance to the institutional aspects of reusing P from wastewater sludge, the interviewees have mentioned the importance of the Swedish sludge certification system – REVAQ. REVAQ has both institutional and technical aspects. As a certification system, REVAQ is an institutionalized system whereby certification of sludge makes it acceptable for the concerned stakeholders to reuse it in agriculture. REVAQ is regulated by a state authority and its implementation at the WWTPs which have voluntarily joined the system requires local decisions that have financial and managerial implications. Whereas on the other hand, as a technical system, implementing REVAQ certification at WWTPs requires that specific standardized quality control and technical processes at WWTPs should be met. Nevertheless, this thesis focuses on the institutional aspects of REVAQ without necessarily going through its technical requirements.
The interviewees from Mjölby and Motala have indicated that the WWTPs in these municipalities implement the REVAQ certification system. They regard the system as a way of improving the technical capabilities leading towards the higher level sludge standards set by the proposed target. Interviewees from these two WWTPs also think that although REVAQ is effective in improving sludge quality, it requires duplicated test analyses and documentation procedures; creating more workloads to the WWTPs personnel. Moreover, the WWTPs find the associated financial costs in implementing the required certification system to the WWTPs to be high. The cost components of REVAQ include membership fees, auditing and salary for follow-up personnel. Expert-2 also reiterated that the sanitization requirements of REVAQ have relatively high cost implications to the smaller WWTPs, due to high energy consumption. All of the interviewees from the studied municipalities suggested that working under the two regulations (REVAQ and the proposed target) would ideally not be the preferred option. They think that the proposed regulation is more stringent than REVAQ and it would eventually duplicate the costs of implementing both standards at the same time. In view of these factors the concerned interviewees anticipate that once the proposed recovery target becomes a national law, REVAQ will no longer be relevant because the WWTPs will have to comply with more stringent recommended levels that would be imposed by the new regulations. The sanitary requirements in the proposed regulation require additional sludge storage and higher energy cost implications in the sludge sanitization process. Most of the concerned interviewees explained that the smaller municipalities in Östergötland have limited resources to expand the required sanitary facilities and undertake further investments required to increase P-recycling. Several of the interviewed WWTP engineers remarked that considering the relatively smaller size of the studied WWTPs and the volume of wastewater they handle; the sanitary requirements of the proposed regulation would unnecessarily increase their operating costs.

5.5.2. Actors and Stakeholders Involved with Wastewater Sludge

With regards to the proposed regulations several of the respondents expressed concerns that without the involvement of different actors and stakeholders, achieving the proposed target would be challenging. Expert-2 explained that currently because of other regulations, Swedish farmers are under pressure to meet higher quality standards in producing agricultural products domestically. This expert mentioned on the other hand that today Sweden imports a significant proportion of its agricultural products from around the world. According to this expert’s view, the regulations applied on Swedish agricultural products should similarly be applied on the imported products which are produced in different standard regimes. Expert-2 further remarks that this would make it possible to restrict the levels of these substances in the products that the society consumes. Similar concerns were also expressed by the engineers as well, that the undesired substances that end up in the wastewater sludge in Sweden originally come from a range of products consumed by the society. Accordingly, these interviewees explained that municipal WWTPs carry out the arduous task of treating wastewater before releasing it back to the environment, while they cannot technically remove the undesired substances from the sludge component. This expert remarked that instead of imposing more demands on the WWTPs by controlling the undesired substance contents of sludge, the key to resolving this challenge lies on restricting the circulation of these substances in every corner of society.
Several interviewees also suggested that organizations such as Kemikalinspektionen (Swedish Chemicals Agency), Lantbrukarnas Riksförbund- LRF (Federation of Swedish Farmers) and Livsmedelsverket (National Food Agency) should collaboratively work together in limiting the contents of the undesirable substances in products consumed by society. On the other hand, the interviewees have also pointed out that due to the presence of undesired substances in wastewater sludge, the actors which have influence over farmers and the food industries do not support the use of sludge as fertilizer. Officer-1 cited the food industry and Naturskyddsföreningen (Swedish Society for Nature Conservation) as some of the actors which object to using wastewater sludge by farmers.
6. Discussion

6.1. Introduction

Several of the steps involved in SFPRR may have overlaps between both the national and the local perspectives. This is due to the fact that national regulations apply uniformly to all Swedish municipalities in terms of the overall environmental objectives framework such as regulations of wastewater treatment processes and chemical uses. Moreover, by regulation similar types of infrastructure and processes are used in the Swedish wastewater treatment sector. As a result, key drivers (Step 1), system boundaries (Step 2), recovery technologies (Step 4) or the concerned stakeholders and institutional arrangements (Step 8) at the smaller Swedish municipalities are the reflections of the national settings. However, as the gathered data show, the local dispositions with regards to implementing the proposed P-recycling target can vary from municipality to municipality. Such peculiarities can be regarding the quantity or quality of recovered P (Step 3), the potential conflicts or synergies (Step 7), local decisions or practices concerning the use of recovered P (Step 8). Nonetheless, the SFPRR will be relevant to the thesis research aim with respect to implementing the national policy goals at the municipal level. This framework approach will particularly be useful in identifying local/national driving forces (Step 1), the quantity or quality of locally recovered P (Step 3) the potential conflicts or synergies of P-recycling (Step 7).

6.2. Sweden’s Driving Forces for Recycling Phosphorus from Wastewater

The initial step of the SFPRR involves the identification of the key drivers for the reuse of P resources. Identifying the key drivers is an important step, because it clearly defines the rationale for P-recycling measures. This step constitutes a formative role for P-recovery measures: ‘Clarifying the key driver upfront is important because it will impact the design and effectiveness of the recovery system’ (Cordell et al., 2011:748). The global key drivers suggested by Cordell et al. (2011) vary from pollution prevention to maintenance requirements that prevent nutrient buildup in WWTPs technical systems. This section discusses the key drivers which play significant role in the Swedish pathway towards sustainable P management.

6.2.1. Experiences from Nutrient Pollution and Substance Deposition Reduction Measures

Cordell (2010) remarks that P-removal measures have been in practice for several decades in different parts of the world, but their prime objective has focused on the prevention of environmental pollution than the recycling of this scarce resource. P-recycling measures technically augment nutrient removal measures. By any means, the successively proposed P-recycling targets (2002 and 2013) signify the shift in Sweden’s policy focus from nutrient pollution prevention towards nutrient recycling measures. Although, the importance of wastewater sludge as a source of nutrients has been recognized long ago (Neset and Cordell, 2011; Bengtsson and Tillman, 2004), the introduction of nutrient recycling measures was a gradual process. Sweden has gained successful outcomes by implementing mandatory regulations for nutrient removal and control of substances in wastewater sludge (Lindeholm et
al., 2012a). As a result, Sweden’s sanitary system has developed an effective nutrient removal capability over the years. The sustainability thinking that had emerged in the 1990s prioritized resource efficiency and led to the formulation of regulations that limit the heavy metals content of wastewater sludge used as fertilizer. The current regulations which limit the presence of undesired substances in wastewater sludge (SNFS 1998:944 and SFS 1994:2) have effectively reduced the deposition of heavy metals on arable lands below the level that could potentially cause immediate environmental risks (Linderhölm et al., 2012b). Furthermore, the Swedish debate on the agricultural use of sludge has been a pushing factor which highlighted the need to limit the deposition of undesired substances on farmlands. Naturally, the long-term experiences gained throughout this transition can be regarded as the inevitable course that finally led to the development of a parallel nutrient recycling measure.

6.2.2. The National EQOs as the Drivers for Local Action-Plans

Various publications indicate that the awareness on the P-scarcity challenge peaked internationally during the 2007/2008 global fertilizer prices hike (Cordell, 2010; Ulrich and Schnug, 2013). Awareness of the P-scarcity challenge is a key element for the effectiveness of appropriate measures which are aimed to address the challenge. This perspective is based on the assumption that awareness of an environmental challenge leads to the formulation of responsive measures that aim to effectively address such challenges (Blake, 1999). Cordell et al. (2011) emphasize that other than the need to prevent pollution, the recycling of P should also be the main driver behind P-recovery measures for the obvious reason that P is a scarce resource. Hence, the interviews conducted in this thesis partly probed on whether the local decisions or policies were driven by the same perception of the P-scarcity challenge held internationally (see ‘Interview Guide’ in Appendix II). The qualitative results of the study imply that the studied municipalities have not yet concretely formulated their own separate action-plans to guide local decision-making in response to the global P-scarcity challenge. Contrarily, the results also show that at the individual level, the interviewed WWTP Engineers or the municipal Environmental Coordinators are aware of the global P-scarcity challenge. The municipal waste management plans (in Motala and Finspång) and the political will (in Mjölby and Motala) reflect the generic sense of recycling as a means of maintaining resource efficient cycles. However, it would be misleading to conclude that local environmental decisions at the studied municipalities do not reflect the perception that regards the scarcity aspect of P.

What the qualitative results in this thesis imply is that the local policies concerning P-recycling are supposed to be designed under the guidelines of a framework of national environmental policies and codes. The underlying fact is that local environmental decision-making is supposed to be guided by the EQOs, which constitute Sweden’s broader national ambitions towards a sustainable future (Nilsson et al., 2008). Perhaps the global fertilizer market crisis might have led the Swedish government in commissioning SEPA to make revisions to the 2002 target proposal. Although SEPA’s 2013 report on the P-recycling target proposal refers to concepts such as P-scarcity or Peak Phosphorus, the proposed target is designed to be an integral part of Sweden’s overall sustainable development strategy. The 2013 report states that: ‘The starting point for this [target] is the generational goal’s subparagraph on resource-efficient
eco-cycles that are free of undesirable materials to the extent possible’ (SEPA, 2013:11). The Generational Goal is a broader definition of Sweden’s visualization of a sustainable future and it is translated into the 16 EQOs which are formulated to be achieved within the lifetime of a generation. Sweden’s national EQOs are further broken down into 24 milestone targets for the gradual attainment of these objectives (SEPA, 2012). It is not surprising at all that SEPA had initially proposed the 2002 P-recycling target, three years after the adoption of the EQOs by the Swedish Parliament and long before the awareness of P-scarcity began to emerge internationally. Interestingly, the national EQOs take precedence over the influence of the growing international awareness on P-scarcity in Sweden. The EQOs constitute Sweden’s visualization of sustainable development and local decisions are meant to be steered accordingly.

6.2.3. Reduced Dependence on Commercial Fertilizers

Although, most of the Swedish agricultural lands have relatively moderate P stocks (Lindeholm et al., 2012a), Sweden relies on the import of commercial phosphate fertilizers. Considering the fluctuating trends of P prices in the global market, the supply of less-costly recovered P would potentially be beneficial for the local agriculture. A sustainable P-recycling pathway requires ‘both a decrease in phosphorus demand and an increase in alternative phosphorus supply sources’ (Neset and Cordell, 2011:2). If the proposed target is implemented effectively, with an increased P-recycling from wastewater sludge, it will to a certain extent decrease dependence on imported fertilizers and the vulnerability to global market fluctuations will be reduced. Moreover, a P-security measure should also link to the other sustainable development measures such as enhancing local agricultural productivity (ibid). As results from the qualitative data in this thesis indicate, there is an expectation from the majority of the interviewees who participated in the study, that the proposed target can potentially play an important role in reducing the dependence on imported phosphate fertilizers. Today Sweden imports industrially processed phosphate fertilizers with low Cd contents from the international market and such products are relatively expensive. When the proposed standards come into full implementation under the three phases, there is an opportunity for increasing the supply of recycled P domestically. Moreover, the average Cd contents of sludge in the studied WWTPs are significantly lower than the current threshold for wastewater sludge (see Table 6 and Tables 1-3 in Appendix I).

Moreover, the results in this thesis indicate that despite the presence of undesired substances, the agricultural use of wastewater sludge has multiple ecological and economic benefits (Bengtsson and Tillman, 2004; see also Appendix III). As a bio-fertilizer, clean wastewater sludge with the minimum possible contents of undesired substances has sustainable ecological benefits which augment soil productivity (Linderholm et al., 2012b). As a cheaper alternative to commercial fertilizers, the agricultural use of wastewater sludge is a cost-effective way of enhancing agricultural productivity. Provided that the level of undesired substance contents in Swedish sludge continues to decline to acceptable levels, the acceptance of spreading wastewater sludge on arable lands should gradually improve (SEPA, 2013). The targeted increase in the P-recycling rate is aimed to increase the supply of inexpensive and renewable
P fertilizer from wastewater sludge. Ultimately, the impact would potentially reduce Sweden’s vulnerabilities from the dependence on commercial phosphate fertilizers, as the global phosphates demand continue to push the price escalation further (SEPA, 2013).

6.3. The Quantity and Quality of Recovered Phosphorus from Wastewater

Identifying the quantity and quality of recovered P from the sanitary system is one of the vital steps of the SFPRR. The quality aspect of this particular step is concerned with the concentration of P fractionations and the contents of heavy metals including other undesired substances in wastewater. Consequently, potential conflicts are likely to arise between the various systems involved in P-recycling and are exclusively analyzed in the commencing section (6.4.). If the total estimated quantities of recoverable P from the sanitary system are known, the potential reuse rate of the recovered P can be estimated (Cordell et al., 2011). In terms of the rate of agricultural use of wastewater sludge, the three studied municipalities lie in contrasting positions (see Table 5). Motala is closely approaching towards achieving its own goal of totally reusing wastewater sludge on arable lands, while in Mjölby the rate is growing inconsistently despite implementing REVAQ certification for its sludge. For Motala, adherence to its goal of 100% wastewater sludge usage rate and implementation of REVAQ certification in its main WWTP seem to have paid off. In Finspång, since REVAQ is not being implemented, no sludge has been used during the period (2010-2013). Perhaps, the contrasting situation of the three studied municipalities could be the reflection of the overall situation in the medium-sized Swedish municipalities in terms of the reusing of P from wastewater.

As explained in the previous chapter, quantities of wastewater sludge used as fertilizer do not indicate the quantities of P which are actually recycled back to arable lands. Cordell et al., (2011) remark that the P-concentration level in wastewater determines the potential quantities of P which can be recycled from wastewater. The quantities of P recovered by WWTPs have implications on the required energy consumption, the recovery options, logistics and the economic costs of the overall processes involved (ibid). This indicates the possibilities for variations in the P concentration of wastewater among WWTPs in a socio-economically homogenous region. In this case, dietary habits may be ruled out, while the different chemicals and processes applied in the WWTPs could be the possible causes (ibid).

<table>
<thead>
<tr>
<th>Municipality</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mjölby</td>
<td>N/A</td>
<td>N/A</td>
<td>9.34</td>
<td>9.30</td>
<td>9.98</td>
<td>10.14</td>
<td>9.72</td>
</tr>
<tr>
<td>Motala</td>
<td>24.1</td>
<td>23.5</td>
<td>28.9</td>
<td>26.3</td>
<td>33.8</td>
<td>30.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Finspång</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>11.08</td>
<td>10.93</td>
<td>11.56</td>
<td>6.63</td>
</tr>
</tbody>
</table>

Source: Mjölby, Motala and Finspång WWTPs, 2014

Based on the P-concentrations data presented in Table 5, the average annual dry weight P recovered from the studied municipalities is summarized in Table 9 below. The estimated
quantities of the recovered P for the studied period (2007-2013) are three times higher in Motala than in Mjölby and Finspång (see Table 9). One way of estimating the fertilizing potential of the recovered P from wastewater is by converting the recovered quantities into a corresponding area of arable land. Linderholm et al. (2012a) estimate that the average annual intake of P by ordinary cereal crops in Swedish farmlands corresponds to 17kg P/ha. From table 9, we find that in 2011 Motala recovered the highest quantity of P from wastewater which corresponds to 33.8t P. If we convert this value into the annual average P intake required by cereal crops from the Swedish arable lands, we find that this P-quantity can potentially fertilize an area of about 1,988 ha of arable land.

6.4. Identifying Conflicts in Phosphorus Recycling

Identifying conflicts in the systems linked with P-recycling is a necessary step in order to alleviate the constraints that limit the sustainability of P-recycling measures (Cordell et al., 2011). Accordingly, the data gathered in this thesis indicate so far that there is a goal conflict in the proposed P-recycling measure itself. The competing goals between reducing the undesired substances and the need to increase P-recycling from wastewater sludge are analyzed from two interrelated perspectives. Technically, Sweden’s proposed thresholds are stringent and it will be challenging for WWTPs to attain the target within the first half of the initial milestone (2018), since the amount of sludge that would be fit for use under the thresholds could decline (SEPA, 2013). From the policy aspect, what the conflicting goals signify is the gap between the national policy intentions and decisions at the local level. The conflicting goals will put the Swedish municipal WWTPs with conflicting options that hinder the WWTPs from effectively implementing the proposed measures. In terms of the overarching sustainable development dimensions, the conflict lies between the goal that aims for resource efficiency and protecting environmental and health factors.

6.4.1. The Challenges of Reducing Undesired Substances

Although, Sweden’s WWTPs use modern wastewater treatment processes, they are only capable of releasing the treated water by separating the solid waste which contains the nutrients and organic matter including the undesired substances. From the systems perspective, recycling P from wastewater is likely to raise conflicts among the sanitary, agricultural, food processing and distribution systems. The key conflict arises from the heavy metals and other persistent substances that are found in wastewater sludge. SEPA’s 2013 report states: ‘There is a conflict between a more resource-efficient use of phosphorous sources that are in circulation today and the goal of A Non-Toxic Environment. Indeed, the higher the requirement for low concentrations of undesirable materials in phosphorous components, the greater the challenge to increase the recycling of phosphorous and other nutrient materials’ (SEPA, 2013:18). The intention behind the stringent thresholds for the undesired substances is to consistently reduce these substances in wastewater sludge and pave the way for sustainable P-recycling. Nevertheless, SEPA has also assessed that for the interim period, the stringent
thresholds to be introduced can counteract with the intended outcome by reversing the recycling rate even from the current levels (ibid).

The data obtained from the studied WWTPs in this thesis concur with SEPA’s assessment regarding the challenge of increasing P-recycling in the short-term. The average values for the concentration levels of heavy metals in the studied WWTPs under the studied period (2007-2013) seem to imply that Ag in Motala and Cd in Finspång are higher than the recommended levels for the first milestone (2015-2023) (see Table 6). However, the trends in the average annual concentration levels (see Graphs 2b, 3b and 4b; Tables 1.1 and 1.3 in Appendix I) show that the average annual concentration level of Ag in Motala has actually been declining below the proposed thresholds, while Cd in Finspång remains to be higher. The concentration levels for the remaining heavy metals at the studied WWTPs are currently within a safe margin in comparison with the recommended levels for the first milestone (see Table 6).

The quantitative data obtained from the studied WWTPs had been summarized into annual average values and do not show the weekly or monthly fluctuations in the concentration levels of heavy metals. However, the qualitative data reveal that the main challenge for the studied WWTPs is the sudden rises in the concentration levels of some of the heavy metals. Although, the sources for the sudden rises in the concentration levels of heavy metals are believed to be mainly households, the specific sources have not yet been identified and further investigations are required. It is challenging to identify the specific chemical sources that cause the irregular influxes, as households use various products – from foodstuff to cosmetics which contain numerous substances. Sweden imports substantial quantities of animal feeds and food products (50% of Sweden’s food consumption) from other parts of the world, where they are produced with inputs that have substance contents much higher than what is recommended in Sweden (Linderholm et al., 2012b). For that matter, Linderholm et al. (2012b) also find that the amount of Cd in imported products is actually unknown. Moreover, these authors suggest that other sources such as storm water that drains into the sewage system can also be significant sources of Cd (ibid). Hence, what the conflicting goals imply is that reducing the concentration levels of substances in wastewater sludge is a formidable challenge and it is beyond the control of Sweden’s WWTPs.

6.4.2. Goal Conflicts and Local Decisions

The role of the national EQOs as the guiding framework for local environmental decision-making has already been discussed above. In fact, the EQOs are Sweden’s unique approach of governing environmental sustainability through an objective-oriented policy framework. The aim of managing environmental policies by objectives is to translate the Swedish society’s aspirations for environmental sustainability into quantified targets. Basically, this framework is a top-down process, where at the national level the EQOs are broad in context and the municipalities play an important role for their implementation. At the local level, their implementation is meant to be carried out by local decision-making, while at the regional level the regional county boards have a coordinating role. Nevertheless, Nilsson et al., 2008 find that there is ambiguity and lack of coordination along the hierarchy. Consequently, the national
EQOs are in effect not part of the routine decision-making process at the local level (ibid). Edvardson deduces: ‘The core problem is that some of the environmental objectives do not guide action sufficiently well’ (2004:170). For local decision-making, the objectives are contextually broad and lack precision that local decisions are in practice not implemented concurrently to the national policy intentions (ibid). The EQOs are the outcome of a national policy-making process, but they are not explicit and precise enough to be effectively translated into local actions which lead towards the attainment of the intended goals. The inexplicitness and ambiguity of the EQOs imply that the objectives need to be further contextualized in terms of their practical implementation at the local level.

Another important drawback in the national EQOs framework which has already been mentioned is that there are goal conflicts among the objectives themselves. Although, it is not possible to avoid goal conflicts in environmental policies, the framework exhibits weaknesses in providing the means which can guide local decision-makers in resolving the conflicts (ibid). Consequently, these shortcomings have led local decisions to end up in inconsistency with the intentions behind the national objective framework. Findings from a study conducted by Nilsson et al., (2008) indicate that there are discrepancies between those ambitions that are behind the national EQO framework and local waste management practices. According to these findings, the national ambition which gives priority to waste recycling has led to the unintended expansion of waste incineration for energy and heat production in many Swedish municipalities (ibid). Since 2000 a series of bans and regulations have gone into effect in Sweden with the intention of reducing landfilling and as a result, only 1.5% of the household waste was deposited in landfills by 2013 (Avfall Sverige, 2014); while waste incineration for energy production has outpaced waste recycling (Nilsson et al., 2008). This instance clearly exemplifies how the national policy intention of promoting resource efficiency has practically ended up with unintended outcomes. For several Swedish municipalities, expansion of waste incineration is a cheaper alternative to fossil fuels, but it comes into conflict with Sweden’s objective that prioritizes waste recycling.

The above analysis also bears several implications to how the potential goal conflict in the proposed P-recycling target will affect decisions at the local level. The instance of the Finspång WWTP clearly indicates that municipalities where wastewater sludge is not used as fertilizer or contains higher concentrations of heavy metals are already facing the dilemma of likely encounter contradicting options concerning the problem of handling the sludge that will not be fit for use under the stringent thresholds. SEPA assesses that during the interim period, wastewater sludge which contains higher concentrations of undesired substances above the recommended levels will probably be incinerated (SEPA, 2013). By law, the landfilling or incineration of organic waste including wastewater sludge has been banned in Sweden since 2005. These disposal options come into conflict with one of the core guiding principles of the EQOs, which is resource efficiency. Eventually, many landfills in Sweden are being closed and the remaining ones are also on the way of being phased-out in the coming few years. The ash from incinerated sludge can only be used as construction material, as P-recovery methods from sludge ash are not yet operationally feasible. Considering that a significant challenge is to be encountered in reducing the undesired substance concentrations of wastewater, a
substantial amount of P will end up without being reused at least during the initial phase of the milestone. Nevertheless, as the studied WWTPs have indicated, further guidelines are required to help the WWTPs make decisions in resolving the conflicting goals.

6.5. Identifying Synergies: Opportunities for Linking P-Recovery with Other Systems

Identifying the potential synergies between the various systems that can be linked to P-recovery is important for the sustainability of P-recovery measures. Unless P-recovery measures are linked with other systems or processes, their impacts cannot address the overarching sustainable development goals (Neset and Cordell, 2011). The recovery of P from wastewater can virtually be inter-linked with sanitation, environmental protection, agricultural productivity, energy production and a subsequent reduction in GHG emissions. Synergies are created when P-recovery is linked with these systems and processes. Linkages of P-recovery with other systems or processes should be diversified as much as possible, so that strong synergies could be created (Cordell and White, 2011). In such a way, net-negative impacts are minimized and the overall outcome of P-recovery could follow a strong sustainability pathway.

A key rule-of-thumb for creating synergy out of P-recovery measures is that ‘the phosphorus system should have no net negative impact on society and ideally value-add’ (Cordell and White, 2011:753). Principally, removing P from wastewater does not only bear positive externalities to the environment, but it saves society from the otherwise mitigation costs of dealing with nutrient pollution (Molinos-Senate et al., 2011). The P and organic matter which are found in wastewater sludge are vital inputs for agricultural production. Furthermore, depending on the recovery option, alternative energy can be produced with the subsequent GHG emissions reduction (Cordell and White, 2011).

6.5.1. Fertilizer Input from the Sanitation System to Agriculture

Despite the risk for deposition of undesired substances, the LCA study regarding the Swedish P-system conducted by Linderholm et al. (2012b) has shown that spreading wastewater sludge on arable soils is the most efficient option in terms of energy production and emissions. As far as the studied municipalities in this thesis are concerned, the collected data indicate that synergies have already been created between P-recovery and other systems. One aspect of analyzing the synergy of P-recovery at the studied WWTPs is assessment of the value-adding effect in terms of P-fertilizer output. To analyze the value added to the agricultural system by the studied WWTPs, estimating the P quantities (Table 9) in terms of monetary value would be more descriptive. The commercial value of the P in wastewater can be compared with the monetary value of an equivalent commodity. The commonly used fertilizers are manufactured as complex (N-P-K) chemical fertilizers in the form of either DAP (Di-ammonium Phosphates) or MAP (Mono-ammonium Phosphates). Compared to the P in wastewater sludge, the P in industrially processed fertilizers is of a superior quality in terms of grade and solubility in soils (Cohen et al., 2011). The market price of phosphate rock has been used in several studies to compare the equivalent price of the recovered P from wastewater with the market price for phosphate rock (Roeleveld et al., 2004; Molinos-Senate et al., 2010). Accordingly, the annual
average P quantities recovered in the studied WWTPs have been converted here into monetary values in terms of the world market prices for phosphate rock (see Table 10).

**Table 10: Estimated Market Values of the Average Recovered-P at the Studied WWTPs (USD/Year)**

<table>
<thead>
<tr>
<th>Municipality</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mjölby</td>
<td>N/A</td>
<td>N/A</td>
<td>1,027.4</td>
<td>1,023</td>
<td>1,097.8</td>
<td>1,115.4</td>
<td>1,069.2</td>
</tr>
<tr>
<td>Motala</td>
<td>2,651</td>
<td>2,585</td>
<td>3,179</td>
<td>2,893</td>
<td>3,718</td>
<td>3,300</td>
<td>N/A</td>
</tr>
<tr>
<td>Finspång</td>
<td>N/A</td>
<td>N/A</td>
<td>1,218.8</td>
<td>1,202.3</td>
<td>1,271.6</td>
<td>729.3</td>
<td></td>
</tr>
</tbody>
</table>

*Source: Mjölby, Motala and Finspång WWTPs, 2014.*

Looking at the market values of the average quantities of P recovered annually in each of the studied municipalities in Table 10, we find that the amounts are apparently modest. For instance, the maximum estimated average P output which was 33.8t in 2011 at the Motala WWTP (see Table 9) corresponds to an equivalent PR value worth USD 3,718 per year (see Table 10). Since the studied WWTPs are smaller in size than the WWTPs in the larger Swedish municipalities, their value-adding effect is relative to the smaller amount of wastewater sludge they produce. From the strong sustainability perspective, value-addition should not be entirely looked at from the face-value economic benefits of P-recovery. Value-addition at WWTPs should be considered in terms of the positive externalities that contribute to strengthening of a resource-efficient cycle in society; after all the primary goal of WWTPs is not generating profit (Molinos-Senante et al., 2011). However, it is important to implement cost-effective processes and management practices at WWTPs in order to reduce the social costs of P-recovery. The studied municipalities anticipate that due to their relatively smaller operational scale, implementing the proposed target could result in inefficient operating costs.

### 6.5.2. Bio-gas Production

Other than the prevention of nutrient pollution and recovery of a scarce mineral resource, sustainable P-measures can potentially address other environmental challenges as well (Neset and Cordell, 2011). The production of alternative energy from P-recovery increases resource efficiency and addresses the challenge of climate change. Alternative energy production is one of the key synergies that can potentially be leveraged out of P-recovery. Over the past decade, generation of alternative bio-energy at municipal WWTPs from wastewater treatment processes has been growing substantially. In the studied WWTPs, there is somewhat a positive trend as far as value-addition in the form of energy production from P-recovery processes is concerned. Accordingly, the technical processes of treating wastewater, particularly in Motala and Finspång WWTPs are already connected to anaerobic sludge digesters. In Finspång, the sludge digester is relatively small, but the methane gas produced at the WWTP adequately meets the entire heating energy requirements within the plant. The scale off biogas production needs to be expanded in Finspång, in order to maximize value-addition from the increased bio-
gas production. However, biogas is produced at a relatively larger scale at the main WWTP in Motala municipality. Motala’s biogas production is sufficient enough to meet the WWTP’s energy requirement. Additionally, biogas is used as fuel for up to 30 of the urban/regional buses stationed in Motala municipality and around other 100 biogas driven vehicles. Beside the overall impact of GHG emission reduction, linking P-recovery processes with energy production minimizes the energy costs of WWTPs; with possible financial gains to be derived from the commercializing of bio-fuel production. In fact, bio-gas production at the smaller Swedish WWTPs could reduce the energy costs of implementing the proposed regulation which requires energy-intensive sludge sanitization. Even though, expanding bio-gas production at the studied municipalities offers substantial economic benefits for the WWTPs, this should not be prioritized over the goal of increasing P-recycling.

6.6. Identifying Key Stakeholders and Institutional Arrangements

The institutional dimension of P-scarcity is defined as one of the five key contexts of the global scarcity (Cordell, 2010). In order to address this scarcity challenge, it would be necessary to appropriately realign the institutional aspects of the challenge that facilitate the sustainable management of P-resources. Hence, identifying the key stakeholders and institutional arrangements of P-recovery has been incorporated as one of the key steps in the SFPRR. In this respect, SEPA has identified that the challenge of increasing P-recycling in Sweden requires a broader institutional approach. In its proposed target, SEPA has clearly indicated that ‘Sweden’s waste and sewage stakeholders cannot solve all of the problems’ (SEPA, 2013:18). Technically, the role of municipal WWTPs is confined only to removing the undesired substances from the wastewater and they have no control over the various types of chemicals that flow into the Swedish municipal sanitary system. The quantitative data gathered from the studied WWTPs indicate that the numerous types of chemicals found in the products consumed by society pose substantial challenge in the effort to increase the reuse of P from wastewater sludge. One of the key EQOs which is directly linked with reducing undesired substances in wastewater sludge is the objective for ‘A Non-Toxic Environment’ (SEPA, 2013) and the responsible government agency in following-up the achievement of this particular objective is Kemikalinspektionen (Swedish Chemicals Agency). Nevertheless, reducing the undesired substances flowing into the sanitary system requires controlling and regulating the chemical contents of an array of products consumed by the entire society. Overcoming this challenge requires the direct or indirect participation of many other organizations outside the wastewater community, such as Livsmedelsverket (National Food Agency), LRF (Federation of Swedish Farmer), Naturskyddsföreningen (Swedish Society for Nature Conservation) and the food and retail industries, among the few.

The qualitative data gathered from the studied municipalities indicate that local stakeholders from the food and retail industries do not accept food produced by the use of wastewater sludge which is not REVAQ certified. This position is legitimate in terms of taking precautionary steps in minimizing the health and environmental risks of deposition of undesired substances. REVAQ has been developed to ensure sustainable recovery of nutrients from wastewater and their safer use in agriculture as the current regulation consists of outdated standards developed
in the 1990s (Malqvist et al., 2006 and SEPA, 2013). REVAQ consists of advanced quality control mechanisms which the current regulations lack. Particularly, the traceability of sludge consignments from a particular WWTP to a specific field where sludge had been used is what makes REVAQ more effective in controlling the deposition of substances better than the current regulations. Although, REVAQ has been developed to encourage the use of certified sludge, by the end of 2013 there were only 39 WWTPs which joined the certification system (Svenskt Vatten, 2014). There are several factors which could limit REVAQ’s implementation at the smaller municipal WWTPs. Firstly, as the qualitative data gathered from the studied WWTPs suggest, joining the sludge certification system requires additional costs and the implementation of duplicated quality control procedures. Since REVAQ is a voluntary certification system, the WWTPs in the smaller and mid-sized municipalities may not find it economically rational to invest in the system and; still find their sludge unfit for use due to higher levels of undesired substances than the system recommends. For the mid-sized municipalities such as Finspång, the cost factor can be inhibitive for them to voluntarily join REVAQ. The smaller WWTPs have limited operating budgets which are proportional to their relatively fewer numbers of residents. Secondly, in many aspects the proposed regulations are more stringent than REVAQ (see Table 1.4. in Appendix I). It has not been possible to find information which indicates how the implementation of REVAQ will continue in conjunction with the proposed regulations. Nevertheless, the qualitative data gathered from the studied municipalities suggest that those WWTPs which currently implement REVAQ could be compelled to discontinue implementing the certification system once the proposed regulations go into force.

With regards to the management aspect of implementing the proposed P-recycling measure, particularly at the smaller municipal WWTPs, significant capacity-building works are needed. Such WWTPs require support in terms of upgrading their wastewater treatment systems to meet the requirements of the proposed regulation. Further investments to install and expand bio-gas production in the smaller WWTPs could be substantial, but there is an opportunity for municipalities to benefit from the synergy of energy production. In Finspång the current biogas production can potentially be upgraded to a larger capacity so that the production could be linked with the supply of fuel to local transport. The main WWTP in Mjölby can also leverage from the production of biogas, but upgrading works require changes in the current technical systems applied in the WWTP and the installation of sludge digester. Additionally, the proposed regulations require upgraded technical systems at WWTPs and it is possible that the smaller WWTPs might require additional financing for the required upgrading works. Meeting the requirements of the regulations opens opportunities for WWTPs to cooperatively work in seeking solutions to some of the operational challenges.

One of the key factors that drive municipalities to take initiatives in working together to effectively implement the proposed regulations is in the area of capacity building. The lack of coordination in implementing the EQOs affects not only municipal decision-making, but also the county administrative boards (Nilsson et al., 2008). The regional bodies find it difficult to effectively play their coordinating roles, due to the lack of clear guidelines as to how the national objectives should be implemented locally (ibid). Inter-municipal cooperation among
WWTPs with regards to wastewater treatment works can facilitate for the development and achievement of regional objectives. Especially, horizontal integration among larger and smaller municipalities can be mutually advantageous. The qualitative data gathered in this thesis indicate that the concerned body of the Country Administrative Board of Östergötland is already engaged in facilitating experience sharing within the region’s wastewater treatment sector. Cooperation can serve as a capacity building platform for municipal WWTPs. Each WWTP has its own advantages or disadvantages which are associated to scale of operations, technical systems and specific problems that each WWTPs encounters. WWTPs can jointly engage in the exchange of information and experiences concerning the management of wastewater treatment operations in relation to implementing the proposed national target. For instance, the municipalities of Mjölby and Boxholm from the Östergötland County have jointly developed a common waste management plan (2012-2017) with the municipality of Tranås which is found in the neighboring Jönköping County (Mölby Municipality, 2012). Similar trends of cooperation in wastewater treatment between larger and smaller municipalities would engage them in jointly identifying effective strategies. As a result, the WWTPs jointly collaborate in creating enhanced implementing capacity.

Differences in economies of scale can also drive WWTPs to jointly manage their operations. The larger WWTPs benefit from the proportionally better financial resources and cost advantages than the smaller WWTPs. It is also possible that the larger WWTPs can have redundant operational capacity which could potentially be accessed by the smaller WWTPs. For the smaller WWTPs which operate under cost-inefficiency due to relatively high operating costs and investment requirements for upgrading works, integrating their operations with larger WWTPs can be a cost-effective alternative. However, proximity of WWTPs is an important factor, so that it would be financially viable for them to invest in the required pipeline connection. Perhaps a notable instance of working together between municipalities in wastewater treatment is the cooperation between Söderköping and Norrköping municipalities. The WWTP in Söderköping has used to operate outdated water treatment systems and discharged higher levels of nutrients than recommended into the Balkan Sea. Consequently, the phasing-out WWTP faced total closure with a penalty of 20 million SEK for environmental damages unless it modernizes its technical systems to meet the standard requirements by the end of 2015 (Tersmeden, 2014). The total investment required to modernize the main WWTP in Söderköping was eventually estimated to cost at least 100 million SEK (ibid). Instead of upgrading the ageing WWTP in Söderköping, constructing a 16 km long pipeline that transports wastewater to the WWTP in Norrköping was taken as a viable solution. Construction of the pipeline started early in 2014 and was completed by mid-2015 (Selsfors, 2015). As a result, both WWTPs will benefit from the collaboration. The Söderköping WWTP will benefit from the advantage of the excess capacity in the Norrköping municipality, while avoiding the required overhauling investments. On the other hand, besides the payments it will be receiving for treating Söderköping’s wastewater, the WWTP in Norrköping will benefit from increased quantities of biogas production. This instance shows that under certain circumstances where the conditions are favorable, cooperation between WWTPs is mutually beneficial. With respect to implementing the proposed P-recycling target, operational integration should be increasingly sought wherever it is physically and economically viable.
7. Conclusion

Sweden’s strategy for sustainable P management can perhaps stand out uniquely in being exemplary to others. The proposed Swedish P-recycling measure is an integral part of the broader national EQOs framework for the overarching attainment of sustainable development goals. During the intermediate phase, there will be formidable challenges that need to be addressed in implementing the proposed measure at municipal level. Reducing the concentration of undesired substances in wastewater minimizes the risk of substance deposition in arable soils and is a necessary precondition for increasing P-recycling in the long-run. Eventually, the proposed stringent regulations can foreseeably limit the goal of increasing the targeted rate of P-recycling. Although the recovery of P from wastewater is undertaken by the wastewater treatment sector, a concerted engagement of a spectrum of actors from the entire society will be crucial to regulate the circulation of substances. Therefore, future research needs to extensively focus on the impacts of various actors and stakeholders with regards to implementing the proposed measure. However, in the long-run the opportunities for effectively implementing the proposed P-recycling measure can outweigh the challenges.

Local decisions play a central role in implementing the proposed measure and are influenced by local dispositions. The findings indicate that financial resources and technical capacities of municipalities are important for the effective implementation of the proposed measure. Some of the support needed by the municipalities can take the form of investments and exchange of information at all levels regarding the implementation of the national target at municipal level. Local decision-makers also need to be supported with adequate facilitation that enables them to interpret the local contexts of the policy intentions that are behind the nationally proposed measure. This should at least ease the transition from the old regime and contribute to resolving the anticipated goal conflict.

Beyond responding to national objectives, local decisions also need to account for national vulnerabilities in anticipation to future scarcity related effects on the international phosphates market. Local actions can contribute in addressing national vulnerabilities towards P-scarcity by reducing local dependency on phosphates imports. Furthermore, the study conducted in the three Östergötland municipalities underscores the importance of integrating the streamlining of P-recycling with other systems at the local level in the attainment of other sustainable development goals. With progressing technical advancements, it would be possible to intensify synergy with other processes with enhanced efficiency, value-addition and emission-reduction outcomes of P-recycling. The Swedish self-governance system, as elsewhere in Europe gives municipalities the autonomy to initiate local action-plans with regards to addressing the P-scarcity challenge. Provided that the national EQOs can effectively guide local actions, the autonomy that Swedish municipalities are bestowed with can positively contribute in realizing the national P-recycling goal to local circumstances.
Acknowledgements

First and foremost, I would like to thank the Almighty God for the wisdom and energy He has given me to complete this thesis. I am also immensely indebted to my supervisors Tina and Birgitta, for their unreserved and solid support; thank you both for the valuable comments and advices you gave me. My gratitude also goes to Teresia Svensson and Susanne Eriksson from the Masters Programme Office for the support they have given me. I would also like to extend my heartfelt thanks to the experts, engineers, and environmental protection officers who greatly contributed to the thesis. This thesis would not have been possible without their unreserved assistance. Finally, this goes without appreciating my family for their constant support and encouragement. I would like to especially thank my baby daughter Rediet for enduring my frequent absences at her delicate young age. I hope to compensate by making something meaningful out of all this. I dedicate this thesis to you – Rediet.
References


APPENDIX
Appendix I: Heavy Metal Concentration

Table 1.1.: \textit{Average Concentrations of Heavy Metal Contents in Wastewater Sludge in Motala 2007-2013 (mg/kg)}

<table>
<thead>
<tr>
<th>Substance</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tr>
<td>Lead (Pb)</td>
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<td>14.75</td>
<td>16.28</td>
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<td>16.93</td>
<td>14.88</td>
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<td>Cadmium (Cd)</td>
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<td>0.73</td>
<td>0.75</td>
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<td>0.81</td>
<td>0.82</td>
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<td>Copper (Cu)</td>
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<td>341.67</td>
<td>375.42</td>
<td>375.42</td>
<td>416.25</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>22.5</td>
<td>24</td>
<td>25.42</td>
<td>27</td>
<td>26.5</td>
<td>24.63</td>
<td>23.92</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
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<td>0.73</td>
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<td>0.69</td>
<td>0.72</td>
<td>0.62</td>
<td>0.73</td>
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<tr>
<td>Nickel (Ni)</td>
<td>16</td>
<td>16.25</td>
<td>14.91</td>
<td>15.88</td>
<td>17.08</td>
<td>16.17</td>
<td>15.46</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>645</td>
<td>577</td>
<td>590</td>
<td>625.42</td>
<td>585.42</td>
<td>580.42</td>
<td>588.75</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>6.2</td>
<td>5.35</td>
<td>4.86</td>
<td>4.72</td>
<td>4.98</td>
<td>4.55</td>
<td>4.79</td>
</tr>
</tbody>
</table>

Source: Motala WWTP, 2014

Table 1.2.: \textit{Average Concentrations of Heavy Metal Contents in Wastewater Sludge in Mjölby 2008-2013 (mg/kg)}

<table>
<thead>
<tr>
<th>Substance</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
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<th>2012</th>
<th>2013</th>
</tr>
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<tbody>
<tr>
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<td>7.3</td>
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<tr>
<td>Cadmium (Cd)</td>
<td>0.5</td>
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<td>0.4</td>
<td>0.5</td>
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<tr>
<td>Copper (Cu)</td>
<td>310.8</td>
<td>286.7</td>
<td>311.7</td>
<td>305.8</td>
<td>305.8</td>
<td>341.7</td>
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<tr>
<td>Chromium (Cr)</td>
<td>17.0</td>
<td>13.3</td>
<td>13.9</td>
<td>14.8</td>
<td>13.7</td>
<td>14.2</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.4</td>
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<td>0.5</td>
<td>0.3</td>
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<td>0.3</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>11.3</td>
<td>9.1</td>
<td>8.6</td>
<td>8.8</td>
<td>9.3</td>
<td>10.3</td>
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<tr>
<td>Zink (Zn)</td>
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<td>269.2</td>
<td>270.0</td>
<td>288.3</td>
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<tr>
<td>Silver (Ag)</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Source: Mjölby WWTP, 2014

Table 1.3.: \textit{Average Concentrations of Heavy Metal Contents in Wastewater Sludge in Finspång 2010-2013 (mg/kg)}

<table>
<thead>
<tr>
<th>Substance</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
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<td>12.9</td>
<td>18.1</td>
<td>17.6</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
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<td>1.1</td>
<td>1.1</td>
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</tr>
<tr>
<td>Copper (Cu)</td>
<td>354.0</td>
<td>402.5</td>
<td>401.0</td>
<td>446.9</td>
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<tr>
<td>Chromium (Cr)</td>
<td>27.5</td>
<td>25.4</td>
<td>29.3</td>
<td>27.0</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
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<td>21.4</td>
<td>19.9</td>
</tr>
<tr>
<td>Zink (Zn)</td>
<td>494.0</td>
<td>526.9</td>
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<td>609.4</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>-</td>
<td>2.45</td>
<td>2.5</td>
<td>1.4</td>
</tr>
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</table>

Source: Finspång WWTP, 2014
Table 1.4.: Comparative Thresholds for Heavy Metal Concentration Levels in Wastewater Sludge Spread on Arable Lands (g/ha)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Recommended Limits (g/ha per year)</th>
<th>REVAQ max Addition Level by 2015 (g/ha per year)</th>
<th>REVAQ max Addition Level by 2025 (g/ha per year)</th>
<th>Limits According to Alt. B by 2015 (g/ha per year)</th>
<th>Limits According to Alt. B by 2030 (g/ha per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
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<td>0.64</td>
<td>0.37</td>
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</tr>
<tr>
<td>Copper (Cu)</td>
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<td>-</td>
<td>-</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
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<td>0.87</td>
<td>0.23</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>25</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>-</td>
<td>4.18</td>
<td>0.56</td>
<td>3.5</td>
<td>2.5</td>
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<tr>
<td>Zink (Zn)</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>600</td>
<td>550</td>
</tr>
</tbody>
</table>

*Source: SEPA, 2013*
Appendix II: Interview Guide (Municipalities)

1. How many households are connected to the wastewater treatment plant/s WWTP/s in the municipality and how many use their own wastewater tanks?

2. What are the main economic activities in the municipality (e.g., Agriculture, manufacturing, food industry, fishing, hospitality and tourism ... etc.)?
   a. How important are these activities in terms of their share in the municipality’s economy?
   b. What is the contribution of wastewater to the WWTP/s from these economic activities? Do the larger economic activities also contribute to the flow of wastewater into the WWTP/s?

3. How is wastewater sludge mainly used in the municipality currently and why is it used?
   a. □ As landfill covering material □ As fertilizer on agricultural land □ Other :____________________________
   b. Is the extracted sludge potentially sufficient to satisfy local fertilizer demand or there is a potential for it to become surplus and would need to be transported to other municipalities?

4. What further processes does the sludge undergo after being separated from the waste water at the WWTP/s?

5. Are there any phosphorus recovery methods currently applied in the municipality's waste water treatment plant/s (WWTP)? If so, please mention them.

6. What quality control certification standards are used at the WWTPs? Are the municipality’s WWTP/s part of the REVAQ certification? If no, please explain why the municipality is not part of ReVAQ and mention if there are any plans to be part of it.

7. Are there any strategies, plans or studies undertaken on phosphorus recovery in the municipality/WWTP?
   a. Have there been any studies made concerning the feasibility of recovering phosphorus from wastewater sludge differently than the current methods in the municipality? If so, please mention them. (Municipality/WWTP)
   b. If there are any plans to recover phosphorus, which method/s of recovery have been considered? □ Struvite □ Incineration □ Biological □ Spreading sludge on agricultural lands □Landfill covering □Others (Municipality/WWTP)

8. How does the municipality's/WWTP’s environmental plan tend to consider phosphorus? Does it consider phosphorus from the environmental protection perspective or as a scarce nutrient that needs to be recycled?

9. Which actions (if any) have so far been implemented in the municipality/WWTP in response to SEPA’s national proposal to recover 40% of phosphorus from wastewater by 2018?
10. According to your opinion, what challenges or opportunities in achieving the SEPA proposed national phosphorus recovery target?
   a. According to your opinion, what particular challenges or opportunities will affect the achievement of SEPA’s phosphorus recovery target in your municipality?
   b. Are the challenges or opportunities more of financial, political or technical nature?
11. Are there any comments or reflection that you would like to add concerning phosphorus recovery?

   Thank you for your time!
Appendix III: Options in Recovering Phosphorus from Wastewater Sludge

1. Chemical (Wet) Recovery Method

Chemical (Wet) phosphorus recovery methods have 40%-50% P recovery rate, and they use chemicals to crystalize and separate phosphate compounds from the wastewater. Cornell and Schaum (2009) find that in Germany, the per capita cost of recovering phosphorus from wastewater by 2009 amounted to € 2-6/kg annually and this was found to be much higher than the market prices for phosphates. Nevertheless, the authors also remark that there are still no sufficient experiences on industrial-scale phosphorus recovery from wastewater. On the other hand, Molinos-Senate et al (2010) find that phosphorus recovery as struvite using new wet methods as having promising prospects because they reduce chemical costs and sludge output. These authors (ibid) also conclude that the cost of phosphorus recovery (€ 2-8 /kg) of the struvite method is still higher than current phosphates prices. However, through a Cost-Benefit analysis the authors (ibid) show that phosphorus recovery with the struvite method is economically viable only when the positive externalities from the application of the method are considered. This means that operating the struvite recovery technology would cost more than the amount of recovered P. This might be more feasible when the WWTP is large with higher economies of scale and when the P recovery rate from the technology is closer to the maximum attainable level. Even so the above-mentioned economic evaluations show that the method does not recover at least 50-60% of the P in the wastewater and another method should be employed to recover the remaining percentages of P. The unrecovered P remains in the precipitated sludge and can be spread on agricultural lands, even though the P contents are low and the undesired substance concentrations are relatively higher. Nevertheless, with the wet chemical phosphorus recovery technologies phosphate fertilizers in the form of pellets can be produced and applied as fertilizers on agricultural soils.

2. Thermal Phosphorus Recovery Method

Other than the wet chemical phosphorus recovery methods there are new technologies which use the thermal phosphorus recovery method being currently developed. This process involves the incineration of wastewater sludge at very high temperature with a very high phosphorus removal rate from the incinerated sludge ash. Currently several of the leading European thermal technologies still being developed include the Austrian ASH DEC (2008-2011), the German Mephrec (Metallurgical Phosphorus Recovery) and RecoPhos of Belgium. The company which developed the ASH DEC process had built a pilot plant in Austria where it planned to build full-scale plants which would cost-effectively manufacture good grade phosphate fertilizers from incinerated sludge ash. Even though the ASH DEC technology was planned to become commercially available by 2011, the company that developed it was acquired earlier in that year by a Finnish company. On the other hand, Weigand et al (2012) mention that results from the pilot phase evaluation of the RecoPhos technologies at an industrial scale production show that it is possible to commercially manufacture fertilizers comparable to conventional fertilizer grades. In Sweden one instance is the large-scale thermal technology currently being developed by EasyMining AB, which the company expects it to
have a significant role in achieving the national recovery target. Although these methods require considerable amounts of energy for incineration, the output energy from the process could potentially be utilized for further power generation. The sludge from wastewater needs to be dried prior going through the incineration process. According to Dichtl et al. (2007) sludge drying by solar power is a cost-effective method of saving energy during incineration. Extended sludge dewatering before incineration can reduce the moisture content by 90% dry matter weight (Lundin et al., 2004).

The main challenge with thermal technologies is that the operating and installation costs of extracting phosphorus from incinerated ash are rather high (Linderholm et al., 2012b). As Reoeleveld et al. (2004) also show in the case of the Netherlands, during the mid-2000s phosphorus recovery was technically feasible while it remained quite challenging economically. Similarly, Balmér (2004) found that in Sweden the estimated annual cost of recovering phosphorus from sludge incineration was 58 SEK/kg, which was still higher than the market prices at the time. The key disadvantages of the thermal method P recovery technologies are the huge amount of high energy requirements and the loss of other components of the sludge such as N and carbon matter. Furthermore, installing such a recovery system requires huge investment costs (Cohen et al., 2011). From the economic perspective, thermal P recovery technologies can benefit from economies of scale when plant sizes are large and the initial investment costs are compensated by the higher amounts of output. One significant challenge with this technology is to miniaturize the scale and make it efficient enough to be deployed at WWTPs handling wastewater sludge from urban centers with population sizes even less than 100,000.

3. Spreading Wastewater Sludge on Agricultural Lands

Spreading of wastewater sludge on agricultural lands has been in practice for several decades in many industrialized countries. According to Cohen et al. (2011) sludge contains more than 90% of P in wastewater. Compared to the other phosphorus recovery methods the loss of P fractionations is insignificant with this method. The recovered P fractionations remain in the sludge and spreading it over agricultural soils prevents losses unlike the technologies using other extraction methods. Additionally, sludge also contains other macro-nutrients such as N and the carbon matter which are important for soil fertility while most of the N is released from the sludge as a by-product in the digestion phase before the sludge is spread on the agricultural lands. On the other hand, the main disadvantage of this method is that wastewater sludge also contains undesired substances. Another drawback of spreading wastewater sludge on agricultural lands is the logistical problem of transporting the sludge to the agricultural lands (Cohen et al., 2011). Nevertheless, Lundin et al. (2004) find that in Sweden wastewater sludge is transported an average distance of 80 km to the agricultural fields. From an environmental perspective another drawback of this method is that transportation and spreading of the sludge requires the emission of CO$_2$. Normally WWTPs use solar heat to dewater the moisture in the sludge, while it is possible to reduce the logistics costs with further dewatering. Similarly, at WWTPs during the pasteurization process of the sludge, the bio-gases produced as by-products are used for the generation of heating and other energy requirements in the plants.
Despite the presence of undesired substances in wastewater sludge, spreading sludge on agricultural lands has significant contributions on agricultural productivity. Singh and Agrawal (2008) cite various studies conducted to study the long term impacts of using wastewater sludge on agricultural soil and find that the organic matter in the sludge increased the microbial biomass as a result of long term spreading of sludge. This has also been similarly confirmed by Börjesson et al. (2013) who also studied the long term impacts of spreading sludge on Swedish agricultural soils and found that the carbon matter in the sludge does actually increase soil fertility. Nonetheless, due to the presence of the undesired substances in wastewater sludge spreading it on agricultural lands remains to be controversial. To investigate the effects of heavy metals on crops and the agricultural soil itself an ongoing experiment which spanned more than 30 years is being carried out in the Southern Sweden region of Skåne. A report from this long-term experiments show that so far spreading of wastewater sludge on agricultural lands has not caused any negative effect neither on the soil nor on the plants (Andersson, 2012). The results from the experiment further show that the concentrations of heavy metals especially Cadmium, remained low in the crops even when the amount of sludge spread was tripled. With regards to the effects on soil, the soils in the experiments were found to have higher concentration of heavy metals, while the phosphorus concentration and carbon matter content were also high. Nevertheless, the maximum allowed Cadmium content in imported fertilizers is 100gm/t P (0.1g/kg P), while the threshold for Cadmium concentration in wastewater sludge is only 2 mg/kg of dry matter substance (0.002 g/kg) (SEPA 1998:944).

References:


Börjesson, G., Kirchmann, H., Kätterer, T., 2013, Four Swedish long-term field experiments with sewage sludge reveal a limited effect on soil microbes and on metal uptake by crops, Springer-Verlag Berlin Heidelberg, Berlin, Germany, 14, 164-177.


Appendix IV: Population Sizes of Municipalities in Östergötland

Table 4.1. Population Sizes of Municipalities in Östergötland (2014)

<table>
<thead>
<tr>
<th>Municipality</th>
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<tr>
<td>Mjölby</td>
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Source: SCB (Swedish Statistical Bureau), 2014b