Energy and nutrient recovery from dairy manure
Process design and economic performance of a farm-based system

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Preface

This paper, *Energy and nutrient recovery from dairy manure – process design and economic performance of a farm based system*, was written during the 2014 spring semester and is a Master’s thesis as well as the final project in the engineering programme *Energy, Environment & Management*, pertaining to the section of Mechanical Engineering at Linköping University. It was written in collaboration with ReTreck AB and Againity AB, and the thesis results are the property of the authors Filip Celander and Johan Haglund.

Before moving on to the thesis, we would like to take the opportunity to credit persons that despite limited time and resources helped us to make the thesis as comprehensive as possible. Regarding the academic aspects, we have had excellent advice from our examiner Niclas Svensson, our tutor Michael Martin and our support resource Roozbeh Feiz, as well as our opponents Emilia Björe-Dahl and Mikaela Sjöqvist. A special credit goes to Jakob Olai, the manager of the case farm, who has tolerated a fair amount of calls and visits, for us to be able to design an appropriate model. Our collaborate companies have given us constructive support regarding the scenarios and their content, and thus we want to thank David Frykerås and Joakim Wren at Againty AB as well as Leif-Erik Thörnblom at ReTreck AB. Helene Oscarsson (coordinator at Vreta Kluster) and Peter Borring (chairman LRF Östergötland) deserve credits for their help in validating the theoretical framework. The potential suppliers for installing nutrient recovery processes have given us constructive offers and feedback on the scenarios, why we also want to thank Gunnar Thelin at Ekobalans AB and Henrik Lindsten at Noxon AB. When it comes to other aspects of the thesis, such as questions about regulations within agriculture, we have had many constructive discussions with Johannes Eskilsson (Jordbruksverket) and Lars Törner (Hushållningssällskapet) for which we would like to extend our gratitude. In addition, we would like to thank friends and family for giving feedback and being supportive.

Joyful reading!

Linköping, June 2014

Filip Celander

Johan Haglund
Abstract

A growing global population with an increasing overall wealth puts an intense pressure on food production, which in turn requires a highly functional agriculture. For agriculture to maintain and potentially increase productivity, the use of fertilizers is vital. However, the production of mineral fertilizers has a significant environmental impact, including depletion of fossil fuels and minerals. Simultaneously, large amounts of plant nutrients flow through the socio-ecological system without being utilized. One such over-looked resource is manure, which is the mixture of faeces, urine, waste water and bedding material that is generated in all farms with livestock. Many farms have a problematic situation today, where the regulation on phosphorus from organic sources (e.g. manure) generates a large amount of excess nutrients that cannot be applied to the farm fields.

This thesis assessed the technical and economic premises for installing systems that process manure in order to recover nutrients and inherent energy. The main purpose of recovering nutrients was to extract phosphorus from the manure, so as to be able to distribute more of the manure on the farm without exceeding the phosphorus regulation. Three other scenarios were included as reference; conventional manure handling, solid-liquid separation only and solid-liquid separation including energy recovery. Since most important parameters for modeling scenarios in agriculture are site-specific (e.g. soil type, crop rotation and manure composition), the thesis results were based on a case farm. The case farm is a 675 ha dairy farm with approx. 1400 milking cows, located in Östergötland, Sweden.

As for the results, it was first concluded that the central characteristics of manure were the content of dry matter (DM), nitrogen (N), phosphorus (P) and potassium (K). The higher the DM content, the more fuel for energy recovery, and the higher the N:P-ratio, the more on-farm N can be utilized before having to consider the P regulation. The technical premises for farm-scale nutrient recovery were limited to commercial techniques from companies operating in Sweden, and included various possible processing methods, such as; pH modification, anaerobic digestion, coagulation-flocculation, precipitation, filtration and reverse osmosis. However, most methods were either too costly or simply not realistic to install on stand-alone farms, resulting in only two feasible options; struvite precipitation and secondary solid-liquid separation with a decanter centrifuge.

The comparison in economic performance for all scenarios resulted as follows: nutrient recovery by struvite precipitation was the most profitable scenario of all, if struvite was allowed to replace mineral P fertilizer (i.e. end-product on-farm utilization). If not, it was more profitable to invest in only energy recovery, as nutrient recovery by secondary solid-liquid separation or struvite precipitation with end-product sales were not as profitable. However, the absolutely largest increase in profitability lies within investing in a primary solid-liquid separation. As for the case farm, this investment reduced costs by more than 2 MSEK, while any of the latter scenarios reduce costs by 0.1-0.2 MSEK. Furthermore, the possible utilization of the waste heat from energy recovery increased profitability by a factor of ten.

To conclude, this thesis has proved that there are many options for utilizing farm resources more wisely. By recovering both energy and nutrients in the manure, the farm may increase profitability significantly and improve the overall resource efficiency. Such an approach is particularly interesting within organic farming, where plant nutrients are generally more expensive. However, the transition from theoretic conclusions to real life results presents challenges, as a farm operates with a pragmatic approach, and since there are legislative and policy related barriers to overcome.
Sammanfattning

En växande världsbefolkning med stigande välfärd ökar efterfrågan på livsmedel, vilket i sin tur förutsätter ett väl fungerande lantbruk. För att bibehålla, och möjligtvis öka, lantbrukets produktivitet behövs stora mängder växtnäring. Modernt jordbruk grundar sig dock i användandet av mineralgödselmedel, vilka har omfattande miljöpåverkan. Framställningen av kvävegödsel baseras på fossil naturgas, medan utvinningen av fosfor och kalium utnyttjar ändbara mineralresurser. Samtidigt flödar stora mängder växtnäring genom samhället utan att nyttjas till fullo. En av dessa outnyttjade resurser är stallgödsel, vilket är den blandning av träck, urin och strömedel som alla gårdar med djurbesättningar genererar. På grund av en reglering i mängden fosfor som får komma från naturliga källor (t.ex stallgödsel) har många gårdar idag problem med att avsätta sitt stallgödsel.

Denna uppsats undersökte de tekniska och ekonomiska möjligheterna att installera processer som behandlar stallgödsel på gårdsnivå, i syfte att nyttja växtnäring och energi i större utsträckning. Främst avsågs metoder som extraerar fosfor ur systemet, så att mer stallgödsel kan spridas innan forforregleringen träder i kraft. Tre andra scenarier inkluderades som referens: konventionell stallgödselhantering, flytgödselseparering samt flytgödselseparering inkl. energiåtervinning. Eftersom många aspekter inom lantbruk är platsspecifika, t.ex jordmån och odlingsföljd, utgick kalkylerna från en referensgård. Denna ligger i Östergötland och är en mjölkgård med ca 1 440 mjölkor exkl. rekryteringsdjur.

Vad gäller resultaten kan det först påpekas att de parametrar som är viktiga vid analys av stallgödsel i huvudsak är torrsubstanshalten (TS) samt innehållet av kväve (N), fosfor (P) och kalium (K). Ju högre TS-halt, desto mer bränsle till energiåtervinning, och ju högre N:P-kvot destro mer N kan spridas innan fosforregleringen begränsar. De tekniker för näringsåtervinning som undersöktes begränsades till kommersiella tekniker på den svenska marknaden, och utgjordes bl.a av: pH-modifiering, rötning, koagulering-flockulering, utfällning, filtrering och omvänt osmos. Många av dessa var dock antingen för dyra eller orealistiska att installera på gårdsnivå, vilket resulterade i att endast två tekniker inkluderades: struvitfällning och sekundär gödselseparering i form av dekantercentrifug.

Vid jämförelse av scenariernas ekonomiska resultat erhölls följande resultat: näringsåtervinning via struvitfällning med återförsel av struvit på gården var det mest lönsamma alternativet. Därefter var det mest lönsamt att endast energiåtervinna, eftersom struvitfällning utan återförsel samt sekundär gödselseparering hade lägre lönsamhet än så. Den största vinsten ligger dock i att installera gödselseparering överhuvudtaget – för referensgården uppgick denna besparing till 2 MSEK, medan den potentiella besparingen i större nyttjande av energi och/eller växtnäring uppgick till 0,1-0,2 MSEK. Det bör även påpekas att ett eventuellt nyttjande av överskottsvärmen från energiåtervinningen ökade lönsamheten med faktor tio.

Det finns alltså många möjligheter för svenskt lantbruk att utnyttja befintliga resurser i större utsträckning. Genom att bättre nyttja växtnäring och energi i stallgödsel kan den enskilda gårdn öka sin lönsamhet markant, medan samhällets resurseffektivitet samtidigt förbättras. Dessa resultat är i synnerhet intressanta för ekologiska gårdar, där extern växtnäring ofta är förhållandevis dyr och svår att få tag på. Innan dessa teoretiska resultat kan omsättas i praktiken måste dock några hinder överkommas, främst gällande regler och lagar, samt rådande praxis inom lantbruket.
Energy & nutrient recovery from dairy manure
Terminology

Terms

**Digestate**
Output material after a process, e.g. the liquid that remains after anaerobic digestion in biogas production

**Permeate**
The diluted substance that builds up during filtration or osmotic processes

**Reject**
The final permeate after one or more stages of filtration or osmotic processes, considered as waste water

**Retentate**
The concentrated, remaining substance after filtration or osmotic processes

**Substrate**
Input material into a process, e.g. organic material for biogas production

Abbreviations

**DM**
Dry matter content of the substance

**LF**
Liquid fraction, i.e. the wet fraction from solid-liquid separation

**N:P:K**
Weight ratio of nutrient content in fertilizers

**N:P-ratio**
Weight ratio between TN and TP

**ORC**
Organic Rankine Cycle, i.e. a Rankine cycle with an organic medium with low temperature evaporation and condensation

**SF**
Solid fraction, i.e. the dewatered fraction from solid-liquid separation

**TAN**
Total ammonium nitrogen (NH₄⁺)

**TKN**
Total Kjeldahl nitrogen (specific method of measuring TN)

**TN**
Total nitrogen

**TP**
Total phosphorus

**TSS**
Total suspended solids
Economic Parameters

<table>
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<tr>
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<th>Revenues (+) or costs (-)</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td><strong>Bedding materials</strong></td>
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<tr>
<td>Purchased straw</td>
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<td>Case farm</td>
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<tr>
<td>Wood shavings</td>
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<tr>
<td><strong>Electricity</strong></td>
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<tr>
<td>Produced*</td>
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<td>SEK/kWh</td>
<td>NordPool &amp; SVK Cesar</td>
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<tr>
<td>Purchased</td>
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<td>Deep litter</td>
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<td>Case farm</td>
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<td>Liquid fraction</td>
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<td>SEK/ton</td>
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<td><strong>Investment interest rate</strong></td>
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Table 1: List of revenues and prices for thesis-related materials and items, as well as financial aspects.
*Calculated using average spot prices in region SE3 (NordPool) and average electricity certificate prices (SVK Cesar), 2013.
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1 Introduction

The thesis introduction includes as brief background to the current situation, as well as the thesis objective, aims, questions and limitations.

1.1 Background

A growing global population with an increasing overall wealth puts an intense pressure on food production, which in turn requires highly functional agricultural systems. For agriculture to maintain and potentially increase productivity, the use of fertilizers is vital. It is estimated that artificial fertilizers feed half of the world’s population, and by the beginning of the twenty-first century, human sources of nitrogenous fertilizers were two to three times that of natural terrestrial sources (Galloway, et al., 2013). The global demand for nitrogen fertilizers increased from 10 Mt in 1960 to 90 Mt in 1998 (Uludag-Demirer, et al., 2005) and is currently around 120 Mt per year (Galloway, et al., 2013).

Unfortunately, the production of fertilizers has a significant environmental impact. Around 29 GJ/t from fossil natural gas is required for the synthesis of plant available nitrogen through the Haber-Bosch process (Vaneecchauta, et al., 2013), which translates to around 2% of the world’s primary energy consumption (Michalsky & Pfromm, 2011). Phosphorus and potassium fertilizer production is depleting natural mineral resources, and phosphorus in particular is a nutrient with fast increasing scarcity (Vaneecchauta, et al., 2013). Estimates of the current phosphorus and potassium reserves are highly uncertain, but based on population growth and future nutrient demand, it is predicted that phosphorus and potassium will be completely depleted in 93-291 years and 235-510 years respectively (Golkowska, et al., 2012). The significant consumption of natural gas and depleting natural resources also causes the price for mineral fertilizer to be volatile with an increasing trend (Vaneecchauta, et al., 2013).

Simultaneously, large amounts of nutrients form a linear flow through agriculture and society just to end up in rivers and other water resources. Waste water and manure from farm animals has become a major problem in regions with a lot of livestock, such as the Netherlands and southern Sweden (Thörneby, et al., 1999; Eskilsson, 2014). A large animal to field ratio means over-application of manure, turning an environmentally sound resource into a potential problem. Excessive application of manure as well as soil saturation cause leaching of nutrients into the water resources, ultimately increasing eutrophication (Uludag-Demirer, et al., 2005). To cope with such a development, current EU regulations and consequently also Swedish legislation prevents farmers to add more than 110 kg/ha of phosphorus from organic fertilizers (e.g. manure and sewage sludge) onto their soil during a five year period, which translates to 22 kg phosphorus per hectare and year (Jordbruksverket, 2013).

While this limit hopefully decreases eutrophication, it also presents a huge challenge to all farms with livestock, since the excess volume of manure has to be managed and the nutrient deficit replenished with mineral fertilizers. The simplest possible solution to excess manure would be to transport it to farms with similar nutrient demands but less access to local nutrients. Due to the high water content however, the costs of transporting, storing and distributing manure exceed the costs of purchasing mineral fertilizers (Avfall Sverige Utveckling, 2011). Instead, the general treatment of excess nutrients has commonly been a nutrient removal, either on a waste water treatment plant or by off-setting excess manure and sewage sludge on low-value soil, such as landfills or golf courses.

It seems ironic that the struggle to mitigate eutrophication forces the already economically strained farmers to waste their own, local plant nutrients and purchase mineral fertilizers that are both expensive and carry a large environmental impact. As an attempt to solve not only the local nutrient
excess problem but also reduce the negative environmental impact from mineral fertilizer production, the nutrients in manure could be recovered instead of removed, and processed in a way that enables increased on-farm utilization and possibly cost-efficient transport of excess fractions. The need for a range of such products is apparent and urgent, but it is important to understand that such manure management will generate additional costs and potentially an environmental impact (Avfall Sverige Utveckling, 2011). Most existing methods are currently not feasible due to high costs of input material and low perceived value of the end-products. Thus, the challenge is to reduce the costs and improve the efficiency of the processes while adding value to the separation products (Petersen, et al., 2007). It seems that strategies to increase product and by-product valorization could be beneficial both to individual farmers and the food- and agriculture industry as a whole. Perhaps a novel system that not only recovers nutrients but also produces heat, electricity and bedding material could solve the economic puzzle and enable commercialization.

In this context, it is worth noting that manure management consists of several interrelated operations carried out from the time the manure is removed from the animal stables until it is used for production of fertilizer and bio-energy (Petersen, et al., 2007). Therefore, a whole-system approach should be considered when developing the technology for optimizing the recovery of plant nutrients and energy in dairy production.

1.1.1 Case farm presentation
The thesis is primarily based on site-specific data originating from a case farm located just outside Vikingstad, Sweden. It is a 675 hectare farm, out of which 435 hectares are devoted to cereal crops and the remaining 240 for fodder crops. In addition to the harvest, the cereal crops also generate 500 tons of straw. The core business is dairy production, and after planned expansions have been completed, the farm will have approximately 1400 dairy cows plus recruitment animals (totalling approx. 5400 animals). Almost all of the animals will be housed in stables with cubicles. The cubicle floor is covered with a bedding material, to allow the cows to lie down comfortably. The floors of the stables are cleaned with an automated manure removal scraper. Faeces, urine, bedding and wash water are scraped into trenches that run underneath the stables, and the resulting liquid manure (slurry) accumulates in a storage basin outside the stables. The cows in cubicles produce 46 000 tons (or m³) of slurry every year, including rainfall and dishwasher from milk production.

Some animals, such as birthing sows and young calves, are temporarily housed in deep-litter beds, which are not automatically scraped. The deep-litter beds produce a solid fertilizer that can be sold to external partners. The deep-litter beds use substantially more bedding material per cow than the cubicles.

All manure calculations are further described in Appendix II – Scenario platform calculations.
1.1.2 Problem overview

The three nutrients that represent some of the largest fractions and costs in modern agriculture are nitrogen (N), phosphorus (P) and potassium (K) (Dawson & Hilton, 2011). As stated above, there is a 110 kg per hectare and five year period restriction of P from organic fertilizers (e.g. manure), which translates to 22 kg per hectare and year (Jordbruksverket, 2013). This restriction puts a limit on the amount of organic fertilizer that can be applied to the fields of the farm, whether it originates from the farm or not. The substrates included in this thesis all have a certain ratio of N and K to P, and this means that for a certain substrate, there is a set limit on the amount of N and K that is possible to apply to the fields as well.

As a case farm average, cereal crops and fodder crops require 170 kg N/ha and 275 kg N/ha respectively (Olai, 2014), which combined with the areas dedicated to each crop results in an average need of 207 kg-N/ha (see Figure 3 below). Now, the N:P-ratio of the raw slurry on the farm is too low to allow for all of this N to come from the on-farm nutrients, and is limited by the P restriction. In addition, the 22 kg-P/ha does not satisfy the total crop need, which is 27 kg-P/ha in average and thus leave a 5 kg-P/ha deficit. The deficit of both N and P fertilizer is currently compensated by the purchase of mineral fertilizers, which are not bound by the 22 kg-P/ha limit.

The supply of on-farm K widely exceeds the crop needs, averaging 14 kg-K/ha. There is no legislative restriction on the application of K in Sweden that is affecting the farm, and thereby it is not a part of the case farm problem. However, the purchase of N- and P mineral fertilizer represent a major cost of operation. It would therefore be of great benefit to better utilize the nutrients available in the manure, so that less mineral fertilizers have to be purchased.

Consequently, the suitable approach in this thesis is to increase the current utilization of potentially useful nutrients until the total crop need is satisfied. In other words, P should be extracted from the system, without significantly decreasing the N content. It is this approach that the nutrient recovery process below will strive towards.
1.1.3 Assignment framework
The thesis was written in collaboration with ReTreck AB\(^1\) and Againity AB\(^2\). ReTreck AB is a small company specialized in screw-press separators for manure separation (see 2.4 for description of separators), while Againity AB is developing an ORC unit (see 3.3.3 for description of an ORC unit) for converting low-grade heat into electricity. The agenda of these companies set a framework on the thesis, where the equipment from ReTreck AB provided several slurry substrates and Againity AB was interested in any substrate that could function as a fuel for the production of heat and electricity. Thus, the nutrient recovery refers to utilization of substrates that are part of a system where the inherent energy is recovered by means of heat and electricity production. To clarify, the case farm currently has a screw-press separator installed, while both the ORC unit and the nutrient recovery process are hypothetical future investments.

Per the wishes of the collaboration companies, the economic result was presented as both an annual economic performance and a pay-off time, as opposed to a more comprehensive economic calculation where e.g. net present values and depreciation is included.

1.2 Objective
The objective of the thesis was to evaluate the techno-economic premises for installing a manure processing system on a dairy farm in Östergötland, Sweden, to increase the utilization of available on-farm nutrients.

1.2.1 Aims
The aim of this thesis was to design and quantify several scenario models of processes that recover inherent energy and plant nutrients in dairy manure. The models were to include material flows and on-farm nutrient utilization as well as economic performance. Three other models were used as comparison; conventional manure handling, manure solid-liquid separation and energy recovery.

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\(^1\) http://www.retreck.se/
\(^2\) http://www.againity.com/
1.2.2 Research questions

- What aspects of the case farm dairy manure and its derivatives are important to characterize?
- Which processes for nutrient recovery are technologically and economically realistic on farm-scale?
- How do such processes perform regarding on-farm nutrient utilization and economic performance on the case farm, compared to other realistic scenarios?

1.3 Limitations

The thesis was limited in some ways by the case farm circumstances. No other type of manure than dairy manure is considered, and the already installed solid-liquid separation equipment somewhat limited the possible model designs. In accordance with the assignment framework (see 1.1.3) an ORC unit was included in the proposed scenario models.

Although the manure processing model may be novel in itself, it was to be composed by processing equipment that is commercial and available on the market. Methods that are still experimental were thus not considered. Furthermore, only Swedish companies or companies operating in Sweden were included.
Energy & nutrient recovery from dairy manure
2 Theoretical background

This chapter offers a basic background on plant nutrients, agricultural practices and manure processing methods that will facilitate an understanding of the following chapters of the thesis.

2.1 Plant nutrients

Crops need nutrients in order to grow and produce a satisfactory harvest. These nutrients are part of complex physiochemical interplays with their environment, where the specific matters can exist in several different forms. It is necessary to have a basic understanding of this interplay, since it determines plant availability and ultimately the effectiveness of a fertilizer.

Nutrients can be divided into macro- and micronutrients depending on the volume necessary to the crop (Dawson & Hilton, 2011). Micronutrients, e.g. boron (B), copper (Cu) and manganese (Mn), are required in small quantities that many fertile soils are capable of supplying without addition of fertilizer. Some macronutrients, such as calcium (Ca), sulphur (S) and magnesium (Mg) are generally available in the soil, whilst others need to be added in large quantities. These are nitrogen (N), phosphorus (P) and potassium (K), which are described further below.

2.1.1 Nitrogen

Air contains 78% N gas (N₂), which is in constant exchange with N in the soil. The vast majority of the soil N is bound in organic matter, such as plant residues, bacteria and fungi (Claesson & Steineck, 1991). However, to become available to the plant, the air N and organic N have to be converted into either ammonium (NH₄⁺) or nitrate (NO₃⁻) (see Figure 4 below). The slow process of fixating air N and degrading organic material into its inorganic components (mineralization) is mainly carried out by microorganisms. Air N is converted to nitrate (fixation) while organic N is mineralised to ammonia (NH₃) which is then either released to the air or converted to its corresponding ion, ammonium. Ammonia and ammonium exist in a dynamic equilibrium balanced by pH and temperature: cold, alkaline conditions generate more ammonia, while acidic and warm conditions are favoured by ammonium (Huang & Shang, 2006). Part of the ammonium is absorbed by the plant, while the majority is converted to nitrate (nitrification), which is either released to the air as N gas (denitrification), absorbed by the plant or leached to surrounding environment (Claesson & Steineck, 1991).

![Figure 4: Chart over the N cycle.](image-url)
In other words, a N fertilizer that contains nitrate and ammonium has a relatively immediate effect and a quick plant uptake, while a fertilizer with ammonia and organic N is slow-releasing and not as effective (Borring, 2014). Figure 5 below summarizes the different chemical forms of N.

![Figure 5: Chart over different forms of N, where the dark green boxes show N directly available to plants, while light green boxes show forms of N that can be converted into plant available N through processes described above.]

2.1.2 Phosphorus

Since plants in general need only around 30 kg P per hectare and the soil contains between 200-3000 kg P/ha, it seems the addition of P fertilizer is rather unnecessary (Johnson, 1997). However, only a minimal fraction (around 0.01-0.1%) of the total P in the soil is available to the plant. Instead, the vast majority of P exists in other forms with very complex relations that mainly depend on soil pH and composition (see Figure 6 below). Plant available P is phosphate ions (PO₄³⁻) dissolved in the soil liquid, originating from either particulate-, organic-, mineral- or precipitated P. Particulate P are P ions adsorbed to colloidal particles in the soil, that can quite effortlessly become dissolved in the soil liquid. The amount of particulate P is marginal and varies with soil pH and mineral composition. A rather large part of the total P is precipitated with e.g. calcium (Ca) or iron (Fe). These precipitations are not directly available to the plants, but their low solubility generates a slow release of plant available phosphate to the soil liquid. P also exists in different minerals, where apatite is most common. Minerals are insoluble and moulder slowly; hence it is not plant available. However, it is believed that plants can absorb P through apatite by first letting the mineral pass through microorganisms. A major fraction of the total P is organically bound in e.g. plant residues and microorganisms. Although decomposition of this material into inorganic P (mineralisation) is presumed to release P into the soil liquid, this process is still relatively unknown.

Commonly, P fertilizers contain phosphates in different precipitated forms that dissolve when put in the soil, although different precipitations differ greatly in dissolution rate (Borring, 2014).
2.1.3 Potassium

Similar to P, K is abundant in soil but the absolutely dominant fraction is bound as minerals (Claesson & Steineck, 1991). K is available to plants as ions ($K^+$) dissolved in the soil liquid, originating from colloidal particles as described with P above (see Figure 7 below). The available amount corresponds mainly to soil composition: if the soil contains a large amount of clay the particles are withheld, while a sandy soil that cannot contain as much colloidal particles leaches K.

Thus, the design and suitability of K fertilizers depend much on soil type. In general they are designed similar to P fertilizers though, as precipitates with different dissolution times (Borring, 2014).

Figure 6: Chart over forms of P in soil, where the dark green box shows plant available P.

Figure 7: Chart over possible forms of K in soil, where the dark green box shows plant available K.
2.2 Current fertilizer practices
When developing a fertilizer innovation it is essential to consider the agricultural market situation, in order to fit into existing practices and infrastructures. The farmer’s perceived value for a specific fertilizer is primarily affected by its content (substance, concentration and chemical form) and its structure (liquid, solid or granulate) (Borring, 2014), both of which are further described below. Of course this is a generalization; in reality the farmer’s preference depends on many case-specific factors such as soil conditions, crop rotation, local nutrient availability, current word-of-mouth etc. But there are still some general trends that can prove useful when weighing otherwise similar fertilizer end-products.

2.2.1 Fertilizer content
All farms have a unique need for fertilizer. Consequently, pure fractions of either nutrient are valued higher than mixtures (Avfall Sverige Utveckling, 2011). Traditionally a fertilizer is valued based on either its content of N or P, where N is demanded in larger quantities and also more difficult to retain as a local nutrient (Borring, 2014). The demand for P and K is generally lower, although it depends greatly on type of soil and crop rotation. The addition of organic matter is important for maintaining a productive soil, but from a historical perspective its value has been perceived as low (Avfall Sverige Utveckling, 2011). Furthermore, farms are often self-sufficient with organic matter. The demand for a specific fertilizer also depends on the concentration of nutrients, where the general correlation is an increasing value with an increasing concentration. However, a liquid fertilizer with very high N content (> ca 30%) tends to harm the plants by “burning” the leaves if applied directly onto the plants, but such significant concentrations are uncommon (Borring, 2014).

Perhaps the most important aspect for valuing a specific nutrient is the chemical form in which it is applied to the soil, as different chemical forms of the same substance differ greatly in plant availability (see 2.1 for descriptions of the different chemical forms). Under the assumption that the fertilizers in mind share the same structure and concentration (Borring, 2014).

As for the case farm, the generalized perceived values in Table 2 above are somewhat misleading. While the demand for N (ammonium and nitrate in particular) is very high and thus corresponds with the generalization, the situation is different with P and K. The on-farm excess of P and K in relation to crop need and P restrictions (see 1.1.2) reduces their perceived values significantly. For P it is rather the opposite, where the case farm would benefit from the removal of on-farm P.

2.2.2 Fertilizer structure
The commercial techniques for applying fertilizers onto soil are well established in modern agriculture, and can be broadly categorized by fertilizer structure; liquid, solid or granulate (Borring,
Energy & nutrient recovery from dairy manure

2014). Any excess end-product from the manure processing would benefit from fitting into any of these structures, further described below.

**Liquid fertilizers**

Typical liquid fertilizers are slurry, biogas substrate or anaerobically digested sewage sludge, characterized by a low content of dry matter (DM) and nutrients, with a texture that varies from tea water to lumpy sludge (Hellström, 2014) (see Figure 8 below). The major advantage of liquid fertilizers is the quick plant uptake, caused by the fact that most nutrients are already dissolved when distributed. Liquid fertilizers are distributed by several techniques. In Sweden, the most common method is to use a band spreader (see Figure 8), where a tank feeds a number of evenly distributed hoses that places the slurry close to the ground. The low nutrient concentrations require the volume of the slurry to be large in order to supply the plants with enough nutrients. The large quantity of slurry increases the weight of the distribution equipment, contributing to problematic soil compaction. Another mechanism to distribute large volumes of a liquid fertilizer is an umbilical hose, where the liquid is fed to the tractor by a drag hose, connected to the fertilizer storage directly or via satellite storage tanks. Such a system contributes less to soil compaction, but requires a more complicated infrastructure and could damage the crop as the hose drags across the ground.

The dry-matter content and particle size distribution will affect the handling of the liquid fertilizer. If a fertilizer with a high quantity of large particles is being spread, the hoses risk clogging, forcing the operator to back-flush the system.

Alternatively, the liquid fertilizer could be concentrated into a smaller volume that is still large enough to be distributed by the common band spreader (Borring, 2014). This would enable lighter and faster spreading of the same amount of nutrient, resulting in reduced costs for fuel and soil compaction.

![Figure 8: To the left, a band spreader typical for spreading liquid fertilizers (Anon., 2009a) and to the right, cattle slurry as an example of liquid fertilizer structure (Haglund, 2014).](image)

**Solid fertilizers**

A solid fertilizer is commonly a clay-like composition of straw-rich manure and bedding material, but can also be the solid fraction of dewatered slurry, sewage sludge or biogas digestate (Chambers, et al., 2001; Hellström, 2014). It is in most cases distributed by some type of rear discharge spreader, where solid material is delivered from a trailer to the rear of the spreader, fragmented by a beater and discharged with a spinning disc (see Figure 9 below). This fertilizer structure is marginal, as most of modern agriculture is based on liquid or granulate fertilizer distribution. It is also somewhat problematic, since the distribution of solid fertilizers tends to spread odour to the surrounding regions.
Granulate fertilizers
The granulate structure is applied within the mineral fertilizer industry and thus it is the dominating fertilizer structure in modern agriculture (Hellström, 2014). Granules are highly-concentrated on nutrients and are distributed either by a mechanical spreader or a comi-drilling device (Lundin, et al., 1997). The mechanical spreader could have a simple construction that distributes the granules evenly behind the trailer, or a centrifugal spreading mechanism that distributes the granules over a wide area (see Figure 10). The latter method requires granulates of high quality that stay intact as they exit the centrifuge in velocities up to 200 km/h. A comi-drilling device sows the seeds while placing granules beneath the seeds simultaneously (Bertilsson, 1996). It is widely used since it improves fertilizing precision and thus generates higher yields, but it is also more expensive than mechanical spreaders (Hellström, 2014; Bertilsson, 1996). The main advantages of the granulate structure are the precision in which one can apply fertilizers to a specific zone, and its high concentration on nutrients in relation to volume, enabling the farmer to top up with fertilizer during the whole growing season without damaging the plants. However, since nutrients are not dissolved in a liquid, the granules need rain or some other form of irrigation to dissolve into the soil.

Under the assumption that the fertilizers in mind share the same content and concentration, the demand based on fertilizer structure can be seen in Table 3 below.
<table>
<thead>
<tr>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid fertilizer</td>
<td>Liquid fertilizer</td>
<td>Granules</td>
</tr>
</tbody>
</table>

Table 3: The farmer’s perceived value for different fertilizer structures (ranked from low to high) assuming the same fertilizer content (Böring, 2014).

As for the case farm, the generalized perceived values in Table 3 above correspond very well. The liquid fertilizer is distributed with an umbilical hose, and mineral fertilizers are distributed with a centrifugal spreader (Olai, 2014). The negative aspects of liquid fertilizers (mainly soil compaction) and solid fertilizers (odour), in contrast to the benefits of granules (precision), are the main reason why the granulate structure is appreciated highest by the case farm manager.
2.3 Slurry characterization

The manure processing is based entirely on the slurry generated on the farm. As such, it is important to gain knowledge on the character of this material, which is why it is characterized in general terms in this part of the thesis, so as to function as a reference when the case farm slurry is characterized in Case farm substrate characterization. To give a context, slurry is liquid animal manure, which is a mixture of faeces, urine, bedding material, waste feed and wash water (Hjorth, et al., 2010; Claesson & Steineck, 1991). Manure characteristics vary greatly depending on animal species, diet and age as well as storage time, collection system and the amount of water used in the stalls (Møller, et al., 2002). It is common to sort manure into three broad categories: slurry (liquid), semi-solid and solid (see Figure 11) (Claesson & Steineck, 1991). The amount produced of each category depends on the methods of manure collection, storage and handling, which differ for each farm (Hjorth, et al., 2010).

![Figure 11: General categorization of manure (Claesson & Steineck, 1991).](image)

Characteristics of slurry suggested for investigation in optimizing the efficiency of slurry separation include particle size distribution, concentration of nutrients, pH and buffering capacity, as well as physical properties (Hjorth, et al., 2010).

2.3.1 Dry matter content and particle size distribution

Knowing the content of dry matter (DM) and particle size distribution is important for efficient handling of the slurry, since particles of different sizes respond to processing methods in different ways. For instance, particles smaller than 1 µm are colloidal and move through the liquid by diffusion, while larger particles are subject to gravitational forces and settle at the bottom (Hjorth, et al., 2010). Diet and animal type has an effect on the DM content and particle size distribution in slurry, but in general around 6 weight-% of the slurry is constituted by dry matter, of which about 50% can be found in the <0,125 mm category (see Table 4). Because approximately 80% of P and 30% of N (i.e. organic N) is contained in, or adsorbed to, small particles, the <0,125 mm category holds a large percentage of the total nutrient content in the slurry.

![Table 4: Total dry matter (DM) content and a general particle size distribution.](image)

2.3.2 Concentration of nutrients and other compounds

The feasibility of nutrient recovery is completely dependent on accurate data on the content of nutrients and other compounds. The amount of nutrients in slurry is the balance between what the animal has been fed and what has been used to produce milk or meat (Claesson & Steineck, 1991). Slurry contains all 13 of the essential nutrients that are used by plants, which are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), copper (Cu), zinc (Zn), chlorine (Cl), boron (B), iron (Fe) and molybdenum (Mo) (Clemson University Cooperative Extension, 2003). However, unlike mineral fertilizer, slurry is a heterogeneous product
with varying levels of specific nutrients (Claesson & Steineck, 1991). This uncertainty factor complicates the agricultural process, and indicates that generic data is often different from the real data from a specific site. Table 5 below presents some nutrient related characteristics for dairy cattle slurry from Møller et al (2002) to give an idea of the order of, and relation between, different nutrients.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Untreated dairy slurry (Møller, et al., 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN [kg/ton]</td>
<td>2,5</td>
</tr>
<tr>
<td>TAN [kg/ton]</td>
<td>1,7</td>
</tr>
<tr>
<td>TP [kg/ton]</td>
<td>0,69</td>
</tr>
<tr>
<td>K [kg/ton]</td>
<td>3,54</td>
</tr>
<tr>
<td>N:P-ratio</td>
<td>3,6</td>
</tr>
</tbody>
</table>

Table 5: Key nutrient characteristics of untreated dairy slurry.

Seemingly, the concentration of total N is in average 0,25%, out of which a little more than half is ammonium (ammonia ions dissolved in the liquid). The remaining N of the total N fraction is either organically bound (approx. 30%) or suspended in the liquid as gaseous ammonia (Hjorth, et al., 2010). The P concentrations amounts to 0,07% in average out of which around 5% is organically bound and around 30% is dissolved in the liquid. The remaining majority pertains to the particle fraction, where it is either organically bound or adsorbed onto particles (Hjorth, et al., 2010). The relation between total N and total P (N:P-ratio) is just under 4, which is relatively low. K levels are in line with total N, and are in average 0,35%.

2.3.3 pH and buffering capacity
As described in 2.4 below, the modification of slurry pH is a common method to adjust the content for different purposes, which is why an understanding of the pH dynamic and buffering capacity is important. Raw cattle slurry is often slightly alkaline, with a pH value interval at around 6,8-8,3 (Pagliari & Laboski, 2013). A number of natural underlying processes affect the slurry pH: the emission of CO₂ increases pH, while the emission of NH₃ reduces pH (Hjorth, et al., 2010). Regarding nutrients, acidic slurry tends to have higher concentrations of dissolved P and K. Total N levels remain unaffected, but the equilibrium between gaseous ammonia and dissolved ammonium is shifted towards a concentration of ammonium (Gerardo, et al., 2013). Consequently, alkaline slurry tends to contain higher levels of ammonia and precipitated compounds of P and K. These dynamic reactions to pH are important to consider when designing the manure processing model, since different pH values result in different nutrient contents.

If attempting to modify the pH of slurry, it is important to consider the barrier from the natural buffering system, mainly constituted by carbonic acid (H₂CO₃) (Hjorth, et al., 2010). A typical buffering curve for dairy slurry was generated by Gerardo et al (2013) (see Figure 12), showing strong buffering capacity between pH 7,5 and 5,5, and below pH 2,5.
2.3.4 Physical properties

Both density and viscosity of slurry correlate entirely to the DM-content (Hjorth, et al., 2010). It has been concluded that, for a DM content up to 50%, the density of dairy cattle slurry can be calculated from the following equation:

\[ \rho = 1000 + 14.6 \times DM + 2.38 \times DM^2 + 0.0367 \times DM^3 \ kg/m^3 \]

Regarding viscosity, slurry with a relatively high DM content makes the handling difficult, as pumping and other processes may be damaged or clogged (Hjorth, et al., 2010). For simple flow considerations however, an apparent viscosity control will often be sufficient. Thus, the viscosity parameter is not further investigated.
2.4 Slurry processing methods
There are various methods for processing slurry, each with its own purpose and requirements. The compilation of methods below is included as a means to facilitate the understanding of the nutrient recovery models in the thesis results below. As stated in 1.3, the nutrient recovery models are limited to technologies that are available on the market, and this compilation is primarily based on (Hjorth, et al., 2010).

In general, the vital part of processing slurry is almost always some form of solid-liquid separation that separates the solid parts in the slurry from the liquid, thus generating two substrates: a solid and a liquid fraction. It is common to strive for a solid fraction rich in both DM and nutrients, and a liquid fraction with low levels of nutrients and solids, so as to enable a considerable volume reduction and a more cost-effective transport of excess nutrients (Hjorth, et al., 2010). However, as stated in 2.3.1, most nutrients are either dissolved in the liquid or adsorbed to very small particles, why the majority of the nutrients end up in the liquid fraction. Additional processing methods can be applied before or after the separation, and these differ from case to case, depending on circumstances. The methods included in this thesis were organised as displayed in Figure 13 below. Methods that take place before solid-liquid separation are categorized as pre-treatments and share the purpose of enhancing separation efficiency or facilitating nutrient recovery further down the process. After the solid-liquid separation, methods for altering and/or concentrating nutrient fractions from the liquid fraction are called treatments. Only the liquid fraction is considered, since the solid fraction already has other purposes on the case farm (see 1.1.3).

![Figure 13: The categorization of available manure processing methods.](image)

2.4.1 Pre-treatments
The purpose of pre-treatments is to either enhance separation efficiencies, or to alter the composition of the slurry to facilitate nutrient recovery further down the process.

Storage
As with any other biologically active substance, the slurry is affected by storage. Biological decomposition contributes to the transfer of nutrients and solids between different fractions and chemical forms (Møller, et al., 2002). Total N levels decrease by around 10% mainly due to ammonia volatilization (Hjorth, et al., 2010), but within the remaining N, ammonium levels increase (Møller, et al., 2002). Anaerobic bacteria digest the dissolved solids and hydrolyze suspended solids into dissolved solids, which leads to a decrease in total solids. Consequently, the DM level may decrease as much as 25% during five months of storage at 20°C. However, at lower temperatures the biological decomposition will have a significantly lower rate, resulting in DM reduction rates that are ten times lower at 10°C than at 20°C (Hjorth, et al., 2010). In other words, storage time reduces levels of total N and DM, and consequently it is beneficial to minimize it.
In most cases however, storage is rather a question of following legislation than a pre-treatment. Many countries regulate the minimum storage time to prevent manure soil application during certain periods of the year. Swedish legislation on minimum storage time differs depending on species, livestock size and region (Jordbruksverket, 2013) but varies between 6 to 10 months. Through personal correspondence, it has been concluded that there is no legislation that requires the storage to contain untreated slurry (Eskilsson, 2014). Thus, a process that divides the slurry into several fractions, and thereby reduces the total volume, is an interesting strategy for more cost-effective storage. Figure 14 below demonstrates a typical slurry storage.

![Figure 14: A typical slurry storage, in this case an image from the case farm (Celander, 2014).](image)

**Anaerobic Digestion**

During anaerobic digestion, the manure is affected in a similar way as during storage (Møller, et al., 2002). However, the process is carried out in a controlled temperature and enclosed atmosphere, resulting in the capture of methane and significant decrease in organic matter and DM. The resulting digestate can be separated just as slurry, with the difference that the solid fraction generated is not as suitable as bedding material as if no digestion has taken place (Tonderski, 2014). Thus, it is an altogether interesting option for most farms but not for the case farm, since the solid fraction is necessary as bedding material. Anaerobic digestion as a pre-treatment is further discussed in 9.5.3.

**pH modification**

As stated in 2.3, the modification of slurry pH affects its composition in several ways, and whether it is a suitable pre-treatment or not depends on the purpose of the processing system. In general, it is a method that requires large amounts of additives since slurry has a strong natural buffering capacity. Raising pH (liming) is done by stripping the slurry of CO₂ and/or adding a liming agent, such as calcium hydroxide (Ca(OH)₂) (AgroTechnologyATLAS, 2014). The main purpose of liming is to sterilize the slurry from pathogens and to favor phosphate precipitation as a slurry treatment. However, the higher pH also increases the undesired volatilization of ammonia (Tonderski, 2014).

Lowering pH (acidification) is common practice in The Netherlands and Denmark (Fangueiro, et al., 2009). The primary purpose is to reduce the problematic ammonia volatilization during storage, due to the fact that a lower pH value shifts the ammonia/ammonium equilibrium towards a concentration of ammonium. Another significant effect acidification has on nutrients is the increase of dissolved
phosphates, due to the high solubility of phosphates in low pH (Gerardo, et al., 2013). A pH decrease from 7 to 3 of untreated slurry resulted in an almost 3-fold increase of phosphates (PO$_4^{3-}$P) in the liquid fraction (see Figure 15 below). Although the study was conducted on pig slurry, it is reasonable to assume a similar phosphate increase for cattle slurry.

Thus, a slurry acidification could be beneficial if the purpose is to concentrate the amount of nutrients dissolved in the liquid, while alkaline slurry is perhaps better suited if the purpose is to precipitate P.

Figure 15: The concentrations of N and P for different pH values of pig slurry. Reproduced from (Gerardo, et al., 2013).

Coagulation-flocculation as pre-treatment

The pre-treatment coagulation-flocculation process is common practice in traditional waste water treatment plants, and its main purpose is to enhance the separation of solids and P (Hjorth, et al., 2010). Coagulants remove negatively charged particles dissolved in the slurry (e.g. phosphates), while flocculants act as a bridging agent, adsorbing particles such as particulate P and organic N (as well as agglomerates from coagulation) to the tail of the flocculant. Thereby, the process has little impact on nutrients dissolved in the liquid with positive charge (i.e. ammonium and K) (Sjögren, 2014) (Hjorth, et al., 2010).

Average separation efficiencies (solids relative to untreated slurry) of solid-liquid separation after the slurry has gone through coagulation-flocculation is reported by Hjorth et al (2010) to be; 70% DM, 43% TN, 20% TAN and 79% TP. Results obtained from Martinez-Almela & Barrera (2005) on pre-separation flocculation indicate that this type of treatment is not only highly efficient in the separation of total suspended solids (84-95%), but also requires a very low chemical dosage.

Typical coagulants and flocculants are polyelectrolyte polymers, aluminium and iron chlorides, aluminium and iron sulphates as well as calcium and magnesium oxides (Schoumans, et al., 2010). However, if the recovered fractions are to be used in agriculture, coagulants or flocculants containing iron or aluminium must be avoided. The most commonly used flocculants within the waste water industry are polyelectrolyte polymers (Tengliden, 2014). These additives are unfortunately somewhat controversial, since their derivatives could potentially affect humans and the environment (Tonderski, 2014). Most sewage sludge in conventional waste water treatment plants is flocculated with polymers, but the use of polymers is currently not allowed for the production of bio-fertilizers in Sweden.
according to the SPCR 120 certification body (Avfall Sverige Utveckling, 2011). For further discussion on this matter, see 9.3.2.

Coagulation-flocculation processes are commonly used before solid-liquid separation, but can also be employed after separation (Riaño & García-González, 2014). The methods are similar, but while the primary objective of pre-treatment flocculation is to enhance separation efficiency, the primary objective of post-separation flocculation is purification of the liquid fraction to facilitate further processing of the liquid. The main difference from pre-treatment coagulation-flocculation is that the input fraction at this stage is already separated, thus containing far less DM. The output is a flocculated liquid that requires further processing (e.g. filtering or a secondary solid-liquid separation) to obtain a solid and a liquid fraction. Many solid-liquid separation methods, such as decanter centrifuges and lamella separators, use flocculants to increase performance.

Coagulation-flocculation is suitable if the purpose of processing slurry is to concentrate mainly P and DM to the solid fraction, while the liquid fraction holds relatively high levels of N. Thus, it represents an interesting option for the case farm.

### 2.4.2 Solid-liquid separation methods

The overall purpose of solid-liquid separation is to divide the untreated slurry into a solid fraction rich in DM, and a liquid fraction low in DM. The way by which the manure is dewatered will affect the possibilities for nutrient recovery, since different methods affect the ratios of nutrients in the liquid and in the solids (Hjorth, et al., 2010; Møller, et al., 2002). The many different methods for solid-liquid separation that have been developed and that are currently used on farms have been reviewed and summarized by Hjorth et al, (2013), see Table 6 below.

<table>
<thead>
<tr>
<th>Separation mechanism</th>
<th>Description</th>
<th>Typical products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural settling</td>
<td>Slurry solids settle at the bottom of the tank, from where they can be removed</td>
<td>Sedimentation tanks, Lamella separator</td>
</tr>
<tr>
<td>Forced settling</td>
<td>A centrifugal force is added to reduce settling time</td>
<td>Decanter centrifuge, vertical or horizontal</td>
</tr>
<tr>
<td>Gravitational filtration</td>
<td>The slurry liquid is drained from solids by a filter</td>
<td>Filter bed separators, drum filters</td>
</tr>
<tr>
<td>Pressurized filtration</td>
<td>The slurry is transported into a cylindrical membrane with a screw, allowing the liquid to pass through while the solids are contained and collected</td>
<td>Screw press separator</td>
</tr>
</tbody>
</table>

Table 6: Summary of solid-liquid separation methods (Hjorth, et al., 2010).

In general, centrifugation is the most efficient method for separating DM and P from the slurry to the solid fraction, while screw pressing seemingly generates a liquid fraction with higher levels of both N and P, and a solid fraction with relatively high DM content (Hjorth, et al., 2010). Ultimately, the choice of separation method depends on the objective of the separation. A screw press seems to be a good choice if the objective is to produce a solid with high DM content suitable for incineration. As the nutrient concentrations in the liquid fraction tend to be higher with screw-pressing, it also suits better for recovering nutrients.

Figure 16 below demonstrates the screw-press separator installed on the case farm, where the solid fraction can be seen exiting the screw-press and accumulated beneath the equipment, while the liquid fraction is led to a liquid fertilizer storage.
Figure 16: The screw-press separator installed on the case farm, where slurry is pumped from the slurry storage and separated. The solid fraction falls underneath the screw-press, while the liquid fraction is gathered in a storage outside the frame of the right image. (Celander, 2014).

2.4.3 Treatments

Filtration

Filtration methods remove solids from the liquid, and can do so very effectively (some studies have shown a 100% DM removal) (Hjorth, et al., 2010). These methods can be very effective at P removal since most P is bound to the solids, but are not as effective at N or K removal since these nutrients are mostly dissolved in the liquid. Traditionally, filtration methods are used to treat industrial waste waters (Faaij-Hultgren, 2014). The liquid is pressed through a porous membrane to create a permeate, while solids are retained as a retentate (Hjorth, et al., 2010). The retentate concentration will depend on the level of water needed to wash the filters clean, and can be used directly on the field or sold commercially. Most of these filtration methods will use a cross-flow filtration system, where part of the liquid is re-circulated and flows tangentially over the filter, to continually wash it and prevent fouling. Even so, most filtration methods will encounter sludge build-up on filter surface and in filter pores. This fouling will be more severe for liquids containing a large amount of small particles, why fine filtration methods should be coupled with a previous course filtration step (Faaij-Hultgren, 2014).

The filtration methods can be broadly categorized based on operating pressures and retentate particle sizes (Hjorth, et al., 2010), see Table 7.

<table>
<thead>
<tr>
<th>Category</th>
<th>Operating pressures</th>
<th>Pore size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microfiltration (MF)</td>
<td>100-180 kPa</td>
<td>0.1-10 µm</td>
</tr>
<tr>
<td>Ultrafiltration (UF)</td>
<td>200-800 kPa</td>
<td>5-200 nm</td>
</tr>
<tr>
<td>Nanofiltration (NF)</td>
<td>350-3000 kPa</td>
<td>200-400 Da*</td>
</tr>
</tbody>
</table>

Table 7: Fine filtration categorization.

*Dalton, atomic mass unit

Reverse osmosis

Osmosis is a process where water moves from its original solution through a semi-permeable membrane into a solution of higher solute concentration to equalize the two solutions (Merriam-Webster Dictionary, 2014). This physical process can be utilized to purify separated manure liquids, and the process can be performed in two directions. Reverse osmosis (RO) is driven by a high
operating pressure and reverses the osmotic effect imposed on two membrane-separated liquids. The liquid on the high-pressure side is pushed through the membrane to the low-pressure side, leaving behind particles and ions. RO processes are highly susceptible to membrane fouling, and cannot be operated on a slurry liquid unless it has first been put through a filtration step down to the ultrafiltration level (Hjorth, et al., 2010). In some cases, the permeate concentrations of nutrients can be reduced by 94-98% (Thörneby, et al., 1999).

The retentate is a concentrated nutrient solution, and although its composition will depend on the input liquid it is generally highly suitable as a fertilizer.

**Struvite precipitation**

Struvite is a mineral \((\text{NH}_4\text{MgPO}_4)\) commonly precipitated from waste water treatment plants in crystalline structures (Miles & Ellis, 2001; Sindhøj & Rodhe, 2013). This precipitate is also found in such places as canned seafood and heat exchangers, and is the leading cause of kidney stone formation. Before, struvite was considered mostly as a nuisance in waste water treatment, since the precipitation happened spontaneously and could cause disturbances in the process (Kelly & He, 2014). Now, however, it is considered as a possible source of fertilization (de-Bashan & Bashan, 2004).

The precipitation process can be performed in many ways and sizes, some more simple than others. The pre-filtrated liquid commonly has its pH raised above 7.5, by addition of e.g. NaOH, then magnesium is added if proportion balancing is required (Sindhøj & Rodhe, 2013; Song, et al., 2011). After agitation, the struvite crystals start to precipitate. The fertilizer produced has an N:P:K ratio of 6:29:0, and the permeate can be further treated to increase usability and value (Etter, et al., 2011).

The precipitation efficiency of struvite is highly dependent on the element ratio \((\text{Mg}:\text{N}:\text{P})\) as well as the operational pH (Song, et al., 2011), and studies show that phosphates in the wastewater stream may be reduced by 80-85% (Kelly & He, 2014). However, removal of phosphorus occurs in a balanced reaction, and any one of the three elements \((\text{P}, \text{N} \text{ or Mg})\) may function as a limiting agent. Therefore, struvite precipitation potential will be governed by the availability of the least abundant element in the liquid (de-Bashan & Bashan, 2004). Since dairy manure has a significantly lower amount of P than N, the amount of recovered struvite will depend on P and Mg availability. The performance of the process is also dependent on process design characteristics such as agitation, liquid sedimentation properties and process temperature (AgroTechnologyATLAS, 2014). The quality of the produced precipitation will also decrease with higher presence of organic matter, Ca and other competitive cat-ions, which will form impure precipitates.

Figure 17 below shows a view from the inside of a functional struvite precipitation plant. As is evident, the equipment size is rather compact and is suitable for farm-scale processing.
Struvite precipitation could be suitable as a treatment for the case farm, and the produced precipitates used on-farm or sold to an external partner.

**Ion exchange**

Ion exchange processes are used in industrial applications where low-concentration flows need to be effectively purified. Part of the P and N in wastewaters are dissolved in the liquid as ions, making them available for recovery via an ion exchange process (Johir, et al., 2011). An ion exchange process works by passing the nutrient-rich liquid over an ion exchange resin (Rohm and Haas, 2008). The resin, commonly thousands of small polymeric water-filled beads, has an ionic charge, which swaps the nutrient ions for hydrogen ions (H+) and hydroxide ions (OH-). The nutrients remain trapped in the resin, and the hydrogen and hydroxide form water. When fully charged with nutrients, the resin can be washed in a salt solution and recovered as a liquid concentrate. The resin can then be reused in the exchange process. The liquid needs to be free from large suspended solids, and the process works best after previous filtration.

When using ion exchange processes, it is important to use resins specifically designed for the task at hand. There are anion-exchange resins suitable for phosphorus and N extraction, and studies have shown that under the right conditions, exchange processes such as these can achieve 85-90% removal efficiency, for both N and P (Johir, et al., 2011). A NaCl solution can then recover up to 98% of the nutrients from the resin in the subsequent washing step as a concentrated salt solution.

Ion exchange processes require the nutrients to be dissolved in the liquid as ions ($\text{NO}_3^-$, $\text{PO}_4^{3-}$) and only a small fraction of manure nutrients are in this chemical form. Meanwhile, the investment costs for ion exchange processes are relatively high (Backman, 2014). Thus, it seems difficult to install a process including an ion exchange step on the case farm.
3 Method
This chapter holds a description of how the thesis results were obtained. Also included are the reflections of data quality, references and choice of method.

3.1 General method description
As noted in 1.1.1, the overall thesis method was to base the results on the premises of a specific case farm. The different alternatives for utilizing the slurry on the case farm were then represented by different scenarios. Two hypothetic scenarios, Energy recovery and Energy & nutrient recovery, were given by the assignment framework and thesis objective. Another two scenarios, Default and Solid-liquid separation, were included as references since they represent the conventional manure handling and the current farm situation respectively. The modelling of the scenarios was achieved by a compilation of different methods that are further described below, including interviews, data modelling and a literature study. Before any quantification of scenarios could take place, the farm substrates had to be characterized, which is why a case farm substrate characterization precedes the thesis results. The characterization method was primarily laboratory based, and is included in the description of the modelling method below.

The thesis results were then presented in three separate chapters, in accordance with the research questions. First, the case farm substrates are characterized. Second, the techno-economic assessment of nutrient recovery methods reveals which methods that were realistic to install on the case farm. Third, the quantified scenarios are presented, each with a visualization of the scenario-specific mass flows, nutrient utilization and economic performance. To enable an overview of all scenarios, the results were also compiled and analyzed. Before any conclusions were drawn, certain parameters were adjusted to investigate the robustness of the results. The reason for performing this sensitivity analysis was to identify what parameters are central and thus sensitive to future development.

The alternative to a case-based method would have been to maintain a general approach throughout the thesis. However, many parameters in agriculture are site-specific, such as soil type, local plant nutrient availability and manure supply. In addition, many economic parameters, such as investment and operational costs, are only representative when put in a context. To be able to draw conclusions anchored in reality, the case-based approach seemed like the most suitable method. Of course this also means that the conclusions in this thesis are site-specific and not necessarily translatable to general conclusions.
3.2 Modelling method
The method of building scenarios was a combination of a literature study, interviews, on-farm sampling and data modelling, all of which are further described below.

3.2.1 Literature study
A literature study was conducted to gain knowledge necessary for the theoretical background as well as for the interviews. It was also necessary to be able to compare case farm approximations with similar data from other sources. The method for searching for relevant literature was snowball sampling (or chain-letter sampling), where a first article is used to identify others, which in turn generate further article suggestions (Sage Research Methods, 2006). The generation of new articles could also be suggestions from interviewees. Articles were mainly from the scientific database ScienceDirect, although public articles from official actors, such as the Swedish Board of Agriculture, were also a common source. A total of 98 relevant articles were identified, which resulted in a thorough reading of 22 articles.

Alternatively, the literature study could have had a more systematic approach, with a mapping of key search words and iterative article identification for instance. Since the main purpose was to gain theoretic background knowledge though, it was presumed that the snow-ball method would suffice.

3.2.2 Interviews
The main source of data for modelling the scenarios was material gained from interviews. Similar to the literature study, the method of identifying relevant interviewees was snowball sampling. The interview method depended on the interviewee and alternated between two approaches. For the three first scenarios (Default, Separation and Energy recovery), the scenario specific components were already set and interviews with involved actors (the case farm manager, ReTreck AB and Againity AB respectively) had a pragmatic approach. The interviews did not follow any protocol and the questionnaire depended on the occasion.

For the Energy & nutrient recovery scenario, the specific component (i.e. nutrient recovery) was not set. Thus, a broad range of actors within the industry were interviewed. These interviews were vital to gain an understanding of which slurry processing methods are relevant for the case, and to collect specific data on performance and costs that would not be included in articles from the literature study. All interviews with potential suppliers followed the same method, which is presented in Figure 18 below.

![Figure 18](image-url)
Relevant suppliers were identified partly through snowball sampling and partly by searching a web register of Swedish cleantech companies. A national search by the categories ‘Waste & Recycling (Avfallshantering & Återvinning)’ and ‘Water- & waste water treatment (Vatten- & avloppsvattenrening)’ resulted in a total of 275 companies. An initial relevance filtering based on the on-line company description decreased the number of potential suppliers to 27, which were contacted primarily by phone and secondarily by e-mail. After presentations of the case, companies were sorted as either relevant or not relevant (see Figure 18). The companies that were not considered relevant often had advice on other, more relevant companies and thus generated new potential suppliers. The relevant companies were sent a process specification, and thereby a dialogue was initiated. An offer was given by four companies, out of which two were included in the thesis (see 3.3.4 below).

3.2.3 Sampling & laboratory analysis

To be able to map the performance of the separator and the physical flows of nutrients within the scenarios, a sample of the case farm substrates was analyzed. Untreated slurry, solid fraction and liquid fraction were sampled 2014-03-11. The laboratory analysis was partly made by the authors of this thesis, and partly by ALcontrol Laboratories. ALcontrol’s methods are not public, thus they cannot be accounted for here. The reason for outsourcing some of the laboratory analysis was two-fold; the authors of this thesis possessed neither the competence nor the process equipment necessary for analyzing certain parameters (e.g. nutrient concentrations). Meanwhile, parameters that allowed uncomplicated laboratory methods, such as dry matter weight and particle size distribution, were measured by the authors and are further described below.

Sampling

The manure from the case farm was analysed in a laboratory setting to discern certain characteristics relevant to the design of the Energy & nutrient recovery system. Three samples were taken from the case farm in 2014-03-11, on which the test series were performed.

A sample of the untreated raw manure was taken from the case farm slurry storage by immersing a 10 litre plastic bucket in the manure, filling it half-way up at two points. The two sample locations were diametrically opposite each other in the slurry storage basin. The same procedure was repeated in the liquid reservoir, for a sample of the separated manure liquid. A sample was also taken from the stack of the separated solid fraction, by filling the 10 litre bucket up with bedding material from two separate locations in the stack. Before filling, the bedding material was mixed around, so that a more homogenous sample could be taken.

Figure 19: A picture taken during sampling.

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3 http://www.swedishcleantech.se/sv/hitta_miljoteknik/ [2014-03-14]
4 http://se.alcontrol.com/ [2014-03-12]
DM-content
The dry weight of the various manure fractions were measured, by drying samples of the fractions in aluminium containers in an oven until completely dry. The samples were weighed before and after, as well as the empty boxes, to establish a reference.

The samples tested were:

- Unfiltered slurry
- Solid separated fraction
- Liquid separated fraction
- Filtrate sample (the permeate from the particle size distribution test)

Particle size distribution
The liquid fraction contains a large amount of dry matter, and the size of these particles is of interest for potential filtration steps in scenario D – Energy and nutrient recovery. Testing of the particle size distribution was performed, by sieving 2 litres of the liquid fraction through meshes of decreasing size (2mm, 600µm, 425µm, 180µm & 90µm). The retentate of each mesh size was transferred to aluminium containers before being dried until completely dewatered, and the remaining solids were weighed to determine dry matter weight.

Physical parameters
The density of the permeate from the particle size test was calculated. 200 ml of permeate liquid was carefully measured and then weighed, and a liquid density was extrapolated from this.

pH & buffering capacity
The buffering capacity tests were performed on 500ml untreated manure that was filtered through two mesh screen sizes (2mm and 600µm). The slurry was helped through the mesh by rubbing with a metal spoon. The separation was necessary, since the pH meter needed a less viscous liquid to take accurate readings. After the rough separation, 165 ml liquid remained. From this volume, a 100 ml sample was taken and mixed with 100 ml of de-ionized water to further reduce the viscosity.

HCl (1M & 0.1M) were added to the manure, depending on how much effect the last acid addition had on the liquid. After each addition, the acid was allowed to react for a minute whilst being agitated with a magnetic stirrer. After each addition, the differences in pH were logged. Measurements were performed with a digital electrode pH meter.

Figure 20: Image of the particle size distribution test (left) (Haglund, 2014), and image of the buffering capacity test of the liquid fraction (right) (Celander, 2014).
3.2.4 Data modelling & calculations
The main modelling and calculating software was Microsoft Excel. Each scenario was modelled and calculated separately, except for data common for all scenarios (such as the calculation of annual slurry input and total on-farm fertilizer need) which shared an initial platform.

Since the annual slurry input is a parameter that affects the whole system and all scenarios, it is a central parameter. Thus, the approximated figure used in the thesis was based on case data and validated with STANKinMIND, which is a data model distributed by the Swedish Board of Agriculture. Case farm approximations were then used for comparison (see Appendix II – Scenario platform calculations for more details).
3.3 Scenario models

The definition of scenarios started with the first and simplest scenario, which was the common practice handling of manure on a modern, conventional dairy farm. This default model was then a baseline for adding scenario components (e.g. solid-liquid separation) that gradually increased the scenario complexity (see Figure 21). In other words, the only difference between the scenarios is their specific components. Consequently, flows that are shared by all scenarios are excluded, since these do not change the comparative result.

Figure 21: A visualization of how the latter scenario is a baseline for the next one, and thereby increases complexity with scenario letter.

The scenario approach, where different farm strategies are modelled as separate scenarios, was used to facilitate the comparison of different farm strategies and investments. An alternate option could be to view each component in the scenarios separately, and compare their performance based on e.g. investment costs and other parameters. However, by putting all components that belong to a specific scenario into a model, the scenario approach offers a holistic system perspective. Stand-alone parameters, such as investment costs, are put into a context and thus the thesis conclusions are validated to a higher grade.

Each scenario is further described below, so as to facilitate the understanding of the quantification in the thesis results.
3.3.1 Scenario A - Default

The first scenario is a baseline, representing the conventional manure management practices for modern dairy farms. As can be noted in Figure 22 above, the conventional procedure is relatively simple. Feed, water and bedding material are the system inputs, necessary for the production of milk. The feed and water inputs are identical in all scenarios, and their mass contributions are included in the slurry and deep litter flows. The bedding material used in the cubicles is fine wood shavings, while the deep-litter beds are provided with straw (where only the straw fraction that will later be replaced with Green bedding is included in Figure 22). The slurry is used as a liquid fertilizer, distributed on farm fields once per year.

3.3.2 Scenario B - Solid-liquid separation

As illustrated in Figure 23 above, the second scenario is a model of the current situation on the case farm, where a screw-press separator from ReTreck AB has been installed. The screw-press dewateres the slurry into a liquid fraction and a solid fraction. The solid fraction can be used as bedding material in both cubicles and deep-litter beds, replacing the wood-shavings and straw in the previous scenario.
The excess solid fraction is sold as a solid fertilizer, as is the solid fraction leaving the deep-litter stables, while the bedding material in the cubicles is recirculated as part of the slurry. As much of the liquid fraction as allowed by the P restriction is distributed on the fields, and the remainder is sold to an external partner.

### 3.3.3 Scenario C – Energy recovery

![Process flow chart for scenario C](image)

As presented in Figure 24 above, the third scenario has an expanded system with the addition of an Organic Rankine cycle (ORC), provided by Againty AB. An ORC is a small-scale power plant for production of electricity and heat, equipped with a burner, a turbine cycle and a condenser just like a conventional power plant (Quoilin, 2011). However, an ORC contains an organic liquid as expansion medium instead of water, enabling it to function at lower temperatures.

The excess solid fraction that was sold to an external partner in scenario B, is now a raw material for the production of heat and electricity instead. Before this fraction can be utilized as fuel, it has to improve certain quality aspects. The first step of processing the solid fraction into a fuel is to dewater the material in a dryer, and the dried material is then pelletized for easier handling in the burner. The heat energy required for drying is supplied by the off-heat flow from the ORC unit. After drying and pelletizing, the pellets are incinerated in a solid fuel burner, and the resulting heat is utilized in the ORC unit to produce electricity. The incineration also generates ashes (fly and bottom) and flue gases that leave the system either as waste streams or sales.
3.3.4 Scenario D – Energy and nutrient recovery

Figure 25: Process flow chart platform for scenario D. In this scenario, the nutrients are recovered alongside the energy. The nutrient recovery step is divided into four separate alternatives described below.

The fourth and last scenario is an extension of scenario C, where the liquid fraction undergoes further treatment with the purpose of making more of the on-farm nutrients available for field application. As can be noted in Figure 25 above, the nutrient recovery step is not defined. The reason for this is that part of the thesis assignment was to investigate how the on-farm nutrients could be recovered. Instead, the process flow charts for different versions of scenario D are presented as a thesis result, see chapter 5 below.
3.4 Result presentation

In accordance with the research questions, the thesis results were presented as a case farm substrate characterization, a description over nutrient recovery methods that are realistic on farm-scale, and a compilation of quantified scenarios.

3.4.1 Case farm substrate characterization

The substrates on the case farm were characterized in a manner similar to the general slurry characterization in the theoretical background (chapter 0). For a more detailed method description, see 3.2.3 above.

3.4.2 Farm-scale nutrient recovery methods

The methods that were included in the scenarios are described in this chapter, while the quantification of these are displayed in chapter 6 together with the other scenarios.

3.4.3 Scenarios

Each of the scenarios is unique in some way. A method for comparing them was used, where their performance regarding mass flows, nutrient utilization and economy is visualised in a comparative manner.

Mass flows & nutrient utilization

A mass flow chart is used to visualize the flow of slurry mass and nutrients within each scenario. They are displayed in percent of total slurry availability, and as such are easily comparable across scenarios. The figure arrows indicate the flow volume, where a greater width means a larger flow.

To indicate on how well each scenario performs in terms of nutrient utilization, a pie chart has been constructed for each of them. It is displayed as a percentage of total crop needs, and as such indicates on how much of the crop need is sourced from the farm manure itself. The size of the pie charts indicate on the amount needed of each nutrient, where N is required in greater quantities than P. Remaining fertilizer needs are met by purchasing of mineral fertilizers.

Economic performance

The economic performances of the different scenarios were evaluated as the sum of the costs and revenues allocated to each scenario per year. These figures represent an incomplete picture of overall farm practices, excluding many important factors such as animal feed and crop sales. However, it is a suitable method for comparing the scenarios. All parameters that are identical in all scenarios have been excluded, since they do not indicate on the performance of any one scenario. Investment costs are included in the scenarios as a 3,6% interest rate (Olai, 2014). The life-expectancy of each investment was not taken into consideration.

The annual economic performances were then indexed against the economic performance of the baseline scenario B. Considering that B represents the current situation on the case farm, it was natural to use it as index. Furthermore, the economic differences of recovering nutrients with different processes were visualized more clearly with B as index. If A would have been the indexing scenario, the economic performance of the other scenarios would have been dominated by the result of changing the bedding materials as a consequence of screw-press installation.

The performance of each scenario is only viewed from case-farm perspective. Thus, factors such as nutrient losses in incineration or off-site manure utilization are not considered. The system is thereby not evaluated on a larger scale, socio-economic or other.
**Pay-off time**

To indicate on the economic performance in relation to its investment size, a pay-off time was calculated for each scenario, by dividing the investment with the annual economic performance. The method is commonly used in economic calculations since it gives an easy-to-understand, albeit simplistic, indication of the performance of an investment alternative. The pay-off time in pairing with the economic performance is the preferred method of economic evaluation, in accordance with the assignment framework.

The pay-off times are displayed in two ways. The first using only the investment costs to move from scenario B to whichever scenario is calculated, and the economic performance indexed against scenario B. The second uses the total investment size (that is, the cost to move from scenario A to whichever scenario is calculated) and the economic performance indexed against scenario A. By doing this, the system can be visualised as a whole (indexed and calculated against scenario A), and as an isolated component (indexed and calculated against scenario B).
3.5 Data quality
As with all studies based on quantification, the validity of the thesis conclusions is only as good as the input data quality and the model assumptions. The authors of the thesis are to be held responsible for the model assumptions, whilst the input data is external. To ensure valid results, input data and the generated results have been validated in several ways, presented here.

3.5.1 Theory verification
Parts of the theoretical background, dominated by theory from a specific source, were if possible proof-read by the same source. The contents of 2.1, as well as 4.1, were validated by Peter Borring (chairman of LRF Östergötland), and Helene Oscarsson (agronomist and coordinator of Vreta Kluster).

3.5.2 Data validation
While most data in the thesis originates from measurements or suppliers and thus is to be considered valid, there has been a continuous strategy to validate the input data when sourcing from other external references. This validation strategy had four steps (see Figure 26), where the first step was to search for the same data from several different sources. The second step was to choose which data is most valid, which was based on these validation factors:

- Relevance – how similar is the available data, in regard to method, equipment etc, compared to what is sought? The more similarities, the higher the relevance.
- Accuracy – is the data measured or estimated by the source? Measured data was prioritized over estimated data.
- Geography – from where is the data? Data from the case farm or Sweden was prioritized over data from other locations or countries.
- Time – how old is the data? Data from recent years were prioritized over older data.

The third step was two-folded: the most valid data was used in the calculations and generated an intermittent result, while the less valid data was used to generate comparable intermittent results. Fourth, and last, these intermittent results were compared. If all sources showed similar results, the valid source was used in the following calculations. If there was a significant difference, the strategy iterated back to new research, in order to investigate why there was a difference and to find new input data.

Figure 26: The data validation strategy applied in the thesis.

To exemplify the strategy, this is how data verification worked for bedding material costs:

1. Data on bedding costs were collected from various sources; the case farm manager and bedding material suppliers.
2. The case farm data was chosen as the most valid source, as it was chronologically identical to supplier data, but more valid based on geographical proximity, relevance and measurability.
3. The annual case farm bedding material cost was then calculated and compared to the results if supplier data were used instead.

4. As the results were very similar, the result from the case farm could be used in the thesis.

An alternative strategy for validating data could be to apply a pedigree data quality system, where each data is given a value that reflects its quality. The value is based on several aspects, such as relevance, proximity in time and geography etc. Quality aspects are similar to the aspects in the second step of the data quality validation method above, with the difference that the pedigree system generates a quantified quality value while the method applied in the thesis is only utilizing the aspects qualitatively when selecting which data to use. The authors of this thesis considered such a qualitative approach to be sufficient, particularly when compared to the time necessary for giving all thesis data separate quality values.

### 3.5.3 Sensitivity analysis

After presenting the thesis results, there is an analytical chapter dedicated to examining the sensitivity of the results. By modifying central parameters, such as electricity prices or substrate composition, the results changed. Thereby it was clear which parameters had a large impact, and how these affected the results and subsequent conclusions.

The sensitivity analysis only shows the changes in annual economic performance, and not how that performance affects the pay-off times. This since the pay-off times are directly related to the economic performance, and can be easily calculated using the alternative performance and the investment costs (which can be seen in Appendix IV - Economic performance figures and 0).

It is not absolutely vital to produce a sensitivity analysis, and the alternative option would be to simply accept the thesis results and proceed to draw conclusions. However, with the volatile nature of some central parameters in the models (e.g. the spot price of electricity), it was considered necessary to analyse the robustness of the results before drawing any conclusions.
3.6 Method reflections
In general, the thesis method had a pragmatic and flexible approach. Rather than setting a methodological framework as a platform, the method described above was developed parallel to the progress of the thesis. Although this approach allowed for concurrent modifications and less rigidity, it also offered less structure and planning ability. When considering the objectives however, it seems like this organic methodology suited the thesis better than an approach with a pre-defined structure. The interviews, for instance, could possibly have been better planned and structured, in order to be more time-efficient. But the diversity of companies that were contacted made a general enquiry very difficult to formulate. Given that the objective of the interviews was to identify potential suppliers, it seemed more time-efficient to initiate contact without any generally prepared material.

Regarding the laboratory part, there were some method aspects that may have had a negative impact on the accuracy of the conclusions. Primarily, there was only one sampling occasion and thereby no replicate to validate the substrate characterization. Secondarily, the laboratory methods themselves had some problematic aspects worth mentioning. The sampling method was very simple (two diagonal sampling spots for each sample), which may have affected the quality and accuracy of the samples. Furthermore, ALcontrol Laboratories could not analyze the amount of dissolved P in the samples, only total P. This fact complicated the dialogue with suppliers, since it is necessary to know the amount of available P no matter which process technology that is addressed. Instead, the suppliers had to assume a ratio, which may have affected the results. However, the characterization parameters as well as the amount of available P are both included in the sensitivity analysis.
4 Case farm substrate characterization

This chapter holds a characterization of the on-farm substrates, which represent the basis of the scenario models.

4.1 Substrates

The case farm currently handles three manure fractions from the stables: untreated slurry and a solid and a liquid fraction from the screw press separator. These three are named primary substrates and are characterized by the same parameters as was slurry above (see 2.3). If the solid fraction is partially incinerated (i.e. energy recovery), there will be three additional substrates to handle on-site: ashes, drying gases and flue gases. These are categorized as secondary substrates and are only briefly characterized, since the substrates do not exist yet. In total six substrates are included in the thesis, and their relation can be seen in Figure 27 below.

![Figure 27. Chart over on-farm substrates and their relations.](image)

4.1.1 Primary substrates: slurry and separation derivatives

The primary substrates are characterized by their dry matter content and particle size distribution, nutrient concentration, pH and buffering capacity and physical properties, as suggested by (Hjorth, et al., 2010). Note that Table 8, Table 9 and Table 10 are extended with additional data from two references, so as to put the case farm data into a context. As mentioned in 3.2.3, the case farm data is from sampling 2014-03-11, while the first reference refers to an older case farm sampling (2012) and the second reference to data given by (Møller, et al., 2002).

Dry matter content and particle size distribution

The DM content of the primary substrates is presented in Table 8 below, while the particle size distribution is presented in Figure 28.
Seemingly, the untreated slurry has a relatively high content of DM, while the corresponding number in the liquid fraction lies between the two reference numbers. This indicates a high separation efficiency on the case farm screw press, which is confirmed by the relatively high DM content of the solid fraction.

![Pie chart showing particle size distribution of slurry](image.png)

**Figure 28:** Particle size distribution of the slurry, from sampling 2014-03-11.

As can be noted in the pie chart above, a little more than half of the total DM is separated by the screw press (54%). The other half is contained in the remaining liquid, which in this case is the liquid fraction. In this fraction, the majority of the DM is particles <90 µm (35% if compared to the total DM), which is in line with the fact that around half of the DM in slurry is particles <0,125 mm (see 2.3).

**Concentration of nutrients**

The concentration of key nutrients in the farm substrates are displayed Table 9, and the nutrient distribution between substrates in Figure 29 below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Slurry</th>
<th>Liquid fraction</th>
<th>Solid fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case</td>
<td>Ref. 1</td>
<td>Ref. 2</td>
</tr>
<tr>
<td>DM [%]</td>
<td>9.28</td>
<td>5.9</td>
<td>6.4</td>
</tr>
<tr>
<td>TN [kg/ton]</td>
<td>4.27</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>TAN [kg/ton]</td>
<td>2.13</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>TP [kg/ton]</td>
<td>0.69</td>
<td>0.6</td>
<td>0.69</td>
</tr>
<tr>
<td>TK [kg/ton]</td>
<td>3.06</td>
<td>2.4</td>
<td>3.54</td>
</tr>
<tr>
<td>N:P-ratio</td>
<td>6.2</td>
<td>5.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 9: Nutrient concentrations of primary substrates. Case data is from sampling on-site 2014-03-11 (see Appendix I – Substrate characterization) and is the data used in the thesis. Reference 1 originates from an older sampling (2012) on the same farm, and reference 2 is data from (Møller, et al., 2002).
According to Table 9 above, the total N concentration in all substrates is relatively high in the case data, while the ammonium concentration is more in level with the references. This suggests a relatively high amount of organic N in the case samples, which could be explained by the relatively high DM content (see Table 8 above). Total P concentrations are almost identical for case and both references, except in the solid fraction where reference 2 is double concentration. As for total K, all case data is either within the reference interval or very similar to the first reference.

Regarding the N:P-ratio however, there is a discrepancy. While the general trend, and also part of the overall purpose of manure processing, is that manure separation generates a liquid and a solid fraction with higher respectively lower N:P-ratio than the untreated slurry, the case farm data shows the opposite. On the other hand, both references show results in accordance with the general trend, which is why the misleading N:P-ratio of the case farm is probably due to uncertainties in the laboratory analysis and the absence of replicates (see 3.6 for further discussion on this matter).

In general the case data and Ref. 1 data are very similar for the liquid and solid fraction, while the differences are somewhat larger for the slurry. This is probably because the post-separation substrates are more homogenous than the slurry, and thus the sampling method has less impact.

Figure 29: The nutrient distribution between case farm substrates, based on mass allocation. For calculations, see Appendix III – Scenario specific calculations

When distributing the nutrients based on their concentrations in the substrates and allocated by DM, it can be concluded that most of the nutrients follow the liquid through the separation and end up in the liquid fraction. P acts a little different and tends to remain in the solid fraction to a higher grade than the other nutrients, which is expected since most P is contained in or adsorbed to particles (see 2.3). Also, the amount of N in the solid fraction is about one fourth of the total N in the slurry, which is according to the fact that about one third of total N is organically bound thus contained in the particles.

Note that the concentrations of nutrients in each fraction have been measured, while the absolute masses of nutrients in the same fractions were calculated by allocation based on the DM content. The result is a discrepancy in nutrient mass balances, where for instance the staples of TN in solid and liquid fractions do not add up to the TN staple in slurry. For further discussion on this subject, see 8.4.
pH and buffering capacity

The pH values of the case farm substrates are displayed in Table 10, and the buffering capacities in Figure 30 below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Slurry</th>
<th>Liquid fraction</th>
<th>Solid fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Case</td>
<td>Ref.</td>
<td>Case</td>
</tr>
<tr>
<td></td>
<td>7.2 (±0.2)</td>
<td>6.8-8.3</td>
<td>7.0 (±0.2)</td>
</tr>
</tbody>
</table>

Table 10: The pH values of primary substrates. Case data is from sampling on-site 2014-03-11 (see Appendix I – Substrate characterization) and is the data used in the thesis. The reference is (Pagliari & Laboski, 2013) and is included to validate the sampling results, although data for liquid and solid fractions were not found.

The untreated slurry and the liquid fraction share the same pH (within the measurement uncertainty) and have a normal value according to the reference interval of untreated slurry. The solid fraction has a somewhat higher pH but is still within the slurry reference interval.

![Figure 30: The buffering capacities of untreated slurry and filtered slurry (which is approximated as the liquid fraction).](image)

The buffering curves of the slurry and the liquid fraction show a similar development, just as expected. There is a strong buffering capacity, especially between pH 6.5-4.0, which is in line with the general buffering capacity for slurry between pH 7.5 and 5.5 (see 2.3.3).

Physical properties

The density correlates strongly to the DM-content, and for the case farm substrates the following densities have been calculated (see Table 11), using the equation given in 2.3.4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Slurry</th>
<th>Liquid fraction</th>
<th>Solid fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ [kg/m³]</td>
<td>1007</td>
<td>1006</td>
<td>1010</td>
</tr>
</tbody>
</table>

Table 11: Approximated densities of the case farm substrates.

As expected, the substrates have an increasing density with increasing DM content, although the trend is not very significant and both slurry and liquid fraction can be approximated as water. For scenario calculations, however, these substrate densities are approximated as 1000 kg/m³.
4.1.2 Secondary substrates: ashes & gases

The three secondary farm substrates are ashes, drying gases and flue gases, and are generated if the solid fraction is incinerated. These substrates have not been sampled on-site, and their characterization is thereby approximate and based on literature.

Incineration of manure fibers generates both fly ash and bottom ash, where the bottom ash is recoverable while the fly ash will leave the system as flue gases. The volatile nature of N makes it virtually non-existent in the ash. Thus, the N that pertains to the solid fraction is removed as drying- and flue gases and is lost as emissions. As for P, nearly 100% of the P in the solid fraction is recovered in the ashes (Thygesen & Johnsen, 2012). However, 20% of the P pertains to the fly ash, thus reducing the recoverable portion to 80%. P concentrations for ashes from cattle slurry have been reported to be approximately 4%.

The availability to plants of P in ash depends on its chemical form and on the lime content of the ash, as dissolution of P compounds is reduced at high pH (Kuligowski, et al., 2010). Raising soil pH through adding liming agents eliminates aluminum and manganese toxicity, supplies calcium, increases molybdenum availability and increases the biological activity of the soil. Untreated ash (pH 12) could be used as a combined liming agent and phosphate fertilizer on acidic soil, where soil acidity would dissolve both the lime and apatite.

On the case farm, the quantifiable characterizing parameters would thereby be the content of Table 12 below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ashes</th>
<th>Drying and flue gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0%</td>
<td>100% of TN in incineration solids (39 000 kg/year)</td>
</tr>
<tr>
<td>P</td>
<td>80% of TP in incineration solids (3 900 kg/year)</td>
<td>20% of TP in incineration solids (985 kg/year)</td>
</tr>
<tr>
<td>pH</td>
<td>12</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 12: Quantifiable parameters for characterization of on-farm secondary substrates.
5 Farm-scale nutrient recovery methods

This chapter presents which nutrient recovery methods that are realistic to install on farm-scale, and all data is based on interviews with potential suppliers.

Out of the slurry processing methods described in 2.4, only a few qualified as technologically and economically realistic to install on the case farm. Below is a list of excluded methods and a brief explanation as to why they were excluded.

Pre-treatments

- Anaerobic digestion: does not deliver a satisfactory solid fraction
- pH modification: additives too expensive

Solid-liquid separation methods

- Natural settling: requires a lot of space and/or retention time
- Gravitational filtration: requires same additives as with forced settling with less performance

Treatments

- Filtration: requires many process steps for a satisfying result, which makes the overall process too complicated and time-consuming
- Reverse osmosis: requires preceding filtration
- Ion exchange: same as above

Methods that were both commercially available and suitable for the case farm are presented in the list below, and these are further described below the list.

- Struvite precipitation
- Secondary solid-liquid separation with a decanter centrifuge, including a flocculation step
5.1 Scenario D1 – Struvite precipitation & end-product sales

A possible process for extracting P from the system could be struvite precipitation, as described in 2.4.3 above. The only Swedish company with a commercial process for precipitating struvite is Ekobalans AB\(^5\), who have a fully functional precipitation plant in Helsingborg. The proposed process for the case farm can be seen in Figure 31 above.

In the struvite precipitation step, the liquid fraction is led through precipitation tanks, where magnesium chloride (MgCl\(_2\)) is added that causes struvite to precipitate as micro crystals. The struvite micro crystals are then separated from the liquid in a hydrocyclone and a filtering bag, where the latter is also a struvite storage. In addition to MgCl\(_2\), citric acid is used as an additive for system washing. Apart from refilling the additives, initiating a weekly washing and exchanging the filtering bags, the process is completely automated. Struvite is collected as a clay-like substance, while the reject stream can be utilized as liquid fertilizer with improved N:P ratio. In this scenario, the struvite substance is classified as an organic fertilizer (as opposed to mineral) and thus cannot be utilized on the farm. Instead it is sold to an external partner, just as other excess fractions.

\(^5\) http://www.ekobalans.se/sv/
5.2 Scenario D2 – Struvite precipitation & end-product utilization

While the processing method of this scenario is identical to the scenario above, they still differ in an elemental way. The struvite rich end-product in scenario D1 is classified as an organic fertilizer, which obliges the case farm to remove the P from the case farm according to current legislation on P fertilizers. However, the precipitation method processes the fraction to the point where it resembles a mineral fertilizer more than an organic fertilizer, possibly enabling a re-classification. Such a classification would allow the case farm to close the P-deficit with on-farm struvite instead of mineral P fertilizer, which is why Figure 32 above includes a flow of struvite dedicated to field application. For further discussion on this matter, see 9.3.3.

Figure 32: Process flow chart of scenario D2 - Struvite precipitation & end-product utilization
5.3 Scenario D3 – Secondary separation with decanter centrifuge

In scenario D3, the starting point is the fact that the liquid fraction leaving the screw-press still contains a large amount of DM. Thereby, it could be beneficial to put the liquid fraction through a secondary solid-liquid separation and remove more DM and P. In wastewater treatment plants it is common to use decanter centrifuges to separate out solids, which is the approach in this scenario. The decanter centrifuge is of the model DC20EL and is provided by Noxon AB\(^6\), a well-established company specialized in separating particles from fluids. A decanter centrifuge uses rotational movements to force the process by which sedimentation occurs (see 2.4.2), resulting in two new fractions; a solid and a liquid substrate (see Figure 33 above). The liquid substrate is applied to the fields, while the solid substrate substitutes some of the solid fraction from the screw-press as fuel. To achieve a high performance the decanter uses substantial amounts of electricity and a polymer additive (PAM) as flocculent.

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\(^6\) [http://www.noxon.se/](http://www.noxon.se/)
6 Scenario quantification

This chapter holds the result of modelling scenarios A to D. Each scenario is defined from a nutrient utilization efficiency perspective as well as from an economic perspective. For calculations and assumptions, see Appendix II and Appendix III.

6.1 Scenario A – Default

The quantified model for scenario A is displayed in Figure 34 below.

According to the model, the total amount of slurry produced is about 50 times larger than the amount of bedding material put into the cubicles. The bedding need for the cubicles is based on recommendations by the Swedish board of agriculture (Jordbruksverket, 1995), but adjusted to meet common agricultural practices. Approximately half of the straw need for the deep-litter beds is provided by on-farm straw, while the remaining half is purchased (Olai, 2014). Only the purchased straw fraction is included in Figure 34 above, since the on-farm straw fraction is identical to all scenarios and thus excluded.

6.1.1 Mass flows & nutrient utilization

Almost half of the slurry from the stables is used as a liquid fertilizer, applied to the fields in the spring each year (Olai, 2014). Due to the 22 kg/ha restriction in applying P to the fields, a little more than half of the slurry can be applied to the fields, while the excess half is sold to an external partner (see Figure 35 below, where the arrow widths are visualizing the distribution of total mass within the system).
In scenario A the slurry is applied to the fields without further treatment, with the consequence that more than half the available N and P is removed from the farm system. The resulting on-farm nutrient utilization, which is the ratio between on-farm nutrients and purchased mineral fertilizer required to meet crop needs, is visualized in Figure 36 below.

![Pie chart showing N and P utilization](image)

Figure 36: The ratio between on-farm and mineral nutrient utilization for scenario A. The pie chart sizes are weighed after total quantity required to meet crop needs.

### 6.1.2 Economic performance

Costs and revenues for scenario A are presented in Figure 37 below.

![Economic performance chart](image)

Figure 37: Economic performance for scenario A.

The expenses for the baseline scenario A are mostly constituted by the purchase of bedding materials, in this case straw and wood shavings. Both materials can be purchased relatively cheaply, but with the amounts required (see Figure 34 above) it still represents a major cost.
6.2 Scenario B – Solid-liquid separation

The quantified model for scenario B is displayed in Figure 38 below.

All bedding material flows from an external supplier are now replaced with solid fraction from the screw-press. The separated slurry also generates a liquid fraction that is either applied to the fields or sold to an external partner.

6.2.1 Mass flows & nutrient utilization

The performance of the screw-press separator is illustrated in Figure 39 below. As expected, the main part of the dry-matter mass ends up in the solid fraction, while the total mass is heavily skewed in favour of the liquid fraction. Note that these screw-press performance figures are the same in the following scenarios.

In accordance with Figure 39 above, approximately half of the N and P available in the slurry is utilized on the farm (46.2% and 46.6% respectively). When compared with the total crop need, the resulting utilization of on-farm nutrients is displayed in Figure 40 below.
6.2.2 Economic performance

The economic performance of scenario B is presented in Figure 41 below.

The screw-press investment cost was 650 000 SEK, including installation. With the solid fraction recycled as green bedding, a major expense in form of bedding materials can be avoided. Thus, the largest cost is for N fertilizer, which validates the conclusion in 1.1.2, where it is stated that the most strategic approach for the case farm is to process the slurry so that more on-farm N can be utilized. Just as in scenario A, excess material is sold to an external partner. In this case however, the sale of slurry has been replaced by sales of excess solid and liquid fractions. Note that the liquid fraction fetches a price double the price of slurry, which is due to the fact that the liquid fraction is easier to handle.
6.3 Scenario C – Energy recovery

The quantified model for scenario B is displayed in Figure 42 below.

![Figure 42: Quantified process flow chart for scenario C.](image)

The addition of an ORC-cycle enables an on-farm production of heat and electricity, but also requires some process energy. While the pelleting step requires some electricity, the absolutely dominant energy requirement lies in drying the solid fraction, from a water content of 65% to approximately 15%. Out of the heat energy provided by the burner, 6% is converted into electricity, while 36% is used in the drying process and the remaining 58% is considered waste heat.
6.3.1 Mass flows & nutrient utilization

The mass flow distribution of scenario C is illustrated in Figure 43 below.

Figure 43: Mass- and nutrient flows in scenario C. Figures in percent of total component mass in manure slurry. Mass in gas fraction unquantified. Mass in ashes assumed to be the same as dry matter mass.

Regarding nutrients, the drying and incineration of the solid fraction causes all N pertaining to the solid fraction to dissipate, either as flue gases, fly ashes or via dryer evaporation (see 4.1.2). As for P, 20% of the P in solid fraction dissipates via off-gases as well, while the remaining 80% are found in the bottom ashes after incineration. The resulting on-farm nutrient utilization is displayed in Figure 44 below.

Figure 44: The ratio between on-farm nutrients and purchased mineral fertilizer in scenario C.
6.3.2 Economic performance
The economic performance of scenario C is presented in Figure 45 below.

According to Figure 45 above, scenario C has an improved economic performance compared to the indexing scenario B. The most significant feature of this scenario is the production of electricity, which generates an income that covers almost half the cost of purchasing N fertilizer. The income from selling electricity could be significantly larger if the electricity required by the process was not taken from the ORC. However, since the cost of purchasing electricity from the grid is higher than the selling price, the total cost of electricity is lower with this approach than if all process electricity was purchased.

The prices for the ORC unit and its supporting equipment was 800 000 SEK for the dryer unit, 200 000 SEK for the pelletizer, 750 000 SEK for the burner and 1 300 000 SEK for the ORC unit itself. The maintenance cost of the process equipment assisting the ORC-unit has not been quantified. It is reasonable to assume a relatively low maintenance cost however, since the dominant part of this figure for the other processes is the exchange of filters and other components, which is not necessary in the process equipment. Furthermore, the value of ashes was assumed to be zero. Although this fraction contains a relatively large amount of P, the quantification of its value depends on other aspects (e.g. the presence of heavy metals) (Nystedt, 2014) and would require further analysis. It is not uncommon that the disposal of ashes is instead a cost, and thus the assumption of value zero seemed to be a rational compromise.
6.4 Scenario D1 – Struvite precipitation & fertilizer sale
The quantified model for scenario D1 is displayed in Figure 46 below.

The struvite precipitation plant has a capacity of processing 6 m³ per hour. With the assumptions made by Ekobalans AB (35% of the total P available for precipitation and 80% precipitation efficiency) it was concluded that 5.9 tons of P can be extracted annually on the case farm. This amounts to approximately 47 tons of pure struvite. However, due to the high organic content of the substrate, the struvite has an estimated impurity of 10%, which results in a total of 52 tons of struvite precipitated each year. All performance and economic figures are based on data given by Ekobalans AB.
6.4.1 Mass flows & nutrient utilization

The distributions of mass, DM and nutrients are displayed in Figure 47 below.

Figure 47: Mass- and nutrient flows in scenario D1. Figures in percent of total component mass in manure slurry. Mass in gas fraction not quantified, while the mass of struvite cannot be put in relation to the total mass in slurry due to additives.

The effect of struvite precipitations is clearly visible in Figure 48 below. The whole liquid fraction can be applied to the fields, enabling a significant reduction in mineral N fertilizer. Instead of selling off the liquid fraction, the struvite substance is sold. As a consequence of selling such a large amount of on-farm P, part of the solid fraction is applied on the fields instead of utilizing it as fuel for the ORC, in order to fill the 22 kg-p/ha allowed for organic fertilizers.

Figure 48: The ratio between on-farm nutrients and purchased mineral fertilizer in scenario D1.
### 6.4.2 Economic performance

The economic performance of scenario D1 is displayed in Figure 49 below.

![Figure 49: The flow of costs and revenues in scenario D1.](image)

In scenario D1, the most remarkable change is the significant decrease in mineral N fertilizer purchases (almost five times lower than for scenario B and C), enabled by the improved N:P-ratio of the liquid fraction. Furthermore, an additional revenue is struvite sales, although the income from this revenue is rather small in comparison with the costs for investment, maintenance and operation of the struvite precipitation plant. Investment costs for the struvite precipitation plant was 4 200 000 SEK. Another significant change is the reduced amount of solid fraction utilized as fuel, resulting in a lower electricity balance.
6.5 Scenario D2 – Struvite precipitation & on-farm struvite use
The quantified model for scenario D2 is displayed in Figure 50 below.

As expected, this model resembles scenario D1 except for aspects that concern the off-setting of struvite. Instead of selling the whole fraction, it is first utilized to replace mineral P fertilizer and thus, only the excess struvite fraction is sold.
6.5.1 Mass flows & nutrient utilization

The distribution of mass and nutrients in scenario D2 is displayed in Figure 51 below.

Figure 51: Mass- and nutrient flows in scenario D2. Figures in percent of total component mass in manure slurry. Mass in gas fraction not quantified, while the mass of struvite cannot be put in relation to the total mass in slurry due to additives.

When adding each fraction applied to the fields to each other, the resulting on-farm nutrient utilization is very high (see Figure 52 below). Unique to this scenario is the complete utilization of on-farm P, enabled by the re-classification of struvite as a mineral fertilizer.

Figure 52: The ratio between on-farm nutrients and purchased mineral fertilizer in scenario D2.
6.5.2 Economic performance

The economic performance of scenario D2 is presented in Figure 53 below.

The dominant figures are still mineral N fertilizer purchase, interest on the struvite precipitation and sales of electricity from the ORC-unit. However, the cost of mineral P fertilizer is eliminated and the cost of mineral N fertilizer further reduced, if compared to scenario D1.
6.6 Scenario D3 – Secondary SL-separation using decanter centrifuge

The quantified model of scenario D3 is displayed in Figure 54 below.

![Quantified process flow chart for scenario D3.](image)

When recovering nutrients by means of a decanter centrifuge instead of struvite precipitation, as in scenario D1 and D2, the model looks quite different. As described in 6 above, the liquid fraction is divided into a solid and a liquid substrate, where the liquid substrate replaces the function of the liquid fraction while the solid substrate partly replaces solid fraction as a fuel. In order to achieve the required performance on the decanter centrifuge, polymers (PAM) is added with a dosage of approximately 5 kg-PAM per ton liquid fraction. The removed solids are assumed to contain 50% of N and 95% of P available in the liquid fraction (Katers & Pelegrin, 2012). All other performance and economic figures are based on data given by Noxon AB.
6.6.1 Mass flows & nutrient utilization

The liquid substrate leaving the centrifuge has a DM content of 0.4%, while the solid DM content of the substrate amounts to approximately 30% (Lindsten, 2014). The resulting DM separation efficiency of the decanter centrifuge is 92%, while only 13% of the total mass in the liquid fraction ends up in the solid substrate. The resulting distributions of mass, DM and nutrients are displayed in Figure 55 below.

Figure 55: Mass- and nutrient flows in scenario D3. Figures in percent of total component mass in manure slurry. Mass in gas fraction not quantified.

The separation efficiency of N and P in the decanter is 50% and 95% respectively, which results in a liquid substrate with a very high N:P-ratio. Thus, this scenario also recovers nutrients successfully, and the resulting on-farm nutrient utilization is displayed in Figure 56 below.

Figure 56: The ratio between on-farm nutrients and purchased mineral fertilizer in scenario D3.
6.6.2 Economic performance

The economic performance of scenario D3 is displayed in Figure 57 below.

Regarding the flows of costs and revenues visualized in Figure 57 above, scenario D3 differs from other scenarios in the use of electricity. The substantial amount of electricity required to operate the decanter centrifuge uses a large portion of the electricity produced by the ORC, resulting in an electricity balance significantly lower than for scenarios C, D1 and D2. Another pattern-breaking economic figure is the relatively large cost for polymer additive (PAM), required to achieve a high performance on the secondary solid-liquid separation. The investment cost for the decanter centrifuge amounts to 755 000 SEK.
7 Analysis
This chapter holds a compilation and an analysis of the thesis results, so as to facilitate the comparison of all proposed scenarios.

7.1 Nutrient utilization
The efficiency of each scenario in utilizing on-farm nutrients, as opposed to purchasing mineral fertilizer, is displayed in Figure 58 below. It is an indication of the efficiency of each scenario to use available manure nutrients, and is directly relevant to the farm’s environmental impact.

![Figure 58: On-farm N and P utilization for each scenario, in percent of total crop need.](image)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>N utilization</th>
<th>P utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - Default</td>
<td>66%</td>
<td>81%</td>
</tr>
<tr>
<td>B - Separation</td>
<td>65%</td>
<td>81%</td>
</tr>
<tr>
<td>C - Energy recovery</td>
<td>65%</td>
<td>81%</td>
</tr>
<tr>
<td>D1 - Struvite sales</td>
<td>91%</td>
<td>81%</td>
</tr>
<tr>
<td>D2 - On-farm struvite use</td>
<td>92%</td>
<td>100%</td>
</tr>
<tr>
<td>D3 - Decanter centrifuge</td>
<td>90%</td>
<td>81%</td>
</tr>
</tbody>
</table>

As can be noted in Figure 58 above, scenarios A-C are fairly similar in their nutrient utilization. The screw-press separation does not greatly affect the N:P ratio of the produced fertilizer, and thus the utilization is almost unchanged. Scenarios B and C are in fact identical in terms of fertilization and nutrient utilization, since the difference lies in recovering energy. Even though the utilization is slightly lower in scenarios B and C compared to scenario A, the increased usability in field application of the produced liquid fraction makes them a better alternative.

In all proposed nutrient recovery scenarios D1-3, the nutrient utilization is greatly increased. The dependency on mineral N fertilizers can be reduced from over a third of total crop needs to less than 10%, and in scenario D2 the P need is completely fulfilled.

In scenarios D1 and D2, precipitating struvite from the liquid fraction increases the N:P ratio of the treated liquid. The liquid is used in its entirety as a fertilizer on the field, and it is complemented by using part of the solid fraction as a fertilizer up to the legal P limit. Thus the N utilization is increased by over 25%, meaning that a large portion of mineral N fertilizer use can be avoided. If the struvite can be classified as a mineral fertilizer, as modelled in scenario D2, the P utilization can be increased to 100%.

The mechanical removal of solids using the decanter centrifuge in scenario D3 produces a liquid substrate with a N:P ratio over 60, and all of the liquid substrate is used on the fields as a liquid fertilizer. The produced solid substrate has a DM content of approximately 30%, close to the DM content of the solid fraction produced in the screw-press. Since the solid fraction has a better N:P ratio than the solid substrate, it is preferred as a fertilizer. All of the solid fraction and part of the solid substrate is applied to the fields along with the liquid substrate, and by doing so the N utilization can be increased well above that achieved in scenarios A-C.
7.2 Economic performance

The differences in annual economic performance for the scenarios are displayed in Figure 59 below. Note that the economic performance is indexed on scenario B, which is the current situation at the case farm. Also, note that for scale reasons, scenario A is not included in the diagram in its entirety.

![Figure 59: The annual economic performance of each scenario (in SEK), indexed against scenario B.](image)

As is noted in Figure 59 above, all scenarios have a positive result in comparison to the baseline scenario B, albeit only marginally in some cases. The largest profit is achieved in scenario D2 (where the struvite is used on-farm), and the second largest in scenario C (where no nutrient recovery takes place).

Scenario A represents the conventional farm practice, where bedding material is bought externally and the manure is spread onto the fields as untreated slurry. With the relatively large size of case-farm livestock, the bedding materials would have represented a major cost (millions per year), a cost that is entirely removed in scenario B. Instead, the major expense in scenario B is the mineral nutrient needs. The cost for mineral and manure nutrients are equal in scenario A and B.

The installed ORC unit in scenario C produces enough electricity that it can support its own investment and make a slight profit for the farm. Major costs are mineral fertilizer purchases and ORC investment and maintenance, including burner, pelletizer and dryer.

In scenarios D1 and D2 the N:P ratio of the treated liquid means that a large reduction can be made in the mineral fertilizer expenses. Since the solid fraction is partly used as a fertilizer in this scenario, the reduced fertilizer costs come at the expense of reduced output electricity. Large cost items for both D1 and D2, apart from the ORC unit and its peripheral equipment, are the investment in the struvite precipitation unit and its additives. Also, even with the high N utilization in these scenarios, mineral N purchases still represent a major cost. Scenarios D1 and D2 vary only in that in scenario D2 the struvite extracted from the liquid fraction can be reused on-farm as a mineral fertilizer. This completely removes the cost for P fertilizer, putting it ahead of scenario C.

The performance of scenario D3 barely takes it from the negatives to a positive result. This is in large part due to the cost of the chemical flocculants, but also because the fuel for the ORC unit is greatly reduced compared to scenario C. Apart from this, the ORC unit represents a large part of the costs in the system, along with the decanter centrifuge investment and maintenance.
7.3 Pay-off time

The pay-off times for each scenario are presented in Figure 60 and Figure 61 below. Figure 60 is calculated with the economic performance indexed against scenario A, using all investment costs for the calculated scenario. Figure 61 on the other hand is calculated using the economic performance indexed against scenario B, and only includes the specific investment costs for that particular scenario (i.e. total investment costs excluding those pertaining to the screw-press, scenario B). Summarized investment costs for scenarios A through D3 are displayed in Table 13 below. For a complete presentation of scenario specific costs, see Appendix IV - Economic performance figures.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pay-off time vs A [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3 - Decanter centrifuge</td>
<td>1.75</td>
</tr>
<tr>
<td>D2 - On-farm struvite use</td>
<td>2.88</td>
</tr>
<tr>
<td>D1 - Struvite sales</td>
<td>2.95</td>
</tr>
<tr>
<td>C - Energy recovery</td>
<td>1.42</td>
</tr>
<tr>
<td>B - Separation</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**Pay-off time vs A [years]**

Figure 60: Pay-off times for scenarios B through D3, calculated using the economic performance indexed against scenario A and all investment costs for each scenario.

The differences in farm practices facilitated by the installation of the screw-press in scenario B, as displayed in 7.2, has a large impact on farm economy. The investment costs associated with this change are relatively low, why the pay-off time for scenario B is exceptionally short. The economic performance of scenario B relative to scenario A is indirectly included in the following scenarios as well, since the same operational changes remain (e.g. reduced purchases of bedding material). This means that the pay-off times for scenarios C and up are still quite short, even though their investment costs are drastically increased.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pay-off time vs B [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3 - Decanter centrifuge</td>
<td>443</td>
</tr>
<tr>
<td>D2 - On-farm struvite use</td>
<td>57</td>
</tr>
<tr>
<td>D1 - Struvite sales</td>
<td>116</td>
</tr>
<tr>
<td>C - Energy recovery</td>
<td>32</td>
</tr>
<tr>
<td>B - Separation</td>
<td>-</td>
</tr>
</tbody>
</table>

**Pay-off time vs B [years]**

Figure 61: Pay-off times for scenarios B through D3, calculated using the economic performance indexed against scenario B and scenario specific investments.
The pay-off times for the isolated scenarios when measured against scenario B are all significantly longer. What is clear is that the annual economic performances for the scenarios C and up are far too low in comparison to their specific investment costs. The best performing scenario C, where the bedding is recycled as fuel in an ORC and no nutrients are recycled, has a pay-off time relative to scenario B more than three decades long.

<table>
<thead>
<tr>
<th>Investment costs for scenarios</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B - Separation</td>
<td>650 000</td>
</tr>
<tr>
<td>C - Energy recovery</td>
<td>3 350 000</td>
</tr>
<tr>
<td>D1 - Struvite sales</td>
<td>7 550 000</td>
</tr>
<tr>
<td>D2 - On-farm struvite use</td>
<td>7 550 000</td>
</tr>
<tr>
<td>D3 - Decanter centrifuge</td>
<td>4 105 000</td>
</tr>
</tbody>
</table>

Table 13: Investment costs for scenarios B through D3, in SEK. All costs for the specific scenario are included (e.g. the ORC and the screw-press is included in the costs for scenario D1, as well as the struvite precipitation equipment).

As is evident in Table 13 above, the investment costs for scenarios C and above are significantly higher than the investment costs for scenario B. This is because the equipment used in these scenarios is both new and technologically advanced. The pay-off times for the investigated scenarios indicate that an investment in these technologies could be an economically sound idea, but only if the effects of the recovered nutrients and energy is weighed in with the effects of the screw-press separator. The economic benefits of nutrient and energy recovery alone do not justify an investment.
8 Sensitivity analysis

This chapter holds a sensitivity analysis, with which the objective is to display central parameters in the scenario models that have a large impact on the thesis results, and the consequences of their modification.

8.1 Price sensitivity

The scenario outcomes are greatly dependent on pricing of various commodities, such as electricity, mineral fertilizers, chemicals and equipment investment. These are all subject to fluctuations on the global market, and can decrease or increase with short notice. It is therefore relevant to ascertain the robustness of the scenario outcomes with respect to possible pricing changes. Below are four variations identified as especially influential on system outcomes, due to their significance in current scenario outcomes.

8.1.1 Electricity

Between the years of 2005 and 2010, electricity prices in Sweden varied between 0.276 SEK/kWh and 0.543 SEK/kWh (NordPool Spot, 2014), a difference of nearly 100%. To visualise the change in the scenario outcomes with respect to electricity prices, two cases were calculated using these prices, the highest and lowest seen in Sweden since 2005.

![Graph showing annual economic performance of each scenario indexed against scenario B.](image)

What can be seen in Figure 62 above is that, even though there are small changes in what scenario is the best, the general trend remains. It is a logical conclusion, since all scenarios C and above produce electricity in the ORC unit and thus are all affected by the same price change. Since scenario C produces the most electricity, it has the most to gain or lose with price variations, but will only surpass scenario D2 in the case of a quite drastic price increase. Such an increase in electricity prices is,
historically speaking, not likely to last for longer periods. However, there are indications that Swedish electricity prices might be on the rise permanently (Frykerås, 2014).

8.1.2 Mineral nitrogen fertilizer

One of the major costs in all scenarios is that for mineral N fertilizers, making them sensitive to changes in N fertilizer prices. According to Uludag-Demirer (2005), N demand is in a steady increase, suggesting that its price will follow. The sensitivity of the scenarios with respect to N prices is indicated upon in Figure 63 below, where N prices have been increased by 10% and 20%.

![Figure 63: The annual economic performance of each scenario (in SEK), indexed against scenario B. N fertilizer prices increased by 10% (above) and 20% (below).](image)

As can be seen in Figure 63 above, the outcome of the scenarios is quickly changed with an increase in N prices. Since scenarios A-C approximately have the same amount of purchased N they remain near constant, while the nutrient recovery scenarios quickly increase in economic performance. This is due to them using less purchased mineral fertilizers and thus having a better performance relative the indexing scenario B.

A future scenario where N prices are on the increase is far from unlikely. Global trends in food production are on the increase and fossil fuel reserves on the decrease. With such high sensitivity to N prices it makes good sense for a farm to try and utilize on-farm nutrients as best as possible. N prices also fluctuate over the year (with seasons and market trends), and farm managers commonly keep track of world market prices to purchase at lows (Borring, 2014). To better utilize on-farm nutrients using recovery technology could be a safeguard against these fluctuations.
8.1.3 Struvite process investment
Currently there is only one supplier of struvite equipment on the Swedish market. Their equipment is recently developed, and they have only sold a few units so far. It is a very expensive unit, over four million SEK in investment, with a large influence on the performance for scenarios D1 and D2. It is probable that this price could be lowered, with technological development and added market pressures. Two cases have been calculated, where the struvite process investment costs is decreased by 30% and 50%.

Figure 64: The annual economic performance of each scenario (in SEK), indexed against scenario B. Struvite equipment investment costs decreased by 30% (above) and 50% (below).

As seen in Figure 64 above, scenario D1 and D2 markedly improve when investment costs are lowered, and even a 30% decrease is enough to take scenario D1 past scenario C.

8.1.4 Polymer costs
The decanter centrifuge efficiency relies on polymers to improve separation efficiencies. These constitute a major cost in this scenario, at over 150 000 SEK/year. The polymers are intended to be purchased directly from the decanter centrifuge supplier, but there are other alternatives available that might provide polymers at significantly lower costs. Purchasing polymers from suppliers in China could be a feasible option, where prices could be as low as 5.2 SEK/kg polymer (Thörnblom, 2014).
Figure 65: The annual economic performance of each scenario (in SEK), indexed against scenario B, with polymer prices at 5,216 SEK/kg.

As can be seen in Figure 65 above, the polymer price has a significant impact on scenario D3, and with the lower price it performs better than all other scenarios. It is however not clear what the final price could be, and aspects such as import taxes have not been taken into consideration.
8.2 ORC process efficiency

The technology for the ORC unit is still under development, and it is not unlikely to assume that the conversion efficiency could increase (Frykerås, 2014). With a higher output of electricity, the economic performance of all scenarios C and after will rise since more electricity can be sold to the market. Two cases have been calculated, where the electric output in the ORC unit is increased to 8% and 9%.

![Graph showing annual economic performance of each scenario (in SEK), indexed against scenario B. ORC unit efficiency increased to 8% (above) and 9% (below).]

All scenarios are significantly improved by the increased efficiency. However, as expected, scenario C benefits more from the increased efficiency, nearly doubling its economic performance by a 2% efficiency increase. According to Againity AB, such an increase in efficiency could be achievable (Frykerås, 2014). Currently, scenarios D1-3 use a lot of the available DM as fertilization. With an ORC efficiency increase, it might be beneficial to rework scenarios D1-3, focusing on making more of the total DM available as fuel.
8.3 Alternative waste heat off-setting

The incineration of plant fibers to create electricity via an ORC cycle produces large amounts of waste heat. Only 6% of the produced heat is turned into electricity, and approximately 58% of the heat is wasted at a temperature of 50°C. With so much of the heat left unusable, it could be worth considering changing the energy balance to achieve a more effective system.

In this particular case, an animal feed plant is located right next to the farm, and they have a large need of heat in their production (Olai, 2014). Selling the excess heat to them is a feasible alternative, provided that a distribution system is installed. An alternative heat source for the feed plant is biofuels, such as forest fuels, commonly available for as little as 0.17 SEK/kWh (Nyström, 2014). As a reference, district heating is sold for 0.80-0.90 SEK/kWh (Svensk Fjärrvärme, 2014). A case has been calculated, where forest fuel prices are used as a comparative unit.

![Figure 67: The annual economic performance of each scenario (in SEK), indexed against scenario B, including off-heat sales at a price of 0.17 SEK/kWh.](image)

Even with prices as low as 0.17 SEK/kWh there is a substantial economic profit to be made from selling the off-heat to an external partner. As seen in Figure 67 above, there is nearly a nine-fold increase in the economic performance of scenario C. With so much of the economic performance dependent on the ORC unit, the fact that less of the DM is used as fuels in scenarios D1-3 becomes even more apparent, and if sales of excess heat are to be considered, the mass distributions for the nutrient recovery scenarios should be revised.

Note that investment costs for distributing heat from the case farm to nearby heat sinks, such as the installation of a pipeline, are not included. These investment costs can be quite significant, but the sensitivity results from off-setting the case farm waste heat still indicate a large potential increase in economic performance.
8.4 Total nutrient concentrations

Throughout the whole thesis and all scenarios, the nutrients and their concentrations are the foundation of all calculations. Any variation of these variables will thereby have a large impact on all scenarios. Now, as mentioned in 0, this data is based entirely on one sampling occasion. This absence of replicates may have affected the result. There are two discrepancies in the thesis that regard nutrients and that are worth mentioning here. First, the characterization of the on-farm substrates revealed that the N:P-ratio of the liquid fraction is lower than for the solid fraction, which is opposite the expected result (see 4.1). Both references (an older sampling on the case farm and a scientific article) have opposite results, with an N:P-ratio increase in the liquid fraction, if compared to the untreated slurry. As this is part of the main purpose of having a manure separation, it seems reasonable to assume that the liquid fraction will have a higher N:P-ratio than the one used in the thesis, and that the thesis results are somewhat pessimistic.

Second, there is a discrepancy regarding the nutrient balance between the three farm substrates: untreated slurry, liquid fraction and solid fraction. The concentrations of nutrients in all three substrates were measured in an accredited laboratory and are thus to be considered accurate and valid. When scaling up and quantifying the real flows on the case farm however, it was necessary to allocate the substrates by one variable. This variable was the DM content, and thus the DM mass balance of all substrates adds up (i.e. the mass in the liquid fraction is the mass in the untreated slurry except for the mass in the solid fraction). However, this is not the case with nutrients. If, for instance, adding the absolute mass of N in the solid and liquid fractions, the sum amounts to less than the absolute mass of N in the untreated slurry. As a matter of fact, the allocation by DM generates a system “loss” of nutrients of 6-25%. The addition of up to 25% more nutrients in the liquid fraction would naturally have a significant effect on the scenarios, making all of them more profitable. Since total N for the substrates is calculated via the DM content, the relatively high DM content of the case farm data compared to the references could be a source error for this discrepancy.

To evaluate the cascade effects of DM and nutrient discrepancies, a variation using the old case farm analysis results (Ref. 1, see Table 9) was calculated.

Figure 68: The annual economic performance of each scenario (in SEK), indexed against scenario B, using data measured in Ref.1

What is clear from Figure 68 above is that the incoming data for DM and nutrient content has a significant effect on the outcome for each scenario. When using case data from Ref. 1 the DM content in the slurry is lower, which in turn generates a solid fraction about half as big (3 800 tons versus 7 500 tons). This directly affects the amount of produced electricity, drastically reducing the economic
performance for all scenarios C and above. Although the nutrient concentrations in Ref. 1 are more in line with the primary objective of installing a screw-press, the low DM content also reduces the total amount of nutrients with the current thesis method, thus explaining why the sensitivity results in Figure 68 above are negative.
9 General discussion
This chapter is a platform for discussions on subjects that were not part of the scenario models, and is thematically structured.

9.1 From theory to reality
As is common when academia meets reality, the correlation between the thesis results and the effects of implementing the same processes on the case is not necessarily parallel. First of all, the thesis scenarios are theoretic models. A model is by definition a simplified version of the investigated system, where certain parameters have to be generalized or excluded. There is always a trade-off, with the system complexity and result accuracy on one hand, and problem solvability and available time on the other. Second, there is a discrepancy between theoretic results and the dynamics of reality. The models share a starting point which is only accurate momentarily: current farm practices shift, as does current legislation and other regulations.

9.1.1 Manure handling practices
An example of the difficulties of translating the theoretic results to real implications is the case farm’s practice of N fertilizing. As a consequence of the shifting nutrient concentrations and large volume in relation to nutrient content, the slurry/liquid fraction is currently only distributed on parts of the total field area, and the N content is considered an additional bonus to the mineral N that is distributed on the total area. While the thesis model assumes that all N potential is utilized to its fullest, in reality this is hard to achieve since it requires detailed and precise knowledge of nutrient contents and available manure masses. Before the system expansion, models indicated that the N deficiency was only in the amount of 0.5 MSEK, however the farm manager still purchases mineral N for up to 2 MSEK. The difference is partly explained by volatility in N prices, but perhaps more so in that the farm manager chooses to only distribute manure fertilizers on part of the fields. This was done to ensure that the fields were not over-fertilized with P. It was simply easier to sell more of the slurry than necessary, and replace the deficit with mineral fertilizers, rather than spend a large amount of time and effort on carefully distributing all available manure fertilizer.

9.1.2 Over-use of bedding materials
On a day-to-day basis, the screw-press produces large amounts of bedding material that have to be handled on-farm in one way or another. According to scenario models, there is a precise amount of bedding material available to each offset unit (i.e. cubicles, deep-litter beds and ORC). Making sure that each ton of solid fraction ends up where it is supposed to will be a challenge, since a large part of the economic benefits of scenarios C and upward depend on the ORC unit’s electricity production.

9.1.3 Equipment maintenance
All proposed nutrient recovery scenarios require some technical equipment and the addition of chemicals. They all also require some operational maintenance, such as the refilling of additives or equipment recalibration. Although this is hard to quantify in economic terms, it is an aspect worth considering prior to investment.
9.2 Bridging neighbouring industries
During the mapping of, and interviews with, potential suppliers of process technology for nutrient recovery, it became clear that the combination of investigating a pilot project and limiting the investigation to commercial processes was difficult. A clear pattern emerged, where suppliers seemed to belong either to the waste water treatment industry, or to the water purification industry. Most companies that provide equipment suitable for extracting pure fractions of plant nutrients operate within the water purification industry. However, for these processes to work, the incoming substrate (in this case the liquid fraction) had an upper limit on the amount of particles and organic substances, which was around 20 mg/l. The waste water treatment industry had no trouble processing the liquid fraction, but could only process it from 4% DM down to around 0.4%. The gap between 0.4% DM and 20 mg/l (200 000:1 in mass relation) was a considerable challenge to close and resulted in the exclusion of nutrient recovery scenarios that involved such pure fractions. Both industries, however, focus little on the recovery of nutrients as opposed to removal of pollutants, often resulting in substrates unusable within agriculture.

Seemingly, there are two separate industries and very few companies that operate in both. Judging by their lack of knowledge of each other, and their differences in the use of terminology and units, there does not seem to be much cooperation. However, both industries specialize on solving problems with water, and thereby there should be many possibilities for synergies, such as information and technology exchange. Additionally, projects like the one in this thesis present a business opportunity for both industries, and an enhanced cooperation could present many more business opportunities of other kinds.
9.3 Legislative or policy related barriers

No matter how promising a project is in terms of technology or economy, there is always an important juridical aspect. The topics below discuss legislative and policy related barriers that have been identified during the course of the thesis.

9.3.1 Permissions for incineration

Using manure as fuel in biofuel burners has for a long time been considered as an option of disposal for horse farms in Sweden (Thörnblom, 2014). In a study by Wennerberg & Dahlander (2013) it is suggested that the most economical alternative of manure disposal for horse farmers is incineration using regular biofuel burners. However, the method has not yet spread in a large scale, mostly due to difficulties in attaining legal permits. It also seems that many of the economic benefits in incinerating the manure are lost due to legal costs. Investigations are being undertaken into how to reduce these costs.

Meanwhile, using cow manure as fuel has historically speaking not been as interesting an idea, since cow manure contains much more water. Therefore the legalities regarding incineration of cow manure are not as thoroughly investigated. According to local authorities, part of the problem stems from the question of how to classify the manure, as a waste or as an animal byproduct (Bertholdsson, 2014). It may seem frivolous, but the differentiation has big impacts, since the regulations on waste incineration are far greater than those for byproducts. Further, even if the manure is classified as an animal byproduct, any incineration plant needs approval from the Swedish board of agriculture (SJV) (Werthén, 2014). A case-by-case examination determines if any incineration can take place. However, legislations are likely to come into effect on a European level, banning the incineration of animal byproducts in the form of manure (except for certain cases regarding chicken manure). Further investigation into the question of legal permits for the case farm is required before any definitive answers can be given.

9.3.2 The polymer controversy

In the nutrient recovery scenario that involves a secondary solid-liquid separation (scenario D3), it is absolutely necessary to add polymer as a flocculant. However, as noted in 2.4.3, the use of polymers within agriculture is somewhat controversial. The Swedish certification body for bio-fertilizers, SPCR120, does not allow polymers as additives for dewatering the liquid digestate that remains after biogas production (SP Technical Research Institute of Sweden, 2013). The reason for this restriction is not clear, and from personal correspondence with Bo von Bahr (SP), it was concluded that it is an application of the precautionary principle (von Bahr, 2014). According to Tonderski (2014), it has been concluded that the derivatives of polymer degrading may have carcinogenic effects on humans. On the other hand, the addition of polymers seems to be standard within the wastewater treatment industry. Otherwise, the performance of the separation process does not reach the required efficiency (Tengliden, 2014; Feldthusen, 2014). Accordingly, the treated water fraction and the sewage sludge both contain traces of polymers. Since sewage sludge is a common liquid fertilizer, there seems to be some double standards within the fertilizer industry. As a result, Lantmännens group accept agricultural products that have been fertilized with sludge (i.e. polymers allowed) and SPCR120-certified bio fertilizer (i.e. polymers not allowed) (Lantmännens Lantbruk, 2014). In addition, animal manure is currently excluded from all restrictions above, since it has traditionally not been processed in any way.

For the case farm, it is thereby unclear what consequences it would have if a polymer process is installed. The restrictions regarding polymer use seem to be more political than scientifically based,
and since this thesis is a pilot project, it seems like it is up to local authorities to decide whether polymers can be used or not.

### 9.3.3 Organic or mineral

As mentioned above, in Sweden there is a fertilizing limit of 110 kg P/ha for a five year period, which translates to 22 kg P/ha and year. This limit is based on ecological science and its purpose is to mitigate eutrophication by limiting the amount of plant nutrients that may run off from the cultivated soil into the surrounding environment. The limitations on P application come from directives on a European level (Eskilsson, 2014). Modern agricultural trends, especially in countries with relatively small areas of farmland, have moved towards large livestock sizes on small farms, resulting in a large generation of manure production per hectare. The manure was spread on the fields in excess or simply dumped in piles, resulting in heavy nutrient leaching and eutrophication of surrounding waters. To tackle this problem a restriction was put on manure field application (as opposed to e.g. animal per acre), forcing farmers to dispose of their manure in other ways.

However, the directive does not limit the application of mineral fertilizers, nor is it set to satisfy the crop needs. Consequently, no matter the amount of on-farm bio fertilizer that is available, the farm manager still has to purchase mineral fertilizer, since most crops require more than 22 kg P/ha. Now, the quintessence of this problem is where to draw the line between bio- and mineral fertilizers. If the on-farm P fraction could be processed in a way that re-defines the fraction as mineral, then it may be returned to the liquid fraction, and satisfy the crop without trespassing the 22 kg P/ha limit. Currently there is no legal definition of manure fertilizers in Sweden (Eskilsson, 2014). There is an ongoing process to establish an EU regulation where different types of manure are classified, and it is possible that struvite could be labelled as a mineral fertilizer, even if it stems from on-farm manure. The matter is being discussed further at the Swedish Board of Agriculture.
9.4 Environmental impact

Although environmental impact has not been explicitly quantified in this thesis, it is still a central aspect throughout the thesis, and as such there are two matters that are interesting to discuss.

9.4.1 Nutrient losses

In scenario C and scenarios D1-3 a portion of the separated solids is incinerated in the ORC unit. As a result, some of the nutrients in the solids will dissipate in the off-gases and fly ashes from the burner, see Figure 69 below.

![Figure 69: Nutrient losses for scenarios C-D3, in percent of slurry availability. Losses in scenarios A and B are zero, since excess nutrients are sold.](image)

These nutrients are unrecoverable with current scenario models, and cannot be utilized on other farms. This is of no relevance to the case farm since the lost nutrients are not applicable to the farm fields, but from a socio-ecological perspective, it would be preferable to minimize total nutrient losses within the system. If applying a wider, societal perspective, the only way in which to reduce total mineral fertilizer consumption is to redistribute plant nutrients from regions with manure excess to regions with manure deficit. Such an approach would benefit from minimizing the fractions of unrecoverable nutrients, and thereby strive towards recovering nutrients before incinerating any fraction.

9.4.2 LCA perspective

Although the recovery of nutrients and inherent energy in manure generates apparent environmental benefits, such as increased resource efficiency, it is not automatically better if viewed from a life cycle perspective. It is not clear, for instance, whether organic nutrients run off to a higher degree than mineral fertilizers, thus contributing more to eutrophication than the alternative. Furthermore, while the incineration of manure contributes to fossil-free electricity production, it is not clear how the flue gases affect the surrounding environment if compared to the incineration of fossil fuel. De Vries et al (2012) have conducted a study where dairy manure is separated and the liquid fraction treated with reverse osmosis while the solid fraction is incinerated. It was concluded that the environmental impact categories climate change and fossil fuel depletion were improved, while terrestrial acidification and particulate matter distribution were worse, and marine eutrophication remained equal to the reference scenario where only liquid manure was applied to the field. Although the results are not directly translatable to this thesis, it serves as a reminder that the overall environmental benefit is not obvious and that a proper LCA study has to be conducted in order to rank the scenarios by environmental impact.
9.5 Future research

When considering the scenarios, there were a few options that for several reasons did not become part of the calculations, but still represent fields of interest. These are discussed here.

9.5.1 Other applications of the solid fraction

In the scenarios above, the solid fraction from slurry separation is either sold as a solid fertilizer or incinerated to recover inherent energy. While incineration is an efficient strategy for producing electricity, it comes with the cost of wasting a large portion of the on-farm nutrients through off-gases and fly ashes. In accordance with the EU waste hierarchy, the preferred method before energy recovering (incineration) is to try and offset the fraction by material recycling (European Commission, 2014), thus recovering nutrients and organic matter. One way of doing so is to maintain the fraction as a solid fertilizer, as mentioned above. Another recycling option is to offset the solid fraction as bedding material on other locations with bedding demand. Since the cost of bedding material is about two magnitudes higher than for solid fertilizer, it seems like a promising strategy with a high margin of profit. However, in order to sell the solid fraction as bedding material it has to meet different requirements on safety and quality. First, it has to be sanitised according to the standards of the Swedish board for Agriculture to ensure there is no risk of spreading diseases and bacteria (Samuelsson, 2014). Second, the fraction has to be dried from a water content of 65% down to approximately 30% in order to meet the performance of current competitors (e.g. the absorption capacity). After these modifications, the economic marginal has decreased although it is still an interesting option.

9.5.2 Recirculation

The solid substrate leaving the system in scenario D3 has a DM content of approximately 30%. This means that it contains a substantial amount of N, a nutrient most valuable to the farm. It also contains a large amount of the total DM entering the system. By re-circulating the solid substrate into the slurry stream, the system is given a “second chance” to extract both DM and nutrients from it, into the solid fraction and liquid substrate.

If the solid substrate is recirculated the mass balances, nutrient flows and operational costs will change for the entire system, and only after proper testing on all produced fractions and substrates can an economic analysis be performed. It is also possible that the amount of recirculated solid fraction will be ever-increasing, if the screw-press simply is not able to separate such small solids. In such a case, the solid substrate leaving the decanter centrifuge will have to be disposed of at regular intervals. This, however, does not necessarily mean that the recirculation will not be beneficial.

The N that leaves the system if the solid substrate is sold to an external partner is highly valuable to the farm, since it might help reduce the amount of purchased mineral N. The produced solid fraction is also of great value, since it is a fuel in the ORC cycle. Therefore it could be of good economic and environmental benefit to re-circulate the solid substrate, and it should be considered as an option.

9.5.3 Biogas

Manure fertilizers are of high interest as substrates for biogas production (Tonderski, 2014), and many studies concerning nutrient recovery from digested manure are looking into this subject (Pagliari & Laboski, 2013; De Vries, et al., 2012; Møller, et al., 2002; Gerardo, et al., 2013). What is of significance to the case farm is that the solids in the slurry are decomposed to a large extent during an anaerobic digestion process (De Vries, et al., 2012). This means that the quality and quantity of produced bedding material is significantly reduced. Since the use of a screw-press to produce bedding material is a key factor in this thesis, using an anaerobic digestion process to produce biogas has not
been considered. It should be noted that the results regarding nutrient utilization and economic performance most likely would be entirely different for a system including a biogas production step. However, such a study would be highly interesting. The possibility of using a decanter centrifuge to produce a solid fraction, entirely used as fuel in an ORC cycle, and a liquid fraction dedicated to field nutrient use could be a possible method for further enhancing energy balances and nutrient utilizations in both small- and large scale biogas production units.

9.5.4 Organic farming

The farms who struggle most with attaining sufficient plant nutrients are found within organic agriculture (Borring, 2014). Therefore, the perceived value of on-farm nutrient recovery is higher within this category. The scenarios proposed for the case-farm could also be applied on organic farms, provided that the methods are properly certified. A scenario variation was constructed using prices for organic N fertilizers (Lovang Lantbrukskonsult AB, 2013), see Figure 70 below. No reliable price sources could be attained for organic P fertilizers (partly due to their inherent price volatility) why no changes were made to P prices here. This contributes little to the outcome however, since P fertilizers represent a minor cost for the case farm.

As is evident in this price variation (and also indicated in 8.1.2), the economic benefits of recovering nutrients are far greater in situations where fertilizer prices are increased. All scenarios D1-3 now far out-perform scenarios where no nutrient recovery takes place, having increased their performance at least seven times over. This suggests that organic farms could benefit greatly from applying nutrient recovery systems. What should be noted is that there are many differences between the practices of the case farm and organic farms in general, differences that could influence the economic outcome of the proposed scenarios. However, the figures are highly interesting and deserve further investigation.
Energy & nutrient recovery from dairy manure
10 Conclusions
This chapter holds the conclusions that can be drawn from the thesis results, mainly answering the question framework written in the thesis introduction.

When considering any manure processing on a farm, it is important to have a good idea on the character and content of the main raw material, i.e. the slurry. While aspects such as pH and density are important, the central aspects are the content of DM and the concentration of N, P and K. The dominant fertilizer cost for most farms is mineral N fertilizer, and as such it is strategic to distribute as much of the on-farm N as possible. However, the current restriction of distributing on-farm P also limits the amount of on-farm N that can be distributed. Thus, the relation between N and P (i.e. the N:P-ratio) is a particularly central parameter. As for K, the costs depend on soil type and crop rotation, and the case farm had sufficient amounts.

There are various options for processing manure with the purpose of recovering nutrient, e.g. acidification, coagulation-flocculation, filtration techniques or reverse osmosis. However, most methods are either too costly, require too much maintenance or are simply not realistic to install on stand-alone farms. Currently, there are only two feasible options on the Swedish market for recovering nutrients on the case farm; struvite precipitation and secondary solid-liquid separation with a decanter centrifuge. These remove P from the slurry by precipitating struvite micro crystals and separating a flocculated solid substrate, respectively. Both end-products are rich on P, which increases the N:P-ratio of the remaining fractions and thus enable more on-farm N to be distributed.

When comparing the economic performances of scenarios that represent conventional manure handling, solid-liquid separation only, solid-liquid separation that includes energy recovery and solid-liquid separation that includes recovery of nutrients and energy, the results are very interesting. Nutrient recovery by struvite precipitation is the most profitable scenario of all, if struvite is allowed to replace mineral P fertilizer (i.e. end-product on-farm utilization). If not, it is more profitable to invest in only the production of heat and electricity, as nutrient recovery by secondary solid-liquid separation or struvite precipitation with end-product sales are not as profitable. However, the absolutely largest increase in profitability lies within investing in a primary solid-liquid separation. As for the case farm, the screw-press investment reduced costs by more than 2 MSEK, while any of the latter scenarios reduce costs by 0,1-0,2 MSEK. If comparing to conventional manure handling, the pay-off times for all proposed scenarios are less than three years.

Like any results based on quantification, the results are only as good as input data quality and model assumptions. Although the order between scenarios stays robust, all scenarios that include energy recovery and/or nutrient recovery have improved profitability when the prices of electricity and mineral fertilizers are increased. If decreasing the price for additives in secondary solid-liquid separation, the corresponding scenario becomes the most profitable. However, the absolutely largest effect on the thesis results comes from the possible utilization of the waste heat from energy recovery. By selling the waste heat for a relatively low price, the profitability of energy recovery increases by a factor of ten.

Before any of the scenarios that regard recovery of energy and/or nutrients can be implemented, there are a few obstacles to overcome. The main barriers are legislative or policy related. First, the permits required for incineration of any manure fraction depends on whether they are classified as waste or a by-product. If classified as waste, the fractions should be handled according to the EU waste hierarchy and used as a solid fertilizer before it may be incinerated. Second, the profitability of nutrient recovery depends on where the line between organic and mineral fertilizers is drawn. By re-classifying struvite
as mineral, it may be distributed on the farm and generate the most profitable scenario. However, if struvite is to remain classified as organic, it is more profitable to not recover any nutrients at all. Third, the nutrient recovery scenario that includes a secondary solid-liquid separation is completely dependent on polymer additives as a flocculating agent. There is currently a double-standard within the policies of large actors on the Swedish agricultural market, where some fractions that contain polymers are allowed, whilst others are not. Although manure is not explicitly mentioned in any of these policies (since polymer use in manure processing is a new trend), it is not clear what the consequences of using polymers would be for the case farm.

To conclude, this thesis has proved that there are many options for utilizing farm resources more wisely. By recovering both energy and nutrients in the manure, the farm may increase profitability significantly and improve the overall resource efficiency. Such an approach is particularly interesting within organic farming, where plant nutrients are generally more expensive. However, the transition from theoretic conclusions to real life results presents challenges, as a farm operates with a pragmatic approach, and since there are legislative and policy related barriers to overcome.
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# Appendix I – Test results from ALcontrol

## Slurry test results

### Alcontrol Laboratories

**SLY**: Slurry 1  
**Slurry Type**: Slurry

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### Rapport

Rapport Nr 14078350  
Upptagningsnr: RStreck AB  
Leif-Erik Tornblom  
Tekniska 7  
583 30 Linköping

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<tr>
<td>SS-EN ISO 13393:1 mod</td>
<td>Nitritnitratkvarn, NO₂-N + NO₃-N</td>
<td>&lt; 10</td>
<td>±0,6</td>
<td>mg/l TS</td>
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<tr>
<td>SS-EN ISO 13885:2:2009</td>
<td>Fe-salter, P</td>
<td>7,4</td>
<td>±0,6</td>
<td>g/l TS</td>
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<tr>
<td>SS-EN ISO 11885:2:2009</td>
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<td>33</td>
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<tr>
<td>SS O 23101-1</td>
<td>Kväve total, N (Dovadas)</td>
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<td>±6,6</td>
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<tr>
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<tr>
<td>SS-EN ISO 10304:1:2009 (*)</td>
<td>Sulfat, SO₄</td>
<td>3700</td>
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</tbody>
</table>

(*) Metod ej ackrediterad av SWEDAC

Analys av metaller: provet är uppskattat med kungsvalton (återlämningskvalitet) - SS-EN 13346.

---

Linköping 2014-03-20

Rapporten har genererats och godkänts av

Krisina Hallqvist  
Analysansvarig

Kontakta: 0691 019 009 9502

---

Denna rapport får endast dörrga i samhället, om inte utländska laboratoriet, förrän 120 dagar efter datumet.

I
**Liquid fraction test results**

**A
ccontrol Laboratories**

**LIU-IEI-TEK-14-01883—SE**

**F. Celander**

**J. Haglund**

**RAPPORT**

utförd av akkrediterat laboratorium

REPORT issued by an Accredited Laboratory

**Rapport Nr 14088458**

Uppdragsgivare

Retrecks AB

Löf Erik Törnblom

Teknikringen 7

583 30 Linköping

---

**Slam**

<table>
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<th>Provplats</th>
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**Analysresultat**

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<th>Metodbeskrivning</th>
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<th>Enhet</th>
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<td>SS-EN ISO 10304-1:2006</td>
<td>Nitrat, Nitrit och N2O</td>
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<tr>
<td>St. Methods 18th 450GB-E</td>
<td>Ammoniumväte, NH4-N</td>
<td>41</td>
<td>±4,1</td>
<td>g/kg TS</td>
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<tr>
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<td>&lt;27</td>
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<tr>
<td>SS 028103-1</td>
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<td>Forfot total, P</td>
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<td>SS-EN ISO 16304-1:2006</td>
<td>Sulfat, SO4</td>
<td>&lt;1800</td>
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<td>SS-EN ISO 11885-2:2009</td>
<td>Kalium, K</td>
<td>52</td>
<td>±10</td>
<td>g/kg TS</td>
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(*): Metod ej akkrediterad av SWEDAC

Analys av matoljer: provet är uppsatt vid kungsvatten (återläppteknik) - SS-EN 13346.

**Kommentar**

Förhållande rapporteringssvars för Sulfat, SO4 och Nitrat/Nitrit och N2O-N på grund av störningar från andra ämnen i provet.

Detta medför också att mätosäkerheten är högre än vad som anges ovan.

---

Linköping 2014-03-25

Rapporten har granskats och godkänts av:

Kristina Hallqvist

Analysansvarig

---

Denna rapport får endast återges i sin helhet, om inte uttäckta laborestavlor i förnyg skriftliga godkänt av St.
Solid fraction test results

**Analysresultat**

<table>
<thead>
<tr>
<th>Metodbeteckning</th>
<th>Analyt/Undersökning av</th>
<th>Resultat</th>
<th>Mät precision</th>
<th>Enhet</th>
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<tr>
<td>SS-EN 12176-1</td>
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<td>SS-EN 12880-1:2000</td>
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<td>16</td>
<td>±2.7</td>
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<td>SS 023101-1</td>
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<td>3.5</td>
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<td>SS-EN ISO 11885-2:2009</td>
<td>Fosfor total, P</td>
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<td>±1.6</td>
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<td>SS-EN ISO 11885-2:2009</td>
<td>Magnesium, Mg</td>
<td>2.9</td>
<td>±0.68</td>
<td>g/kg TS</td>
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</table>

Analys av metaller: provet är uppslitat med kungsvatten (sterioppsökningsmetod) - SS-EN 13346

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Linköping 2014-03-25

Rapporten har godkänts av

Britt Karlsson
Granskningsansvarig

 Kontroller 528-1616 9028 1162

En av rapport utfördas i samarbete, om inte närmare labortorium i föregående skrivning anges annat.
Energy & nutrient recovery from dairy manure
Appendix II – Scenario platform calculations

This appendix holds the calculations that form a common platform for all scenarios, including the total annual slurry production as well as the on-farm demand for bedding material and plant nutrients.

Slurry production

The farm will have 1400 milk-producing cows when all stables are fully installed (Olai, 2014). Each cow will birth one calf per year on average, of which half will be male. Males are kept at the farm until they reach slaughter weight, approximately 18 months of age. Therefore, in an average year, 1050 animals in the steer 2-18 months category will live in the stables (700 + 350). The same assumption is made for the heifer 12-26 category, meaning that in the average year 817 animals from this category will live in the stables. For the calves 0-2 months category, the calculated faeces and urine per animal has taken into consideration that the animals only exist within this category for 2 months of the year, why these figures are much smaller in comparison. After total sum is calculated, slurry production for the 10% of animal stock living in deep-litter stables is detracted. This manure does not load the slurry wells. Total slurry production is summarised in Table 14.

<table>
<thead>
<tr>
<th>Animal type</th>
<th>Number of animals</th>
<th>Faeces per animal [kg/year]</th>
<th>Urine per animal [kg/year]</th>
<th>Bedding per animal [kg/year]</th>
<th>Spill water per animal [kg/year]</th>
<th>Total per animal type [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calves 0-2 months</td>
<td>1400</td>
<td>50,00</td>
<td>50,00</td>
<td>100,375</td>
<td>182,5</td>
<td>536 025</td>
</tr>
<tr>
<td>Heifer 2-12 months</td>
<td>700</td>
<td>2 052,00</td>
<td>1 368,00</td>
<td>200,75</td>
<td>365</td>
<td>2 790 025</td>
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<tr>
<td>Heifer 12-26 months</td>
<td>817</td>
<td>4 757,00</td>
<td>3 171,00</td>
<td>401,5</td>
<td>730</td>
<td>7 398 592</td>
</tr>
<tr>
<td>Steer 2-18 months</td>
<td>1050</td>
<td>4 809,00</td>
<td>3 206,00</td>
<td>401,5</td>
<td>730</td>
<td>9 603 825</td>
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<tr>
<td>Dairy cows</td>
<td>1400</td>
<td>11 930,00</td>
<td>5 965,00</td>
<td>401,5</td>
<td>730</td>
<td>26 637 100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>In-house manure slurry production</th>
<th>42 269 010 [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainwater [kg/year]</td>
<td>600 000 [kg/year]</td>
</tr>
<tr>
<td>Milking dish water [kg/year]</td>
<td>3 577 000 [kg/year]</td>
</tr>
</tbody>
</table>

| Total sum [kg/year]               | 46 446 010 [kg/year]  |

Table 14: In-stable manure slurry production, calculated with data from (Jordbruksverket, 2013). Data is calculated assuming a 8000 kg/year milk production from dairy cows.

Apart from manure slurry, the reservoirs also gather rain water from within the farm area. In a 0.2 hectare area with an annual rainfall average of 0.3 m$^3$/m$^2$ that means that 600 m$^3$ of rainwater is added to the in-house manure slurry. The milking line uses dish water, and this too is added to the slurry reservoirs (Jordbruksverket, 1995). Approximately 10.5 kg dish water is used per cow and day. The 1400 milking cows collectively produce milk 8 out of the 12 months of the year, meaning that 3 577 000 kg of dish water is gathered per year.

<table>
<thead>
<tr>
<th>In-house manure slurry production</th>
<th>42 269 010 [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainwater [kg/year]</td>
<td>600 000 [kg/year]</td>
</tr>
<tr>
<td>Milking dish water [kg/year]</td>
<td>3 577 000 [kg/year]</td>
</tr>
</tbody>
</table>

| Total sum [kg/year]               | 46 446 010 [kg/year]  |

Table 15: The total amount of slurry produced on the farm over the year

The final total slurry production, as seen in Table 15 above, used in further calculations is 46 446 010 kg per year.
Bedding material demand
The bedding material recommendations from (Jordbruksverket, 2013) for 12-26 month old heifers, 2-18 month old steers and grown dairy cows is 1.1 kg/day & animal. For 2-12 month old heifers it is assumed that 0.55 kg/day & animal of bedding is used, and for 0-2 month old calves the assumed bedding requirement is 0.275 kg/day & animal. With 10% of the animals on deep litter bedding, this means that 1433 tons of bedding material is needed in the cubicles every year. According to pragmatic farm practices, the real bedding need is approximately 25% lower, 1075 tons/year (Borring, 2014; Olai, 2014).

Before screw-press installation, the farm manager estimates that a total of 1000 tons of straw was needed in the deep-litter beds each year. After installation, 500 tons of this straw was replaced with bedding material. It is assumed that this represents a green bedding need of 1000 tons, making deep-litter bedding needs a total of 500 tons of straw (sourced within the farm) and 1000 tons of green bedding. Since the on-farm sourced straw is used equally in all scenarios, it has been excluded as an economic factor.

Plant nutrient demand
To calculate the nutrient needs for the farm one has to consider the crop rotation. Currently the farm grows 435 ha of cereal crop (wheat, barley and similar) and 240 ha of fodder crop (Olai, 2014). The cereal crop needs 160-180 kg N/ha and 27 kg P/ha, and the fodder crop needs 250-300 kg N/ha and 27 kg P/ha. For N need calculations, an average value of the intervals was taken, 170 kg N/ha and 275 kg N/ha respectively. The K need for the farm is significantly lower, at 40 kg K/ha for the fodder crop only.

**Total nitrogen demand**
Cereal crops: 435 ha * 170 kg – N = 73 950 kg N  
Fodder crops: 240 ha * 275 kg – N = 66 000 kg N 
Sum: 66 000 + 73 950 kg – N = **139 950 kg N** 
Per ha need: \( \frac{139 950 \text{ kg N}}{675 \text{ ha}} = 207 \text{ kg} – \text{N/ha} \)

**Total phosphorus demand**
All crops: 675 ha * 27 kg – P = **18 225 kg P** 
Per ha need: \( \frac{18 225 \text{ kg N}}{675 \text{ ha}} = 27 \text{ kg} – \text{P/ha} \)

**Total potassium demand**
Cereal crops: 435 ha * 0 kg – K = 0 kg K  
Fodder crops: 240 ha * 40 kg – N = 9 600 kg K 
Sum: 0 + 9 600 kg – N = **9 600 kg K** 
Per ha need: \( \frac{9 600 \text{ kg N}}{675 \text{ ha}} = 14 \text{ kg} – \text{K/ha} \)
Nutrients provided by manure fertilizers – an example

The fertilizer substrates provided in the different scenarios contain varying nutrient concentrations. This means that the remaining nutrient needs (generally provided by mineral fertilizers) have to be calculated for each scenario. Using scenario B as an example, the calculation method is explained here.

In scenario B, the separated liquid is applied to the fields. The limiting nutrient when applying natural fertilizers is P, and it can be applied to the field up to a level of 22 kg-P/ha. The farm has 675 ha of land.

Total natural-source P application:
\[22 \times 675 \text{ kg} = 14850 \text{ kg P}\]

The separated liquid contains 0.502 kg-P/ton liquid, meaning that the field-applicable liquid fraction amounts to:
\[\frac{14850}{0.502} \text{ ton liquid} = 29600 \text{ ton liquid}\]

The liquid also contains 3.09 kg-N/ton liquid. When applying 29600 ton separated liquid to the field the N applied amounts to:
\[3.09 \times 29600 \text{ kg} = 91600 \text{ kg N}\]

The K content of the manure is 2.17 kg-K/ton liquid. Applied K amounts to:
\[2.17 \times 29600 \text{ kg} = 64200 \text{ kg K}\]

This means that additional fertilization has to be provided. The N and P deficit from natural fertilizers in scenario B is:

N deficit: \[139950 - 91600 \text{ kg} = 48350 \text{ kg N}\]

P deficit: \[18225 - 14850 \text{ kg} = 3375 \text{ kg P}\]

K deficit: \[9600 - 64200 \text{ kg} = -54600 \text{ kg K}\]

Thus this amount of nutrients has to be provided from mineral fertilizers. As is evident, K needs are more than satisfied.
Appendix III – Scenario specific calculations

Here some of the calculations necessary to evaluate the performance of process equipment is explained.

Screw-press performance

This chapter includes calculations on the allocation of mass between fractions after screw press separation, as well as the screw press energy demand.

Screw-press mass separation

The separation of nutrients between solid and liquid fractions depends on the ability of the screw press to separate solids from liquid. The screw-press separator operates continuously by pumping slurry from the slurry basin. The separated liquid is gathered in a similar basin from which it is transported via pumps and hoses to storage basins, for field application or further treatment. The solid fraction is gathered underneath the screw-press in a big pile, from which the farm workers retrieves it for spreading in the stables. The masses of liquid/solid fractions are therefore not measurable in absolute numbers, and have to be allocated by mass. The assumptions and calculations necessary to establish said allocation are presented here.

Units

\[
\begin{align*}
T_{\text{slurry}} & \quad \text{Total weight of slurry} \quad [\text{kg/year}] \\
T_{\text{liquid}} & \quad \text{Total weight of liquid fraction} \quad [\text{kg/year}] \\
T_{\text{solid}} & \quad \text{Total weight of solid fraction} \quad [\text{kg/year}] \\
M_{\text{slurry}} & \quad \text{DM weight of slurry} \quad [\text{kg/year}] \\
M_{\text{liquid}} & \quad \text{DM weight of liquid fraction} \quad [\text{kg/year}] \\
M_{\text{solid}} & \quad \text{DM weight of solid fraction} \quad [\text{kg/year}] \\
f_{\text{slurry}} & \quad \text{Fraction of slurry DM in total slurry} \quad [\% \text{ by weight}] \\
f_{\text{liquid}} & \quad \text{Fraction of liquid DM in total liquid} \quad [\% \text{ by weight}] \\
f_{\text{solid}} & \quad \text{Fraction of solid DM in total solid} \quad [\% \text{ by weight}]
\end{align*}
\]

Assumptions

The densities of the various fractions are, for mass allocation purposes, assumed to be equal to each other

There are no losses of DM through the screw-press separator

\[
\begin{align*}
T_{\text{slurry}} &= T_{\text{liquid}} + T_{\text{solid}} \\
M_{\text{slurry}} &= M_{\text{liquid}} + M_{\text{solid}} \\
M_i &= T_i \times f_i \quad \forall i
\end{align*}
\]
Calculations

\[ (2) \& (3) \rightarrow M_{\text{liquid}} = M_{\text{sturry}} - M_{\text{solid}} = T_{\text{sturry}} \cdot f_{\text{sturry}} - T_{\text{solid}} \cdot f_{\text{solid}} \]  

\[ (3) \& (4) \rightarrow M_{\text{liquid}} = T_{\text{liquid}} \cdot f_{\text{liquid}} \Rightarrow T_{\text{liquid}} = \frac{M_{\text{liquid}}}{f_{\text{liquid}}} = \frac{T_{\text{sturry}} \cdot f_{\text{sturry}} - T_{\text{solid}} \cdot f_{\text{solid}}}{f_{\text{liquid}}} \]  

\[ (5) \& (1) \rightarrow T_{\text{liquid}} = T_{\text{sturry}} - T_{\text{solid}} = \frac{T_{\text{sturry}} \cdot f_{\text{sturry}} - T_{\text{solid}} \cdot f_{\text{solid}}}{f_{\text{liquid}}} \]  

\[ f_{\text{liquid}}(T_{\text{sturry}} - T_{\text{solid}}) = T_{\text{sturry}} \cdot f_{\text{sturry}} - T_{\text{solid}} \cdot f_{\text{solid}} \Rightarrow \]

\[ T_{\text{solid}}(f_{\text{liquid}} - f_{\text{sturry}}) = T_{\text{sturry}}(f_{\text{liquid}} - f_{\text{sturry}}) \Rightarrow \]

\[ T_{\text{solid}} = T_{\text{sturry}} \left( \frac{f_{\text{liquid}} - f_{\text{sturry}}}{f_{\text{liquid}} - f_{\text{solid}}} \right) \] (6)

With equation (6) we can calculate the mass of the solid fraction after the screw-press separator, and thereby calculate the mass of the liquid fraction as well as their DM content.

\[ T_{\text{solid}} = T_{\text{sturry}} \left( \frac{f_{\text{liquid}} - f_{\text{sturry}}}{f_{\text{liquid}} - f_{\text{solid}}} \right) = 46\,028\,310 \left( \frac{4.18 - 9.28}{4.18 - 35.9} \right) = 7\,401\,000 \]

\[ T_{\text{liquid}} = T_{\text{sturry}} - T_{\text{solid}} = 46\,028\,310 - 7\,401\,000 = 38\,627\,310 \]

Screw-press operation

Before the expansion the farm used the same screw-press as after, and the manure reservoir gathered slurry from 700 cows. At that production rate the screw-press operated 3.5 hours per day at 20 kW/hour. The 700 cows produced approximately 36 000 kg of slurry per day (Olai, 2014). After the expansion the same screw-press will have to separate 126 000 kg of slurry per day, meaning an approximate operation time of 12 hours

\[ \text{Operation time}_{\text{post-expansion}} = \text{Operation time}_{\text{pre-expansion}} \left( \frac{\text{Manure}_{\text{post-expansion}}}{\text{Manure}_{\text{pre-expansion}}} \right) \]

\[ = 3.5 \left( \frac{126\,000}{36\,000} \right) \text{hours/day} \approx 12 \text{ hours/day} \]

This figure, 12 hours of screw-press operation time per day, is a rough estimate, but is sufficiently accurate to calculate the screw-press electricity needs. At a 12-hour/day operation time, the electricity needs for the screw press are:

\[ 12 \times 365 \times 20 \text{ kWh/year} = 87\,600 \text{ kWh/year} \]
**ORC performance and supporting equipment**

In scenarios C and D the excess solid fraction is used as fuel to power an ORC cycle. The electricity produced will be sold to the grid, and excess heat will partly be used to dry the solid fraction to increase burner efficiency.

**Dryer performance**

According to the mass allocations, $T_{\text{solid}}$ is 7 401 tons per year. Of this, the farm itself has a need of 1 433 tons as bedding material. The remaining 5 968 tons is used as fuel for the ORC cycle. Before incineration, however, this material has to be dried and pelleted.

The solid fraction has a DM content of 35.9%, equalling 2 142 tons per year. The pellets need to have a water content of 85% (Thörnblom, 2014). After drying, the solid fraction will weigh

$$\frac{2142}{0.85} \text{ tons/year} = 2520 \text{ tons/year}$$

Water evaporation, therefore, amounts to

$$5 968 - 2 520 \text{ tons/year} = 3 446 \text{ tons/year}$$

Using heat of evaporation figures of 2 257.5 kJ/kg (Cengel, et al., 2008), the total energy need for the drying process amounts to

$$3 446 000 \times 2257.5 \text{ kJ/year} = 3 446 \times \frac{2257.5}{3600} \text{ kWh/year} = 2 161 000 \text{ kWh/year}$$

However, the dryer has an estimated efficiency of 65% (Thörnblom, 2014), meaning that the actual heat requirements for the drying process are

$$\frac{2 161 000}{0.65} \text{ kWh/year} = 3 325 000 \text{ kWh/year}$$

**Pellet energy content and processing**

After the solids have been dried, they are pelleted to ease handling and incinerating. This process is assumed to operate without any loss of solids. Studies performed on horse manure (Wennerberg & Dahlander, 2013) report a calorific value of 18 140 kJ/kg TS, or 5 039 kWh/ton TS, which is assumed to include dairy manure as well.

The pelletizer and dryer uses process electricity, 6.8 kWh/ton TS processed.

**Burner performance**

The burner incinerates the fuel at an efficiency of 85%, making 4 283 kWh/ton TS available to the ORC cycle.

**ORC performance**

The ORC cycle has a 6% conversion efficiency of input energy to electricity. The remaining 94% is partly used as drying heat, partly cooled off as waste heat.
Decanter centrifuge separation efficiency

The data given from the supplier was that the decanter centrifuge was capable of separating the liquid fraction (from the screw-press) to a solid substrate with 25-35% DM content, and a liquid substrate with 0.4% (Lindsten, 2014). With an incoming DM content of 4.2% (see Appendix I – Substrate characterization; Test results from ALcontrol) and the DM content of the solid substrate as variable, the resulting DM separation efficiency was plotted (see Figure 71 below).

An average DM content on the solid substrate was set as 30%, which according to the plot meant that the DM separation efficiency had to be 91.7% for the DM masses in liquid fraction, solid substrate and liquid substrate to balance.

Figure 71: Plotting of decanter centrifuge DM separation efficiency with the DM content of the solid substrate as variable.
Appendix IV - Economic performance figures

Scenario A

<table>
<thead>
<tr>
<th>Revenues (+) and costs (-)</th>
<th>Result [SEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedding materials</strong></td>
<td></td>
</tr>
<tr>
<td>Wood shaving purchases -2.2 SEK/kg</td>
<td>-2 365 000</td>
</tr>
<tr>
<td>Straw purchases -1.0 SEK/kg</td>
<td>-500 000</td>
</tr>
<tr>
<td><strong>Mineral fertilizer</strong></td>
<td></td>
</tr>
<tr>
<td>N -10.5 SEK/kg-N</td>
<td>- 500 200</td>
</tr>
<tr>
<td>P -20.3 SEK/kg-P</td>
<td>-68 500</td>
</tr>
<tr>
<td><strong>Sales</strong></td>
<td></td>
</tr>
<tr>
<td>Slurry 4 SEK/ton</td>
<td>99 300</td>
</tr>
<tr>
<td>Deep-litter solid fertilizer 4 SEK/ton</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Summation</strong></td>
<td></td>
</tr>
<tr>
<td>Annual economic performance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3 332 500</td>
</tr>
<tr>
<td>Indexed on scenario B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2 710 800</td>
</tr>
</tbody>
</table>

Table 16: Economic performance figures for scenario A.

Scenario B

<table>
<thead>
<tr>
<th>Revenues (+) and costs (-)</th>
<th>Result [SEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedding materials</strong></td>
<td></td>
</tr>
<tr>
<td>Wood shaving purchases -2.2 SEK/kg</td>
<td>-</td>
</tr>
<tr>
<td>Straw purchases -1.0 SEK/kg</td>
<td>-</td>
</tr>
<tr>
<td><strong>Mineral fertilizer</strong></td>
<td></td>
</tr>
<tr>
<td>N -10.5 SEK/kg-P</td>
<td>- 507 900</td>
</tr>
<tr>
<td>P -20.3 SEK/kg-N</td>
<td>-68 500</td>
</tr>
<tr>
<td><strong>Screw-press</strong></td>
<td></td>
</tr>
<tr>
<td>Investment -650 000 SEK</td>
<td>-23 400</td>
</tr>
<tr>
<td>Maintenance -40 000</td>
<td>-</td>
</tr>
<tr>
<td>Electricity -0.94 SEK/kWh</td>
<td>-82 300</td>
</tr>
<tr>
<td><strong>Sales</strong></td>
<td></td>
</tr>
<tr>
<td>Liquid fraction 8 SEK/ton</td>
<td>75 000</td>
</tr>
<tr>
<td>Solid fraction 4 SEK/ton</td>
<td>21 600</td>
</tr>
<tr>
<td>Deep-litter 4 SEK/ton</td>
<td>4000</td>
</tr>
<tr>
<td><strong>Summation</strong></td>
<td></td>
</tr>
<tr>
<td>Annual economic performance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-621 000</td>
</tr>
<tr>
<td>Indexed against scenario B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
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</tbody>
</table>

Table 17: Economic performance figures for scenario B
### Scenario C

<table>
<thead>
<tr>
<th>Revenues (+) and costs (-)</th>
<th>Result [SEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedding material</strong></td>
<td></td>
</tr>
<tr>
<td>Wood shaving purchases</td>
<td>-2.2 SEK/kg</td>
</tr>
<tr>
<td>Straw purchases</td>
<td>-1.0 SEK/kg</td>
</tr>
<tr>
<td><strong>Mineral fertilizer</strong></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>-10.5 SEK/kg-P</td>
</tr>
<tr>
<td>P</td>
<td>-20.3 SEK/kg-N</td>
</tr>
<tr>
<td><strong>Screw-press</strong></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-650 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-40 000</td>
</tr>
<tr>
<td><strong>ORC-unit</strong></td>
<td></td>
</tr>
<tr>
<td>Investment + installation</td>
<td>-1 300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>3% of invest.</td>
</tr>
<tr>
<td></td>
<td>-39 000</td>
</tr>
<tr>
<td><strong>ORC process equipment</strong></td>
<td></td>
</tr>
<tr>
<td>Dryer investment</td>
<td>-800 000 SEK</td>
</tr>
<tr>
<td>Pelletizer investment</td>
<td>-200 000 SEK</td>
</tr>
<tr>
<td>Burner investment</td>
<td>-750 000 SEK</td>
</tr>
<tr>
<td>Installation</td>
<td>-300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Not quantified</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sales</strong></td>
<td></td>
</tr>
<tr>
<td>Liquid fraction</td>
<td>8 SEK/ton</td>
</tr>
<tr>
<td>Ashes</td>
<td>0 SEK/ton</td>
</tr>
<tr>
<td>Deep-litter</td>
<td>4 SEK/ton</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.54 SEK/kWh</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Summation</strong></td>
<td></td>
</tr>
<tr>
<td>Annual economic performance</td>
<td>-517 700</td>
</tr>
<tr>
<td>Indexed against scenario B</td>
<td>103 900</td>
</tr>
</tbody>
</table>

Table 18: Economic performance figures for scenario C.
### Scenario D1

<table>
<thead>
<tr>
<th>Costs (-) and revenues (+)</th>
<th>Result [SEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedding material</strong></td>
<td></td>
</tr>
<tr>
<td>Wood shaving purchases</td>
<td>-2.2 SEK/kg</td>
</tr>
<tr>
<td>Straw purchases</td>
<td>-1.0 SEK/kg</td>
</tr>
<tr>
<td><strong>Mineral fertilizer</strong></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>-10.5 SEK/kg-P</td>
</tr>
<tr>
<td>P</td>
<td>-20.3 SEK/kg-N</td>
</tr>
<tr>
<td><strong>Screw-press</strong></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-650 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-23 400</td>
</tr>
<tr>
<td><strong>ORC-unit</strong></td>
<td></td>
</tr>
<tr>
<td>Investment + installation</td>
<td>-1 300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-46 800</td>
</tr>
<tr>
<td><strong>ORC process equipment</strong></td>
<td></td>
</tr>
<tr>
<td>Dryer investment</td>
<td>-800 000 SEK</td>
</tr>
<tr>
<td>Pelletizer investment</td>
<td>-200 000 SEK</td>
</tr>
<tr>
<td>Burner investment</td>
<td>-750 000 SEK</td>
</tr>
<tr>
<td>Installation</td>
<td>-300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-10 800</td>
</tr>
<tr>
<td><strong>Struvite precipitation</strong></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-4 200 000 SEK</td>
</tr>
<tr>
<td>MgCl₂ (additive)</td>
<td>-74 000</td>
</tr>
<tr>
<td>Citric acid (additive)</td>
<td>-7 500</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-41 000</td>
</tr>
<tr>
<td><strong>Revenues</strong></td>
<td></td>
</tr>
<tr>
<td>Liquid fraction</td>
<td>8 SEK/ton</td>
</tr>
<tr>
<td>Ashes</td>
<td>0 SEK/ton</td>
</tr>
<tr>
<td>Deep-litter</td>
<td>4 SEK/ton</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.54 SEK/kWh</td>
</tr>
<tr>
<td>Struvite</td>
<td>0.58 SEK/kg</td>
</tr>
<tr>
<td><strong>Summation</strong></td>
<td></td>
</tr>
<tr>
<td>Annual economic performance</td>
<td>-556 400</td>
</tr>
</tbody>
</table>

Indexed against scenario B: 

**Table 19:** Economic performance figures for scenario D1.
### Scenario D2

<table>
<thead>
<tr>
<th>Costs (-) and revenues (+)</th>
<th>Result [SEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedding material</strong></td>
<td></td>
</tr>
<tr>
<td>Wood shaving purchases</td>
<td>-2.2 SEK/kg</td>
</tr>
<tr>
<td>Straw purchases</td>
<td>-1.0 SEK/kg</td>
</tr>
<tr>
<td><strong>Mineral fertilizer</strong></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>-10.5 SEK/kg-P</td>
</tr>
<tr>
<td>P</td>
<td>-20.3 SEK/kg-N</td>
</tr>
<tr>
<td><strong>Screw-press</strong></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-650 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-40 000</td>
</tr>
<tr>
<td><strong>ORC-unit</strong></td>
<td></td>
</tr>
<tr>
<td>Investment + installation</td>
<td>-1 300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>3% of invest.</td>
</tr>
<tr>
<td><strong>ORC process equipment</strong></td>
<td></td>
</tr>
<tr>
<td>Dryer investment</td>
<td>-800 000 SEK</td>
</tr>
<tr>
<td>Pelletizer investment</td>
<td>-200 000 SEK</td>
</tr>
<tr>
<td>Burner investment</td>
<td>-750 000 SEK</td>
</tr>
<tr>
<td>Installation</td>
<td>-300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Not quantified</td>
</tr>
<tr>
<td><strong>Struvite precipitation</strong></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-4 200 000 SEK</td>
</tr>
<tr>
<td>MgCl₂ (additive)</td>
<td>-74 000</td>
</tr>
<tr>
<td>Citric acid (additive)</td>
<td>-7 500</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-41 000</td>
</tr>
<tr>
<td><strong>Revenues</strong></td>
<td></td>
</tr>
<tr>
<td>Liquid fraction</td>
<td>8 SEK/ton</td>
</tr>
<tr>
<td>Ashes</td>
<td>0 SEK/ton</td>
</tr>
<tr>
<td>Deep-litter</td>
<td>4 SEK/ton</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.54 SEK/kWh</td>
</tr>
<tr>
<td>Struvite</td>
<td>0.58 SEK/kg</td>
</tr>
<tr>
<td><strong>Summation</strong></td>
<td></td>
</tr>
<tr>
<td>Annual economic performance</td>
<td>-489 000</td>
</tr>
<tr>
<td>Indexed against scenario B</td>
<td>132 600</td>
</tr>
</tbody>
</table>

Table 20: Economic performance figures for scenario D2.
**Scenario D3**

<table>
<thead>
<tr>
<th>Bedding material</th>
<th>Result [SEK/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood shaving purchases</td>
<td>-2,2 SEK/kg</td>
</tr>
<tr>
<td>Straw purchases</td>
<td>-1,0 SEK/kg</td>
</tr>
<tr>
<td>Mineral fertilizer</td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>-10,5 SEK/kg-P</td>
</tr>
<tr>
<td>( P )</td>
<td>-20,3 SEK/kg-N</td>
</tr>
<tr>
<td>Screw-press</td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-650 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-23 400</td>
</tr>
<tr>
<td>ORC-unit</td>
<td></td>
</tr>
<tr>
<td>Investment + installation</td>
<td>-1 300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-46 800</td>
</tr>
<tr>
<td>ORC process equipment</td>
<td></td>
</tr>
<tr>
<td>Dryer investment</td>
<td>-800 000 SEK</td>
</tr>
<tr>
<td>Pelletizer investment</td>
<td>-200 000 SEK</td>
</tr>
<tr>
<td>Burner investment</td>
<td>-750 000 SEK</td>
</tr>
<tr>
<td>Installation</td>
<td>-300 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-10 800</td>
</tr>
<tr>
<td>Decanter centrifuge</td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>-755 000 SEK</td>
</tr>
<tr>
<td>Maintenance</td>
<td>-27 200</td>
</tr>
<tr>
<td>Polymer (additive)</td>
<td>-37,5 SEK/kg</td>
</tr>
<tr>
<td>Revenues</td>
<td></td>
</tr>
<tr>
<td>Liquid fraction</td>
<td>8 SEK/ton</td>
</tr>
<tr>
<td>Ashes</td>
<td>0 SEK/ton</td>
</tr>
<tr>
<td>Deep-litter</td>
<td>4 SEK/ton</td>
</tr>
<tr>
<td>Electricity</td>
<td>0,54 SEK/kWh</td>
</tr>
<tr>
<td>Summation</td>
<td></td>
</tr>
<tr>
<td>Annual economic performance</td>
<td>-612 400</td>
</tr>
<tr>
<td>Indexed against scenario B</td>
<td>9 300</td>
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</table>

Table 21: Economic performance figures for scenario D3.