Pretreatment technologies to increase the methane yields by anaerobic digestion in relation to cost efficiency of substrate transportation.

by

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Abstract

The world needs new energy sources that are durable for long time and which not affect the environment negatively. Biogas fulfills those demands. The biogas process is however not completely optimized. Several of the substrates used today for biogas production are slowly degraded and only partly digested in the process. Other substrates consist of unnecessarily much water which makes transportation costly. To optimize the process and make the biogas process more profitable, several pretreatment techniques are evaluated by direction of E.ON in this report: steam explosion, extrusion, lime treatment and dewatering. The hope is that one of those could increase the profitability and hopefully also enable substrates that not are working today like feathers and straw.

To compare and evaluate the different pretreatment batch digester, experiments were carried out during 31-44 days for untreated and pretreated substrates. Most pretreated substrates were faster degraded than untreated and some also gave a higher methane yield. Chicken waste feathers and wheat straw, which had low methane yields untreated, were affected most by pretreatment. Steam exploded feathers gave after 44 days of digestion 141% higher methane yield and extruded straw gave 22% higher methane yield than untreated samples of the same substrate.

A reference plant with a substrate mixture of 12500 tonnes of maize silage and 11500 tons of horse manure annually was used to make economical calculations. Additionally, chicken waste feathers waste could be included. Obtainable for the reference plant were also chicken waste feathers. Steam explosion appeared to be too expensive for a plant in the size of the reference plant. Its large capacity could probably make it profitable for a much larger biogas plant running on a lot of hard digestible substrates. An extruder could be a profitable investment for the reference plant if the plant gets horse manure with straw as bedding material. To just use the extruder to pretreat maize silage could not make the investment profitable.

Dewatering of manure gave significantly lower methane yield per dry weight but significantly higher methane yield per wet weight. The increase in methane yield per wet weight makes the substrate better for transportation. The dewatering equipment from Splitvision tried in this study had too high operational costs and was too expensive to make dewatering particularly profitable. Only when the farm was situated farther away than 40km from the biogas plant it was cheaper to dewater the manure before transport than to transport the manure without any pretreatment. Other dewatering equipments evaluated in this study had much lower operational costs and among those an equipment that makes dewatering profitable might therefore be found.
Sammanfattning


För att jämföra och utvärdera förbehandlingsteknikerna utfördes batchrötningsförsök i 330 ml flaskor med obehandlade och förbehandlade substrat. De flesta förbehandlade substraten gav snabbare nedbrytning och några gav även högre metanutbyte än de obehandlade. Fjädrar och halm, som från början hade ett lägt utbyte, påverkades mest av förbehandlingen. Ångexploderade fjädrar gav efter 44 dagars rötning 141% högre metanutbyte och extruderad halm gav 22% högre metanutbyte än obehandlad.


Avvattnning av gödsel gav signifikant lägre utbyte av biogas per torrvikt men signifikant högre utbyte per våtvikt. Avvattningsutrustningen från Splitvision, som testades, var för dyr för att bli lönsam. Först när gården låg 4 mil från biogasanläggningen blev det billigare att avvattna gödsel och transporterera den jämfört med att transporterera den obehandlad. Andra avvattningsutrustningar i studien var billigare i drift så det finns möjligheter att tekniken kan bli lönsam med någon av dessa.
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Chapter 1

Introduction

The world needs new energy sources that are durable for long time and which do not affect our environment negatively. In this context biogas is one of the most promising energy sources available today. It is storable, transportable and it can be produced from many types of biomasses including waste.

Industrial scale biogas plants are facing a predicament. The conversion of organic matter like waste or crops into biogas by anaerobic digestion takes weeks or months; the bulk of organic matter like starch or organic acids is quickly degraded within weeks whereas the more recalcitrant fractions like lignocellulosic fibres and some proteins take several months (Nayono, 2009; Jördening & Winter, 2005; Deublein & Steinhauser, 2008).

The profitable operation of a biogas plant relies on low capital and operational expenditures. In order to save capex (capital expenditure) biogas plants have been built with a comparably small fermenter volume, which results in a short residence time of the substrates 10-30 days, and hence an incomplete degradation of the organic matter. In order to produce a certain volume of biogas, more substrate is needed when the the degradation of the organic matter is incomplete. Alternatively, biogas plants have been built with large fermenter volumes, which enables long retention times. During long retention times, 30-60 days, the substrates become more degraded and a higher biogas yield is achieved. The low Opex (operational expenditure) is bought with the cost of a high capex. A solution could be an accelerating of the degradation of the substrates by pretreatment in order to get the higher gas yield in a shorter span of time. Moreover, pretreatment of substrates could enable the use of novel substrates which have been hitherto unsuitable for anaerobic digestion (AD).

In this study two of the most promising pretreatment technologies are compared: steam explosion and extrusion, with a variety of substrates, straw, maize silage and chicken feathers. For the chicken feathers a method with lime treatment has also been tried out, because previous studies have shown that lime treatment might be the only satisfying pretreatment method for chicken feathers(Kashani, 2009; Salminen et al., 2003).

The dominant substrate of many biogas plants in terms of volume (not energy content) is manure. The use of cattle and pig manure has several advantages: the climate benefits
from that methane is not released into the atmosphere, but used, the farmer gets rid of excess amounts of nutrients, and the biogas plant operator gets a cheap substrate. This win-win situation is curbed when the farm is too far from the biogas plant and the costs of transportation exceed the value of the methane produced from the manure. A solution could be to upconcentrate the organic matter in the manure and thus, transport more energy and less water. The challenge is not only to upconcentrate the organic matter but also nutrients like phosphorous or nitrogen that the farmer needs to get rid of. In this study some upconcentration technologies are compared.

E.ON is one of the world’s largest investor-owned power and gas companies. To be a pacesetter in the transition to a low-carbon future E.ON invests about EUR 8 billion in 2007 to 2012 to enlarge their renewables portfolio. E.ON plans to increase its installed renewables capacity from around 3 GW in 2009 to 10 GW by 2015. Biogas is a part of this renewables portfolio. E.ON owns many biogas plants today and is involved in many projects concerning the planning of new biogas plants in Sweden and Germany.

For this thesis a fictive reference plant is used, i.e. a biogas plant running on a mixture of substrates similar to many of E.ONs existing and planned biogas plants in Sweden. The available substrates for the reference biogas plant that could be interesting to pretreat are: 12500 tons of maize silage or wheat silage, 30000 tons cow manure, 11500 tons of horse manure and 5000 tons of chicken waste feathers. Among those, horse manure with straw as bedding material and chicken waste feathers are today unsuitable for biogas production when untreated. Untreated straw and feathers are both material with low density and large particle size which cause mechanical problems in the biogas process where it get stuck in pipes, create floating layers and prevent good stirring. Horse manure and feathers which are very abundant materials without any sustainable fields of application today could possibly become a profitable substrate for biogas production after pretreatment.

The reference plant is producing about 40GWh/a of energy in form of biomethane which makes it a pretty big biogas plant in Sweden. It has a retention time of about 30 days. It would be interesting to see if the costs of pretreatment could be covered by the revenues of a higher CH4 yield for a larger biogas plant like the reference plant with the different pretreatment techniques evaluated in this study. It would also be interesting to see if any of the pretreatment techniques could enable chicken feathers and/or horse manure as a substrate for a normal size biogas plant. All economical calculations in this study have therefore been made for the reference plant to see if any of the evaluated techniques could be a profitable option for a normal size biogas plant.
Chapter 2

Aim and Research questions

2.1 Aim

The aim of this master thesis is to evaluate four different pretreatment methods: extrusion, steam explosion, lime treatment and dewatering to see if any of those could be an economically beneficial alternative for the reference plant.

2.2 Research questions

To adress this aim the following research questions were formulated:

- Does pretreatment by extrusion and/or steam explosion increase the total methane yield from lignocellulose rich substrates like maize silage and straw? Does it increase the rate of biodegradation of the same substrates?

- Does pretreatment by lime treatment and/or steam explosion increase the total methane yield from chicken feathers? Does it increase the rate of anaerobic digestion of the same substrates?

- How is methane yield from manure affected by pretreatment?

- What are the benefits and drawbacks of using steam explosion, extrusion, lime treatment and dewatering for the reference plant?

- Does any of those pretreatment methods enable new substrates like straw, horse manure and feathers to be used for biogas production?
Chapter 3

Background

3.1 Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>TS</td>
<td>Total solids</td>
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<td>VS</td>
<td>Volatile substances</td>
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<td>ww</td>
<td>Wet weight</td>
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<tr>
<td>VFA</td>
<td>Volatile fatty acids</td>
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<td>VOC</td>
<td>Volatile organic compounds</td>
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<tr>
<td>AD</td>
<td>Anaerobic digestion</td>
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<td>THP</td>
<td>Thermal hydrolysis process (steam explosion).</td>
</tr>
<tr>
<td>Capex</td>
<td>Capital expenditures.</td>
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<td>Opex</td>
<td>Operational expenditures.</td>
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3.2 Biogas: applications and benefits

Biogas consists mainly of methane (45-70%) and carbon dioxide (30-55%). It can be produced from many different types of organic materials. It is possible to use waste from industrial processes, agriculture or household as substrate. Accordingly is it possible to produce biogas without affecting the food chain and prices of food and without the need to cut down forests. The biogas produced can be used for electricity, heating or transportation. \(1 \text{Nm}^3\) of methane gas is equivalent to 9.97 kWh of energy or ca 1.1 litres of petrol (Benjaminsson & Nilsson, 2009).

When upgraded to >96% methane, biogas has the same methane composition as natural gas and can be transported in already existing gas grids. It can also be turned into LBG (Liquified biogas) by the use of cryogenic technology where the gas is cooled down to liquid form. Upgraded biogas is suitable as vehicle fuel. \(1 \text{Nm}^3\) of upgraded biogas is equivalent to 1.1 liters of petrol (Biogassyd, 2010).

In Sweden there are 230 biogas plants, producing around 1.4 TWh annually of which 49% is used for heating, 5% for electricity, 36% is upgraded and 10% is flamed (2009) (Sahlin & Lindblom, 2010). Biogas produced from organic waste which is used instead of fossil fuels has a positive effect on greenhouse gas emission.

3.3 Microbiology of anaerobic digestion and biogas production

Biogas is produced under anaerobic conditions by at least three different groups of microorganisms: Acidogenic bacteria, acetogenic bacteria and methanogenic archaea (Jördening & Winter, 2005). The process can be divided into four steps as summarized in Fig. 3.1: hydrolysis, fermentation, anaerobic oxidation and methanogenesis.

1) During the first step, hydrolysis, complex organic materials such as fat, carbohydrates and proteins are degraded to smaller compounds like long-chain fatty acids, amino acids and saccharides. This is done by hydrolytic enzymes (celullases, amylases, lipases and proteases) secreted by the acidogenic bacteria. The composition of the substrate affects the rate at which the organic matter is degraded. For example when a substrate is rich in cellulose like straw or maize stalks, this step becomes rate limiting because cellulose has a complex structure which is relatively resistant to degradation. (Jördening & Winter, 2005)

2) In the second step, fermentation, acetogenic bacteria use the amino acids, long-chain fatty acids, sugars as carbon and energy sources. The intermediate products created during this process are alcohols, short chain fatty acids eg. acetate, hydrogen gas and carbon dioxide. (Jördening & Winter, 2005)

\(^1\text{Nm}^3\) is m\(^3\) of gas at sea level (p=1 atm) and at the temperature, T=0°C
3) In the third step, anaerobic oxidation, long-chain fatty acids and alcohols are oxidized by proton-reducing acetogenic bacteria to acetic acid, CO₂ and H₂. Acetogenic bacteria are slow growing bacteria, which are sensitive to high hydrogen pressure. They are dependent on hydrogenotrophic methane-forming archaebacteria to decrease the hydrogen pressure that they increase. (Jördening & Winter, 2005)

4) In the last step, methanogenesis, methane is produced by methanogenic archaebacteria, which use acetate, carbon dioxide and hydrogen as carbon and energy sources. (Jördening & Winter, 2005) If there are bad conditions in the bioreactor for the methanogenetic archaebacteria this will lead to high hydrogen pressure and this in turn means that the acetogenic bacteria will be affected negatively. This results in an accumulation of fermentation products including organic acids which makes pH drop. This scenario may also occur if there has been an overload of substrate and the methanogens cannot consume all the hydrogen formed. To recover after this kind of event takes time.
3.4 Substrate

There are many different types of substrates available for biogas production. This report is focused on substrates from the agricultural sector. Among these the most widely used are manure and energy crops. This report deals with straw, maize silage, wheat silage, chicken waste feathers, cow, pig and horse manure.

![Feathers](a) and Maize silage (b)

**Figure 3.2:** (a) Feathers from Guldfågel chicken factory in Falkenberg. (b) Maize silage used in Falkenberg biogas plant. Photo: Ylva Borgström

3.4.1 Straw

The largest arable land areas in Europe are used for cereal cultivation. Straw is the dry stalk of a cereal plant or an oil plant left after the grain have been removed. The straw part is approximately half of the total biomass of the plant (Linne et al., 2008). The high availability of straw makes it an interesting substrate.

Today straw is used as bedding for animals, animal feed and fuel for biomass power plants. Fields of application are also basketry, straw hats, rope, paper, decoration and packaging. In Sweden more than 100,000 tons of straw are burned and used for heating, generating 500-600 GWh of heat (Bernesson & Nilsson, 2008). If using the same amount of straw for biogas production instead it would have generated 119-204 GWh energy. However, this energy would occur in a more useful form (transportable, storable etc).

The total amount of straw from cereals respectively oil plants produced in Sweden, 2008, was 4 047 000 ton TS/year and 447 000 ton TS/year (Linne et al., 2008). This makes a total theoretical biogas potential in Sweden of 5.8 TWh/year calculated with the assumptions that it is possible to get a methane yield of 160 Nl CH₄/kg TS in a practical operation. In earlier laboratory studies biogas yield of 145-240 Nl CH₄/kg TS were achieved depending on pretreatment method (Linne et al., 2008). These numbers can be compared to the total biogas potential of all residual materials in Sweden which in 2008 was 10.6 TWh (Linne et al., 2008). The reasons why straw is not widely used as a substrate for biogas production today are:
• High transportation and packaging costs due to its low density. With modern technology straw can at best be pressed into bales with a density of around 100-150kg/m³ depending on method (Bernesson & Nilsson, 2008).

• Low biogas yield and slow digestion process due to its high content of hemicelluloses (30-40%), cellulose (20-30%) and lignin (10-20%) (Thomsen et al., 2008).

• The low density of straw which creates problems in the bioreactor where it floats on the surface forming a cover and preventing good mixing. It can also create problems, when getting stuck in pipes and pumps in the biogas plant.

In order to increase the accessibility for the enzymes and thereby increase the anaerobic digestion, the plant wall (ligniocellulose) needs to be disrupted. This can be done either by thermal, chemical or mechanical pretreatment.

3.4.2 Maize silage

In the year 2009, 16 210 hectares with maize were cultivated in Sweden and 159 million ha in the whole world (Persson, 2010). In Sweden maize is mainly cultivated in the southern parts due to the climate. The average amount of maize as corn per hectare in Sweden is approximately 6.6 ton (Persson, 2010). In maize silage (Fig. 3.2b) the whole crop is chopped down to pieces and ensiled under anoxic conditions to get a preserving effect.

Maize is today mainly used as animal feed and human food or in ethanol and biogas production. The starch from maize can also be made into plastics, fabrics adhesives and many other chemical products (Board, 2009). Maize is one of the most widely used energy crops for biogas production, due to its high energy output/hectare. The energy output/hectare varies depending on crop yield (location, climate, and variety), the management (harvest time and conservation) and the efficiency of the biogas process. In earlier studies methane yield from maize silage of 370 Nl CH₄/kg VS substrate where achieved without pretreatment (Bruni et al., 2010). By simply reducing the particle size of the maize silage, the methane yield could in the same study be increased by approximately 10%.

3.4.3 Chicken feathers

Today are there approximately 7.2 million poultry in Sweden, mainly laying hens and chickens, but also some turkeys. Of these, 5.3 million are chickens for slaughter (Persson, 2010). The poultry industry is continuously producing residues such as feathers, bone meal, blood and offal. Most of these residues are used in animal feed. Feather meal is rich in proteins but since most proteins are in form of keratin, which is undegradable by most proteolytic enzymes it has a low nutritive value. Only 18% of keratin is digestible in rumen (Henderickx & Martin, 1963). Another problem in this field of application is the risk of disease transmission via the food chain and to prevent this there is a substantial legislation in EU for the use of animal feed.
Another field of application is to use the feathers as a fuel in power plants. The energy content of feathers is the same as for wood chips, 4.76 kWh/kg. A Cement factory on Öland, an island in Sweden, is now planning to use 3000-5000 tons of feathers instead of coal in their factory. (Cementa, 2010) Smaller quantities are also used for clothing, insulation and bedding. There is a need for new alternative methods to utilize the enormous amounts of feathers. To use feathers as a substrate in biogas production could hopefully be an economically and environmentally friendly field of application.

Feathers make up approximately 5% of the chickens body mass. It consists mainly of the fibrous keratin and small amounts of lipids and water (Salminen et al., 2003). Because of the complex, rigid and fibrous structure of keratin, feathers are poorly degradable under anaerobic conditions (Salminen et al., 2003). A pretreatment method, where the tough structure is broken down is needed to be able to get a high biogas yield.

3.4.4 Manure

In 2010 there where over 20,000 animal farms in Sweden (Persson, 2010). The manure produced on these farms is used as substrate in biogas production and as organic fertilizer in agriculture where it improves soil structure and adds nutrients to the soil. The use of manure for biogas production has several advantages: less methane is released into the atmosphere, the farmer gets rid of excess amounts of nutrients, and the biogas plant operator gets a cheap substrate.

Manure is an excellent substrate for anaerobic digestion due to its balanced content, which makes the process stable. It contains necessary minerals and nutrients, since most animals on the farms have been fed with feed additives and it contains a natural microflora (Sagdieva et al., 2008). The energy content is however low and there is problem of hygien when handling the manure.

Among the different types of manure, manure from pig farming and poultry has a higher biogas potential than manure from ruminants. This is because ruminants already have some anaerobic digestion in their first stomach (Deublein & Steinhauser, 2008). Manure can be handled as liquid manure (farm slurry) or solid manure (farmyard manure or deep litter manure). Liquid manure consists of feces and urine. Solid manure also contains plant material (often straw or peat), which has been used for animal bedding (Goodrich, 1923).

Horse manure

Today there are 283,100 horses in Sweden (Persson, 2010). The amount of horses in one stable varies from a few up to hundreds. The amount of manure produced by one horse over a year depends on the size of the horse and how much bedding that has been used, but is approximately 1.5 ton TS/horse and year (Linne et al., 2008). Horse manure can be used as a natural fertilizer or as a substrate for biogas production. Many horse stables are today situated near cities and lack agreeable fields of their own, where the manure can be spread. Therefore horse manure often needs to be deposited in a landfill of a substantial
cost for the stable (Hammar, 2001).

The benefits of using horse manure as a substrate for biogas production are many: the stable avoid costs of landfilling manure, greenhouse gas emissions in form of methane gas and nitrous oxide will not be emitted to the air from landfills or fields where the horse manure otherwise would end up and energy in form of biogas becomes available. The biogas yield for untreated horse manure is approximately 170 Nl CH$_4$/kg VS (Kusch et al., 2008).

Horse manure is relatively dry and often contains a large amount of straw and bedding (straw, sawdust or peat). The large amount of straw makes horse manure fairly resistant to anaerobic digestion. A pretreatment method increasing the biogas yield for straw might therefore increase the yield of horse manure.

3.4.5 Cattle and pig manure

Today there are approximately 1.5 million cattle and 1.5 million pigs in Sweden (Persson, 2010). The cattle are living in 20,000 cattle farms with an average size of 70 animals and the pigs in 2000 pig farms with an average of 80 grown up animals (487 if counting for small pigs and slaughter animals) (Persson, 2010). The farms are concentrated in the southern parts of Sweden.

For milk cows and slaughter pigs most of the manure is handled in liquid form. According to statistics from the Swedish Board of Agriculture and the Swedish Environmental Protection Agency the approximate amount of liquid manure produced in Sweden in 2010, is 9,436,000 ton/year from cattle and 3,142,000 ton/year from pig farming. The biogas yield from liquid manure differs, but is approximately 150 Nl CH$_4$/kg TS for cattle and 200 Nl CH$_4$/kg TS for pig manure. Calculated from these figures the total biogas potential in Sweden from cattle manure is 2.7 TWh/year and from pig manure 0.5 TWH/year (Linne et al., 2008).

3.4.6 Livestock manure handling

Of the 9000 animal farms in Sweden today, 240 farms have over 200 cows or 1000 pigs (Kärrmark & Lublin, 2010). For such a farm it could be economically beneficial to invest in a biogas plant. Today approximately 25 farms in Sweden have or are planning to build a biogas plant on the farm (Kärrmark & Lublin, 2010). For these farms the manure is used as a substrate for bio-fertilizer and biogas production (Fig. 3.3a, option 1.)

For the smaller farms the best option is to transport the manure in tank lorries to a biogas plant in the area (Fig. 3.3a, option 2). Since transportation is expensive this option is today only possible for farmers close to a biogas plant. In the area of Falkenberg, several farmers are connected to the biogas plant and transport their manure to the biogas plant. When processed the farmers get digestate, a good bio-fertilizer, in return. For smaller or midsize farms far away from a biogas plant there are today not many other profitable options than to use the manure directly as fertilizer on the land areas around their farm (Fig. 3.3a, option 3).
To use the manure directly as fertilizer has some drawbacks:

- Greenhouse gas emissions in form of methane and nitrous oxide occur in fields and in open manure basins.

- The farmer cannot chose the time for fertilizing to the same extent: when the manure basin is filled up, it needs to be spread on the fields no matter if the plants need it or not. This may result in a excess of nutrients on the field, which sooner or later ends up in lakes and watercourses causing eutrophication.

- The farmer is not allowed to have so many animals on the farm, since there are regulations for how many animals a farm can have in proportion to the land areas where the manure can be spread. If the manure is processed in a biogas plant the farmer is allowed to have more animals because the processed manure contains less phosphorus (Peter Tohlse at Splitvision, pers. comm.).

To avoid these drawbacks it would be an advantage to use manure from smaller farms far away from a biogas plant for biogas production. This could only be done in an economically beneficial way, if the transportation cost problem is solved. One solution would be to transport the manure in pipelines, another solution to dewater the manure prior to transportation to reduce volume and thereby transportation costs (Fig.3.3b).

With a dewatering system at the biogas plant, the transportation costs for biofertilizers back to the farm may also be reduced. Further more less water means less cost for the farmer when distributing the biofertilizer on the fields and less effect on soil structure (Peter Tohlse at Splitvision, pers. comm.).
3.5 Pretreatment

There are several pretreatment techniques available to increase biodegradability of different substrates. The pretreatment methods can be divided into thermal, mechanical, chemical and biological treatment.

Straw, wheat silage and maize silage are lignocellulose rich materials and lignocellulose is in most cases extremely resistant to anaerobic digestion. A suitable pretreatment method should destruct the lignocellulosic structure and thereby release the sugars contained in the biomass to make them more available for the bacteria. This can be done by enzymes or by acids, bases, solvents or oxidants in combination with mechanical pressure and thermal treatment (Hendriks & Zeeman, 2009). In this report two methods are evaluated which both includes mechanical pressure and high temperatures: steam explosion and extrusion.

Feathers consists mostly of keratin proteins which are packed and linked together making a tough keratinous material which is resistant to enzymatic digestion (Salminen et al., 2003). An appropriate pretreatment method needs to hydrolyze the feathers and break down its structure to amino acids and small peptides available to the bacteria. In this report two methods are evaluated for feathers: lime treatment and steam explosion. For manure the largest problem is its low energy content which makes transportation costs high. A pretreatment method where the organic fraction of the manure is upconcentrated would decrease transportation costs and make the substrate more economically beneficial.

3.5.1 Steam explosion

Steam explosion is a method combining heat (up to 240°C) with high pressure (up to 33.5 bar). The substrate is put in a vessel and is exposed to steam at high temperature and pressure for normally 5-30 minutes which hydrolyzes the glycosidic bonds in the substrate. After that, the steam is released and the substrate is cooled down quickly which makes water in the substrate to “explode”, and opens up the structure of the lignocelluloses in the cell wall of the substrate and makes the biomass inside available to the bacteria. (Bauer et al., 2009) Advantages of steam explosion are:

- Increase of biogas and methane yield from lignocellulose rich materials
- Increase of the speed of the anaerobic digestion rate which enables smaller reactors and lower investments.
- Reduce of risks of floating layers in the bioreactor with low density substrates like straw or feathers.
- The material will be easier to transport through pipes and stirring of the bioreactor is improved.
- The homogeneity of the substrate is increased.
Cambi is a Norwegian company delivering steam explosion reactors situated in Asker. They have reactors located all over the world, mainly in Europe and are treating sludge from municipal waste water treatment plants. In earlier studies a 20-30% increase in methane yield of straw has been detected after treatment with steam explosion (Bauer et al., 2009, 2010; Chen et al., 2005). To the best of my knowledge there are no reports on steam explosion trials on keratinous materials like feathers.

Figure 3.4: Pilot plant for steam explosion in Norwegian University of Life Sciences, Ås, Norway. Photo: Ylva Borgström

In more detail steam explosion is divided in two parts: steam exposure and explosions. During steam exposure, the moisture penetrates the lignocellulosic structure and makes the acetyl groups in hemicelluloses undergo complete hydrolysis. This forms organic acids like acetic acid and results in an acidic pH. The organic acids hydrolyze hemicelluloses to soluble sugars e.g. xylose, glucose, arabinose and galactose (Xu et al., 2005). The acidic pH also initiates further reactions of lignin. These reactions are not only degrading lignin, but the acidic conditions are also leading to a repolymerization, which makes lignin less degradable (Hendriks & Zeeman, 2009). At temperatures above 60°C amorphous cellulose is forming hydrogen bonds and at temperatures above 150°C they recrystallizes (Yano et al., 1976). In steam explosion the temperatures are up at
240°C and thus increasing the degree of crystallinity of the cellulose. It has been proven that digestibility is proportionally decreasing with crystallinity on wheat straw (Fan et al., 1980). If temperature or pressure is too high, the acidic conditions could catalyze a reaction where xylose is degraded to glucose which then could be degraded further into furfural or hydroxymethylfurfural. Furfural is an inhibitor for anaerobic digestion and therefore undesirable. Consequently the temperature needs to be high enough to release cellulose from lignin but not too high.

In the reactor the steam has penetrated the lignocellulosic structure by diffusion caused by high pressure. This condensed moisture within the material is then instantaneously evaporated when the pressure is suddenly decreased. When the moisture is evaporated it expands and this expansion within the cell wall creates a shear force on the lignocellulosic structure. If the shear force is big enough this will lead to a mechanical break down of the cell wall structure, an ”explosion”, which opens up the structure making the inside available to bacteria.

Higher temperature and pressure increases the difference to the outside conditions. This result in a pressure and temperature drop and make the shear forces of the evaporating moisture greater. Greater shear forces leads to more disruption of the cell wall structure of the plant cells in the substrate. Retention time is correlated with the extent of hemicelluloses hydrolysis by the organic acids. The chosen temperature and retention time is accordingly important for the outcome of steam explosion. According to earlier studies temperatures around 180-200°C at times of 10-15 minutes has been optimal for the improvement of the biogas yield mostly on straw (Bauer et al., 2009, 2010; Chen et al., 2005).

3.5.2 Extrusion

Extrusion is a pretreatment technique where the substrate is mechanically crushed through a double screw extruder. This crushes the lignocellulososes-rich material into fibers increasing the accessible surface area of the substrate. The accessible surface area is positively correlated to enzymatic hydrolysis (Grethlein, 1985).

As the substrate moves forward the pressure and temperature is increasing up to a maximum of 2 bar resp. 160-180°C (Lehman, 2011). When the substrate leaves the extruder, the pressure and temperature drops fast in the same way as in steam explosion. The advantages of extrusion are to a small extent similar to steam explosion (see section 3.5.1).

Lehmann and Promeco are two companies delivering bio extruders. According to Paolo Rebai at Promeco are the difference between these extruders the size and shapes of the screws (Paolo Rebai, pers. comm.). Promeco uses shorter and wider screws than Lehman which increases stability and shearing strength and enables higher forces without reducing the treatment time for the material since the screw is wider.
3.5.3 Lime treatment

Lime treatment is an alkaline thermal treatment method where the substrate is heated to temperatures around 100-150°C while lime in concentrations around 0.1 g $\text{Ca(OH)}_2/g$ substrate is added. Earlier studies have shown that lime is an effective treatment agent to solubilise chicken feather proteins. At a temperature of 150°C, 80% of the feather keratin were solubilised within 25 min (Coward-Kelly et al., 2006).

In an earlier master thesis, focusing on feathers a biogas yield of 480 Nl CH$_4$/kg VS of substrate was obtained by lime treatment (10 times higher than untreated) (Kashani, 2009). Highest biogas yield was obtained in a trial with the lowest temperature, (100 °C), and shortest time (30 min). This was probably due to the protein and amino acid degradation taking place under lime treatment which is associated with ammonia production. High levels of ammonia could be inhibiting the anaerobic digestion process (Deublein & Steinhauser, 2008). The advantages of lime treatment are that lime is relatively inexpensive, effective, recoverable and safe to use at these low concentrations (Coward-Kelly et al., 2006).

3.5.4 Dewatering of manure

There are several mechanical separation methods for separating manure into a solid and a liquid phase. The advantages of doing this are:
• The solid phase is easier to handle because it often get a reduced particle size and therefore less tendency to plug transfer pipes.

• It is easier to transport because of the reduced volume and mostly at a reduced odour.

• A high percentages of the phosphorous ends up in the solid phase and a low percentage of the nitrogen. This is important for the farmers in nutrient rich areas where accumulation of phosphorous is a big problem (Ford & Flemming, 2002).

The drawbacks are high costs due to capital investment in separation equipment, often high energy demand for the equipment and increased management requirements. Some biogas potential may be lost during the dewatering process. Separation is usually done by gravitation or by using mechanical equipment involving a screen, press or centrifuge. Parameters to look at when comparing different separator equipment are:

• Separation capacity (recovered ton TS/h or processed ton ww/h)

• Capital investment and operational costs: energy consumption, maintenance and labour requirements

• The distribution of physical and chemical constituents in the liquid and solid phase: TS, VS, phosphorous, nitrogen etc.

• Odour and particle size distribution of the solid phase.

Stepwise filtration, Splitbox Agri

Splitvision is a Swedish company, situated in Angelholm, offering a system for dewatering of manure based on stepwise filtration. The whole system of the splitbox agri is sealed inside a container which can be placed on the farm and may there be connected to the manure basin. According to Jan Broberg at Splitvision The Splitbox Agri uses stepwise filtration with continues cleaning of the filters and a roller where mechanical pressure presses out the last liquid (Jan Broberg, pers. comm.)

According to Peter Tohlse at Splitvision the manure is first pumped into a three step-rotating metal filter, where water is pressed out of the material, scrapes are taking away the dry solids in a second step and the filter is cleaned with water in a last step. After that the solid phase is transported into a roller consisting of 5 rolls, which presses out further water from the solid material. The water phase from the three-step rotating metal filter and roller is filtrated through a nylon filter, which is automatically cleaned with water. In the last step magnesium is added to the water phase and this precipitates struvite. Struvite can then be filtrated out of the water. Struvite is a phosphorus mineral which has an economical value and the formula: \(NH_4MgPO_4 \cdot 6H_2O\). The water coming out of this process is so clean that it can be drained off without problems directly into the sewer or may be used on the farm for watering. (Peter Tohlse, pers. comm.)
Decanter centrifuge

Decanter centrifuges have been used for a long time in dewatering of sewage sludge. Recently it has also started to be used for dewatering of manure. In the decanter centrifuges the manure is put inside a large drum and is exposed to centrifugal forces, which presses the material to the sides of the drum. To make the centrifugal forces the drum is rotating very fast, around 3000-4000 revolutions per minutes. The liquid phase is pressed through the small holes in the drum and the solid phase stays inside the drum, where it is conveyed out with a screw transporter. (Persson & Wiqvist, 2008)

Centrifuges have generally higher capacities than screw presses. They are often larger, have a higher energy demand, consists of higher technology parts and demands a larger investment. A decanter centrifuge could maybe be profitable for a very large farm or for a biogas plant to dewater the digestate before transport back to the farms. Fangel biogas plant in Denmark has for example used centrifuges from Westfalia since 2002 to dewater their digestate. They are producing 80 000 ton biofertilizer a year and dewater that to a solid phase with 30% TS (Persson & Wiqvist, 2008). Westfalia and Spalleck are two companies delivering centrifuges for manure separation who demonstrated their equipment at the manure separation field trial in Haverbeck, Germany, the 24th of July 2010. Spalleck has focused on taking away as much phosphorus as possible. This is good for the farmer but makes the separation slower. (Haverbeck, 2010)

Screw press

Screw pressing is a mechanical method, where the manure is transported with a screw through a cylinder full of holes. The liquid phase is pressed through the holes and the solid phase is transported out with the screw (Ford & Flemming, 2002). In earlier studies a lower energy demand has been reported for screw presses than for centrifuges. (Ford & Flemming, 2002).

Figure 3.6: In this picture from the manure separation field test in Haverbeck, Germany can 4 different screw presses are dewatering fresh pig manure from the same manure basin. Photo: Ylva Borgström
In the manure separation field test in Haverbeck, Germany, the 24th of July 2010, 7 different screw presses were demonstrated: Al-2 -Agro A/s from Al-2 Teknik A/S (Hovborg, Denmark), optipress I and II from Big Dutchman (Vechta, Germany), SP 254.1 from Nock/ Tecnotrans (Osnabrück, Germany), Rc 50 and BS 50 from Börger (Borken-Weseke, Germany) and PSS 5.2-780 from FAN (Marktschorgast, Germany). (Haverbeck, 2010) The screw presses demonstrated varied in size, capacity and were constructed differently to solve mechanical problems. The screw inside AL-2-Agro was covered in rubber to avoid wear and thereby get longer lifetime. Börger and Big Dutchman had adjustable pressure which made it possible to chose the dryness of the outgoing solid phase. In this way it was possible to change the pressure to avoid clogging. Nock and FAN had instead more simple construction where a spring resp. a weight created the pressure. Several of the demonstrated screw presses were small enough to fit on a car trailer and were accordingly mobile.
Chapter 4

Methods

4.1 Pretreatment

4.1.1 Dewatering of cow manure

Dewatering of cow manure was performed at Skottorp farm, one of the biggest cattle farms in Halland, Sweden, with a Splitbox-Agri from Splitvision (Angelholm, Sweden). The cow manure used for the test was stable manure with straw as bedding material. The manure was pumped directly from the manure basin and was dewatered in an Splitbox-Agri standing on site. Approximately 5kg of dewatered manure was produced during the test. Samples of dewatered manure and untreated manure was collected and taken to the laboratory for analysis and methane production potential measurement.

4.1.2 Lime treatment of waste chicken feathers

Feathers were cut down to pieces of about 1cm and 0.1g Ca(OH)$_2$/g TS feather was added to a mixture of 50ml water with 40g TS feather/l water. The sample was boiled under stirring for 30min. After cooling down pH measurement was made to control that pH was around 7-8. The sample was stored in a freezer until the start of the batch test. The concentration used, 0.1g Ca(OH)$_2$/g TS feather, was based on the trials described in the master thesis by Kashani (2009). In that report, feathers were prepared before lime treatment: dried, cleaned and milled. To see if money could be saved by deleting this step, no cleaning, drying or milling were done before lime treatment in this experiment.

4.1.3 Extrusion of straw and maize silage

Extrusion was performed with an extruder from Promeco in Como, Italy. To get the extruder into working temperature it was first fed with composted wood waste material. The temperature was measured with an IR-thermometer on the exit hole of the extruder (Fig. 4.3). After 1-2h, the temperature was 80°C and steam was coming from the material. After that maize silage taken from the silo the day before was fed into the extruder. The temperature of the maize coming out of the extruder was first low, 30°C. Thus, the narrow opening where the extruded material was pressed out had to be tightened before the real experiment to get a higher pressure and at a higher temperature.
Later on, fresh maize silage and wheat straw from a farmer nearby were extruded. During the trial, temperature and energy demand was measured and 6 samples were collected: 4 with maize and 2 with straw. The temperatures of the extruder, when the samples were taken are given in table 4.1. Two samples of each substrate was chosen for the batch digester experiments: Fresh maize silage extruded at 40°C and 60°C and straw extruded at 80°C and 100°C. Samples were collected from all tests and were transported to Sweden in a cold bag at around 10°C for 19 h and were later stored in a cold storage room, 4 °C for 33 h until the start of batch digester experiments.

Table 4.1: The samples collected during the extruder trial. Sample 2, 4, 5 and 6 were used in the later batch digester experiment.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature of extruder (°C)</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>1-day old Italian maize silage</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>Fresh Italian maize silage</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>Italian wheat straw</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>Italian wheat straw</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>Italian wheat straw</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>Fresh Italian maize silage</td>
</tr>
</tbody>
</table>
4.1.4 Steam explosion of waste chicken feathers

Steam explosion was performed in a pilot plant of Cambi in Ås, Norway. 5 liters of feathers (around 1 kg) were treated at a time. Three rounds of tests were performed with different temperatures and pressures. By starting at a high temperature and then extruding at lower temperatures to see if feathers pulverizes also at lower temperatures. The settings for the different runs are given in table 4.2. Samples were collected from all tests and were transported to Sweden in a cold bag at around 10°C for 24h before deep-freezing. The samples were stored in a freezer until the start of the batch digester experiment. Samples were also taken from the condensate water to see how much volatiles from the substrate that went with the steam.

Table 4.2: The samples collected during the first steam explosion trial of feathers. All samples were used in the later batch digester experiment, trial 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Temperature (°C)</th>
<th>Time (min)</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feathers</td>
<td>190</td>
<td>10</td>
<td>11.6</td>
</tr>
<tr>
<td>2</td>
<td>Feathers</td>
<td>180</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Feathers</td>
<td>165</td>
<td>10</td>
<td>6 bar</td>
</tr>
</tbody>
</table>

4.1.5 Steam explosion of straw, wheat silage and maize silage

Steam explosion was performed in a pilot plant at Cambi in Ås, Norway. 5 liters of material were treated at a time. Three rounds of tests were performed with the three different substrates: Swedish wheat straw, Swedish maize silage and Swedish wheat silage. All substrates came from a farmer in the Falkenberg area.

The temperatures, times and pressure are presented in table 4.3. The temperatures were chosen after recommendation from Pål Jahre Nilssen from Cambi who had experience with steam explosion of straw and maize silage. The temperatures chosen were similar to the ones used in other successful experiments on steam explosion reported by Bauer et al. (2009), citetBauer2010 and citetChen2005. Samples were collected from all rounds and samples of untreated material were collected. All samples were stored in a cool bag around 10°C, for 24h during transportation and were later stored in a cold storage room, 4°C during 26h until the start of batch digester experiments. Samples of the condensate water before and after the steam explosion of maize silage were collected.

Table 4.3: The samples collected during the second steam exploder experiment. All samples were used in the later batch digester experiment, BE 4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Temperature (°C)</th>
<th>Time (min)</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Straw</td>
<td>200</td>
<td>10</td>
<td>14.5</td>
</tr>
<tr>
<td>2</td>
<td>Wheat silage</td>
<td>200</td>
<td>10</td>
<td>14.5</td>
</tr>
<tr>
<td>3</td>
<td>Maize silage</td>
<td>180</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>
4.2 Batch digester experiments

Four laboratory scale batch digester experiments were performed to be able to compare and evaluate the different pretreatment techniques. During the batch experiments, 320ml glass flasks with rubber septum were used as bioreactors. The batch experiments were carried out for 31-44 days until most of the gas production had stopped.

4.2.1 Substrates

In the four batch experiments different treated substrates were tested:

**BE1** Dewatered and untreated cow stable manure

**BE2** Maize silage extruded at 40°C and 60°C and straw extruded at 80°C and 100°C as well as untreated samples of the same maize and straw.

**BE3** Steam exploded chicken feathers at three different temperatures: 165°C, 180°C and 190°C, Lime treated as well as untreated chicken feathers.

**BE4** Steam exploded maize silage at 180°C, wheat silage at 200°C and straw at 200°C as well as untreated samples of the same substrates.

The untreated substrates were cut down to around 1 cm long pieces to fit into the batch bottles and to make it easier to weigh the appropriate amount of substrate for each bottle. The maize silage was a heterogenous substrate consisting of corn, stalk and leaves (Fig. 4.2). To obtain a representative composition, the composition of the maize silage was analyzed by sorting and weighing the different parts. The maize silage was composed of 20% corn, 20% inner stalk and 60% smaller particles and leaves. The same composition was used as substrate.

![Image of maize silage components](image)

**Figure 4.2:** The components of maize silage. Photo: Ylva Borgström

4.2.2 Analysis of the substrates

For all substrates pH, VFA content, TS and VS were analyzed. For the extruded materials analyse of acid detergent fiber (ADF), acid detergent lignin (ADL), Neutral detergent
fiber (NDF) and Crude fiber (CF), TS, VS, COD, VFA and VOC were carried out in a German laboratory, Analytiklabor Blgg Osterbeek.

**pH**

pH was measured on all substrates using a PHM 93 reference pH meter (Radiometer Copenhagen, Denmark).

**Total solids (TS) and Volatile solids (VS)**

TS was analyzed according to Swedish Standard (SS-028113;25) using an oven of 105°C for 20h to evaporate water and thus determine the TS content, and an oven of 550°C for 2h to combust the organic material and thus determine the ash content. The volatile substances are the difference between TS and ash content.

**Preparation of plant extract and VFA-analys**

For the dry substrates an extraction had to be made before VFA-analys. 1g TS of the substrate was added to a 15 ml plastic tube with 14 ml of milliQ water and the plastic tube was shaken 100 times every 30 minutes for 4h. 1 ml sample was taken out of the plastic tube and was centrifuged for 10 minutes. This method is not a standard method and the results from the VFA-analys therefore just can be compared within the experiment and can just be used as an indication of how much easily available VFAs, there was in the different substrates. VFA was analyzed using the method by Jonsson & Boron (2002) using a GC-FID HP 6890 (Hewlett Packard, USA). The total amount of VFAs in the sample were then calculated.

4.2.3 Inoculum

For the first batch experiment on manure, digestate from Nykvarn sewage treatment plant (Tekniska Verken i Linköping AB) was used as inoculum. For the rest of the batch experiments digestate from Falkenberg Biogas plant was used as inoculum. Falkenberg biogasplant is running on a mixture of mainly maize silage and cow manure. It is a similar plant to the reference plant and therefore this inoculum was chosen for most of the batch experiments.

4.2.4 Batch startup

All batch digester experiments were carried out in triplicates with an OLR of 2.5g VS/L. To ensure anaerobic conditions, all bottles were prepared under flushing of nitrogen gas. Each batch reactor contained 10 g of inoculum, 2 ml of nutrient solution (\(NH_4CL, NaCL, CaCl_2 \cdot 2H_2O\) and \(MgCl_2\)), 0.25 g VS substrate, 0.3 ml \(Na_2S\) to reduce any remaining oxygen and oxygen free milliQ water to a volume of 100ml.

As positive control cellulose supplied as Whatman filtration paper No.3, (Whatman Limited, England) was used as substrate. As negative control no substrate was used, just inoculum. As blank control only milliQ water was used and 50 Nml of methane was
added to the bottle at start of the batch experiment. After the preparation of the batch bottles the gas in the bottles was exchanged for a mixture of 20% carbon dioxide and 80% nitrogen and incubated in a climate room of 37°C.

4.2.5 Gas measurement

Gas pressure was measured regularly using a Testo digital pressure meter (Testo AG, Germany) at every other day in the beginning and once a week in the end of the incubation. Every time gas pressure was measured, the bottles were shaken, samples for methane analysis were collected in a glass vial (13.7ml) with a 1 ml syringe and the overpressure was released from the batch bottles.

![Figure 4.3: Picture showing gas sample collecting. Gas is collected in glass vials from the batch bottles seen in back of the picture. Photo: Ylva Borgström](image)

4.2.6 Methane analysis

The methane content in the glass vial was analyzed with an GC-FID HP 5880A (Hewlett Packard, USA) according to Karlsson et al. (1999). 0.3 ml of the sample was taken out with a 1 ml syringe and was injected through septum of the GC. For calibration 4 standards were used with a methane content of respectively: 0.07%, 0.63%, 1.71% and 3.08%. Two different calibration curves were made, one for lower methane content using standard 0.07%, 0.63%, and 1.71% and one for higher methane concentrations using standard 0.63%, 1.71% and 3.08%. New standards were made every other week.

4.3 Calculations

4.3.1 Economic calculations

To analyze the profitability of the different pretreatment techniques economical calculations have been made for capex, opex and revenues. The prize of the extrusion was also calculated per ton treated material and per MWh energy obtained as biogas. To fully see its potential the payback time was also calculated.

24
Capital expenditure, Annuity method

To calculate the cost of capital investment the annuity method has been used. The annuity was calculated as:

\[ A = NPV \cdot k = \frac{NPV \cdot p}{1 - (1 + p)^{-n}} \]  
(4.1)

Where NPV = net present value, p = cost of capital, n = year of depreciation, k = the annuity factor.

It was estimated that approximately 1/3 of the pretreatment machines value consisted of parts with short lifetime and therefore a depreciation time of 5 years had been chosen for 1/3 of the investment. For the rest, 2/3, a depreciation time of 10 years was chosen. To calculate for unforeseen events 5% of the investment was added. The cost of capital was estimated to 8.5%. Prizes of the different pretreatment equipments have been received from respective manufacturer.

Operational expenditures

The operational expenditures were calculated as the sum of maintenance costs and the electricity costs. The electricity costs, EC, was calculated as:

\[ EC = \frac{AS \cdot ED \cdot EP}{C} \]  
(4.2)

Where AS = Amount of substrate pretreated a year, ED = energy demand of the pretreatment equipment per amount, EP = electricity prize and C = annual capacity of the pretreatment equipment.

The electricity prize was estimated to 0.6 SEK/kWh and data for the capacity and energy demand were received from the manufacturer of each pretreatment equipment. The maintenance cost was either calculated as a percentage of the capital investment, 2.5-5%, or as a sum of the costs of all spare parts needed during a year depending on how detailed data were received from the manufacturer.

Revenues

The revenues in form of more produced methane gas was calculated from the difference between the biogas yields of pretreated and untreated substrate. The estimated prize used for methane was 850 SEK/MWh. For dewatering were savings for transportation and the revenues from struvite also calculated as revenues. The prize of struvite was estimated to 4 SEK/kg and the transportation cost were also estimated to 4 SEK/(TON·km).

Economics of extrusion

One of the aims of this report was to investigate if it would be economically beneficial to install an extruder or a steam exploder on the reference plant. To analyze this three scenarios where established. One scenario where horsemunure and maize silage was pretreated. A large part of the composition of horse manure is straw. If straw also is used as
bedding material in the stable, probably around 90% of the stable horse manure consists of straw. It is therefore realistic to think that a pretreatment method showing good results on straw also would show good results on horse manure. If however this is not true a scenario was also made where only maize silage was treated. The last scenario illustrated a case where the extruder could be used at its maximum capacity treating maize silage.

**Economics of Steam explosion**

If a steam explosion unit would have been installed, feathers would become a possible, promising substrate. So for that pretreatment calculations were made for a plant where feathers could be used instead of maize silage. The maize silage yield was not increased by steam explosion and was therefore not included. To investigate if it would be economically beneficial to install an steam explosion unit on the reference plant, four scenarios were established: one where feathers and horsemannure were pretreated, one where only feathers were pretreated and two scenarios where the maximum capacity of the THP could be used treating wheat silage or horsemannure.

The THP unit needs a substantial amount of energy to produce steam, which in turn means a lot of excess of heat energy. This heat could be used in a biogas plant for heating other substrates during hygienisation if needed. It is hard to estimate how much of this excess heat energy that could be used in reality. Therefore two cases were made: one where all heat could be used and therefore no extra energy would be needed for the steam explosion and one where no heat could be reused. In reality probably most of the heat would be used.

**Economics of Dewatering using a Splitbox Agri**

Economical calculations were made for two different scenarios using a Splitbox Agri: one scenario for a farm situated 15km away from the biogas plant and one at 40 km distance. Some of the data from Splitbox Agri were compared with data from other dewatering equipments collected on the manure separation field test in Haverbeck.

**4.3.2 Statistical analysis**

Statistical analysis was made using Tukey Kramer method with 95% confidence to see if the pretreatment increased the methane yield significantly. The simultaneous confidence intervals for all pairwise comparisons by the multivariate Tukey-Kramer procedure are given by:

$$I_{\mu_i} - I_{\mu_j} = \bar{m}_i - \bar{m}_j = \pm q_{0.05}(k; DF) \cdot \frac{s}{\sqrt{N}}$$  \hspace{1cm} (4.3)

This statistical analysis was done for all the different pretreatment techniques using 1-way ANOVA test to get mean values ($m$), pooled standard deviation ($s$) and degree of freedom (DF). The value for $q_{0.05}$ (k,DF) was taken from a statistical table (institution of Linköping University, 2006). Explanations for the abbreviation used and all statistical calculations are presented in Appendix A.
Chapter 5

Results and discussion

The methane yields in this chapter are presented as Ni CH₄ TS of substrate, Ni is normal liter of gas at sea level (p=1 atm) and at room temperature (T=20°C). To get the methane yield at 0°C, which is another temperature often used to present methane yields, the yield is multiplied by 0.93.

5.1 B1: Untreated and dewatered manure

5.1.1 Dewatering of cow manure

As can be seen in the Fig. 5.1, the dewatered manure mainly consisted of straw which was used as bedding material at the farm. Straw affected the dewatering negatively by becoming stuck in the pipes going from the manure basin to the dewatering system and in that way making the dewatering process unstable.

![Untreated manure](image1.jpg)  ![Dewatered manure](image2.jpg)

(a) Untreated manure  (b) Dewatered manure

**Figure 5.1:** Untreated cow manure from Skottorp farm (a) and the same manure after dewatering with Splitvision Agribox (b). Photo: Ylva Borgström

The characteristics of the dewatered and untreated manure are summarized in table 5.1. According to the manufacturer Splitbox Agri could dewater manure to a TS content of 50%. However, the dewatered manure only got a TS content of 31%. Maybe this could have been due to the high amount of straw in the manure. It would have been interesting
to see if the dryness could get as high as 50% with this equipment when dewatering liquid manure i.e. manure without bedding material.

**Table 5.1:** Results from the substrate analysis of dewatered and untreated manure.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>pH</th>
<th>TS (g TS/kg ww)</th>
<th>VS (g VS/kg TS)</th>
<th>tot. VFA (g VFA/kg TS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated manure</td>
<td>7.2</td>
<td>120</td>
<td>870</td>
<td>88</td>
</tr>
<tr>
<td>Dewatered manure</td>
<td>7.2</td>
<td>310</td>
<td>930</td>
<td>6</td>
</tr>
</tbody>
</table>

Most of the volatile fatty acids got lost during dewatering. Dewatering also resulted in a higher VS content, which show that dissolved inorganic compounds also followed the water phase.

### 5.1.2 Biogas potential of untreated and dewatered manure

The methane yield per VS was 51% higher for the untreated manure than for the dewatered manure (Fig. 5.2). This could be due to the higher straw content, that the dewatered manure seemed to have. Straw is difficult to digest because of its composition of lignin, hemicellulose and cellulose and gives a low methane yield untreated (Thomsen *et al.*, 2008).

![Figure 5.2: Biogas and methane yields after 31 days for untreated and dewatered manure. The error bars shows the standard deviation within the replicates.](image)

The methane yield per TS was 42% higher for the untreated manure compared to the dewatered. This means that some of the biogas potential of the manure got lost during the dewatering. Probably did some of the smaller particles in the manure get through

---

1Easy available VFA content, extraction method described above in section 4.2.2
the filters in the Splitbox and came out with the water phase. As discussed above a lot of the easily degradable VFA content got lost during dewatering and this contributed to the lower methane yield. The lost VFA may explain about 50% of the lost methane yield during dewatering, 37 Nl CH₄/kg TS according to the VFA analysis (Table 5.2).

**Table 5.2:** Theoretical loss of methane yield from lost VFA during dewatering. The theoretical methane yields were calculated using the Buswell equation presented by Buswell & Tarwin (1934).

<table>
<thead>
<tr>
<th>VFA</th>
<th>lost content (g /kg TS)</th>
<th>theoretical methane yield (Nl CH₄/kg)</th>
<th>lost methane yield (Nl CH₄/kg TS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid</td>
<td>55</td>
<td>400</td>
<td>24</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>17</td>
<td>570</td>
<td>9</td>
</tr>
<tr>
<td>Buturic acid</td>
<td>9</td>
<td>640</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>86</td>
<td>-</td>
<td>37</td>
</tr>
</tbody>
</table>

The methane yield per wet weight was 81% higher for the dewatered manure. Thus, the dewatered manure is much better for transportation. The methane content of the produced biogas was 15% higher for the untreated manure, 59% for manure and 50% for dewatered manure. This is probably due to the higher VFA content in manure than in dewatered manure. It is cheaper to upgrade biogas with a higher methane content. Statistical analysis of the results confirms that dewatered manure has a lower methane yield per VS and TS, but a higher methane yield per wet weight (Tukeys test *P* < 0.05).

### 5.2 B2: Extrusion of maize silage and straw

#### 5.2.1 Extrusion

The extruded material got a browner color, lower density, smaller particle size and higher homogeneity (all visible changes, Fig.5.3 and 5.4). Fibers and some larger parts of plant material could still be seen in the substrate after extrusion, the fibers had about the same length as the pieces of plant material had before pretreatment.
The dryness and hardness of the material affected how warm the extruder would become. Straw with a TS content of 85% got a maximum temperature of around 100°C during the experiment whereas maize with a TS content of 38% made it to a maximum of around 60°C. Thus, maize silage were extruded at lower temperature than straw.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>pH</th>
<th>TS (g TS/kg ww)</th>
<th>VS (g VS/kg TS)</th>
<th>scFA VFA1 (g VFA/kg TS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated Straw</td>
<td>7.4</td>
<td>890</td>
<td>940</td>
<td>2</td>
</tr>
<tr>
<td>Extruded Straw, 80°C</td>
<td>6.5</td>
<td>850</td>
<td>940</td>
<td>4</td>
</tr>
<tr>
<td>Extruded Straw, 100°C</td>
<td>6.1</td>
<td>840</td>
<td>940</td>
<td>3</td>
</tr>
<tr>
<td>Untreated Maize silage</td>
<td>4.0</td>
<td>390</td>
<td>950</td>
<td>4</td>
</tr>
<tr>
<td>Extruded Maize silage, 40°C</td>
<td>3.9</td>
<td>400</td>
<td>950</td>
<td>9</td>
</tr>
<tr>
<td>Extruded Maize silage, 60°C</td>
<td>3.9</td>
<td>380</td>
<td>950</td>
<td>7</td>
</tr>
</tbody>
</table>

1Small chain VFA content, extraction method described above in section 4.2.2
Table 5.4: Results from the substrate analysis performed at the German laboratory, Blgg.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>TS (g TS/kg ww)</th>
<th>VS (g VS/kg TS)</th>
<th>totVFA (g VFA/kg TS)</th>
<th>totVOC (g VOC/kg TS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated Straw</td>
<td>935</td>
<td>960</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded Straw, 80°C</td>
<td>869</td>
<td>955</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untreated Maize</td>
<td>364</td>
<td>984</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Extruded Maize, 40°C</td>
<td>401</td>
<td>980</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

The characteristics of the extruded and untreated maize silage and straw are presented in tables 5.3 and 5.4. TS content for maize silage increased slightly by extrusion according to both analysis. It seems that the high temperatures in the extruder made water inside the substrate to evaporate. The TS content of straw did on the other hand decrease, probably because the extruder had been used for other materials before and condensate inside the extruder made the straw damper. The VS content was not affected by extrusion.

The total content of VFAs and VOCs decreased during the extrusion, which probably can be explained by the heat created in the extruder which made some volatile organics to volatilize. The most abundant VOC analyzed in these substrates were ethanol, acetic acid and butyric acid. They have boiling points of 75-165°C (Young et al., 2003). The extruding of straw gave temperatures of over 100°C. The VFAs that were left were more easily available according to the analysis in Table 5.3 probably because the substrates were pulverized to some extent in the extruder. No increase of fibers in the maize silage was seen i.e. 10% decrease in TS content and 7-10% in fiber content and the decrease in fibers can therefore be explained by the evaporation of water (Table. 5.5).

Table 5.5: Results from the substrate analysis of the fiber content: crude fiber (CF), Acid detergent fiber (ADF), Neutral detergent fiber (NDF) and Acid detergent lignin (ADL).

<table>
<thead>
<tr>
<th>Substrate</th>
<th>CF % ww</th>
<th>ADF % ww</th>
<th>NDF % ww</th>
<th>ADL % ww</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated Straw</td>
<td>44</td>
<td>55</td>
<td>80</td>
<td>11</td>
</tr>
<tr>
<td>Extruded Straw, 80°C</td>
<td>31</td>
<td>43</td>
<td>68</td>
<td>8</td>
</tr>
<tr>
<td>Untreated Maize silage</td>
<td>8</td>
<td>10</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>Extruded Maize silage, 40°C</td>
<td>9</td>
<td>11</td>
<td>18</td>
<td>1</td>
</tr>
</tbody>
</table>

The fiber content in straw on the other hand decreased much more than is expected from the decrease in TS content. The decrease in TS content was 7% and the decrease in fiber content was 30, 23 and 15% for straw. The decrease in lignin for straw was 25%. It seems that extrusion decreases both fiber and lignin content in straw, which should make it more available for enzymatic degradation and thereby increase its biogas yield (Jördening & Winter, 2005).
During the extrusion of straw a dust of small straw particles was created and was lost into the air. This could probably be a problem of lost substrate and also affect the working environment negatively. To avoid this problem a cover of the belt conveyor and the opening of the extruder should be introduced. During the experiment, the extruder had to be fed continuously. For a biogas plant is it probably better to have a larger container which can be filled up once and that feeds the extruder automatically. The extruder could also handle hard material like green waste (branches, twigs and leaves) and according to manufacturer make that available for anaerobic digestion.

5.2.2 Biogas production potential of extruded and untreated maize silage

The methane yield per TS of extruded and untreated maize silage are presented in Fig.5.5. The production did differ a lot for maize silage among the replicates (Appendix B). This could probably be explained by the heterogeneity of the substrate. To calculate the economical benefits of a extruder is a yield needed that shows the maximum yield that is possible to achieve by pretreatment after optimization. The two replicates that are similar have higher yield than the one that looks like a outlier and shows the potential of the extruder. Therefore a mean value of those two was used in the following graphs and later used for the economical calculations.

Maize silage from Italy and Sweden was used in this batch digester experiment to compare the substrate used in the extruder test with the one used in the steam explosion test. Swedish maize silage had a 9% higher methane yield if treating the third replicate as a outlier or 1% lower yield if not. It seems that they give about similar yields. After 3 days the extruded maize silage at 60°C had 63% higher methane yield than the untreated. Because of the low replication when the potential outlier was excluded this result could not be statistically verified. (Tukeys test $p < 0.05$). The extruded maize silage at 40°C had a methane yield of 12% less than the untreated maize silage at the same time. Thus it seems that temperature of the extruder is important for the outcome of the pretreatment.

![Figure 5.5: Methane yield per TS for extruded and untreated maize silage after 3, 12, 31 and 44 days. The error bars show the standard deviation within the replicates.](image-url)
At the end of the incubation, after 44 days, the methane yield of the extruded maize at 60°C was still higher than for the untreated samples, 4.7%. It seems that extrusion also increases the total biogas potential of maize silage. This could however not be verified statistically (Tukeys test $p < 0.05$) and if not treating the potential outlier as a outlier the yield is instead 5% lower. The extruded maize at 60°C gave 78% of the theoretical yield which is 442 Nl CH$_4$/kg VS maize silage (Bauer et al., 2010). The methane content of the produced gas ranged from 45 to 49%. The lowest methane content was detected in gas produced from the extruded maize at the highest temperature, 60°C.

5.2.3 Biogas production potential of extruded and untreated straw

After 3 days, the extruded straw at 80°C had the highest methane yield, 85% higher than the untreated straw (Table 5.6). The extruded straw at 100°C at the same time had 69% higher methane yield than for the untreated straw. Thus, extruded straw is significantly faster degraded than untreated straw (Tukeys test $p < 0.05$).

![Figure 5.6](image)

**Figure 5.6:** Methane and biogas yields per kg TS after compensating for negative control for untreated and extruded straw after 3, 12, 31 and 44 days. The error bars shows the standard deviation within the replicates.

At the end of the incubation, 44 days, the methane yield was highest for the extruded straw of 100°C, i.e. 22% higher methane yield than the untreated straw. This is indicating that extrusion increases the total biogas potential of straw. This could however not be verified statistically (Tukeys test $p < 0.05$). The extruded straw at 100°C gave after 44 days, 57% of the theoretical yield, which is 436 Nl CH$_4$/kg VS substrate for wheat straw (Bauer et al., 2010). The methane content of the produced was 50-52%.
5.3 BE 3; Waste chicken feathers

5.3.1 Steam explosion of chicken waste feathers

Steam exploded feathers are shown in Fig. 5.7. Steam explosion of waste chicken feathers changed the feathers into a wet beige powder that formed lumps with a consistency of rubber. The treatment improved the smell, decreased the particle size, increased the density and made the substrate more homogenous. Higher temperature made the color of the substrate darker and made the particle size visibly smaller. Steam explosion reduced the volume of the feathers from 5 liters to approximately 1-1.5 liters.

![Figure 5.7: Feathers after steam explosion with steam at different temperature. A shows untreated chicken waste feathers. B shows steam exploded chicken feathers at 190°C for 10 min, C at 180°C for 10 min and D at 165°C for 10 min. Photo: Ylva Borgström](image)

Table 5.6: Results from the substrate analysis for steam exploded, lime treated and untreated chicken waste feathers.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>pH1</th>
<th>TS</th>
<th>VS</th>
<th>tot VFA2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g TS/kg ww</td>
<td>g VS/kg TS</td>
<td>g VFA/kg TS</td>
</tr>
<tr>
<td>Untreated feathers</td>
<td>5</td>
<td>370</td>
<td>940</td>
<td>1.4</td>
</tr>
<tr>
<td>Steam exploded feathers, 165°C</td>
<td>-</td>
<td>240</td>
<td>990</td>
<td>0.3</td>
</tr>
<tr>
<td>Steam exploded feathers, 180°C</td>
<td>-</td>
<td>190</td>
<td>990</td>
<td>0.8</td>
</tr>
<tr>
<td>Steam exploded feathers, 190°C</td>
<td>5</td>
<td>70</td>
<td>990</td>
<td>0.3</td>
</tr>
<tr>
<td>Limetreated feathers</td>
<td>8</td>
<td>40</td>
<td>870</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Changes in characteristics of steam exploded feathers versus untreated feathers are given in table 5.6. pH of the feathers was low at the beginning and was not affected by steam explosion. The VS content increased by steam explosion and some VFA was lost by evaporation in the steam. The VFA concentrations in the analyzed condensate water were however below the detection limit.
5.3.2 Lime treatment of chicken waste feathers

The lime treatment did not make much visible change to the feathers. It increased pH from 5 to 8. In the master thesis by Kashani (2009) where this method had been tried before a much higher pH was reached (up to 10) and had to be neutralized by carbon dioxide flushing before it could be used as a substrate. This was not necessary here. The characteristics of lime-treated feathers are given in Table 5.6. The decrease in VS is explained by the added lime. 100 g slaked lime/kg TS substrate was added and accordingly a decrease of 70 g VS/kg TS could be detected. Slaked lime, $Ca(OH)_2$, decomposes to lime, CaO, and water at 512°C (Halstead & Moore, 1957) and decomposes accordingly in the oven of 550°C used for VS analysis. The formed water, which is about 24 g of water from 100 g of slaked lime, evaporates and left is 76 g of lime which may explain the decrease in VS.

5.3.3 Biogas production potential of waste chicken feathers

The lowest temperature of steam explosion, 165°C, resulted in the significantly highest methane yield (Tukeys test p=0.05) i.e. 141% higher yield than the untreated (Fig. 5.8). Thus, steam explosion is increasing the total biogas potential of the chicken feathers.

The reason why the lowest temperature gave the highest biogas yield is not certain. When keratin is degraded ammonia and nitrates are formed (Coward-Kelly et al., 2005) which are inhibitors of anaerobic digestion at high concentrations (Deublein & Steinhauser, 2008). If more keratin is degraded at higher temperatures and thereby more ammonia and nitrate are formed this may explain the lower methane yield achieved at higher temperatures. The methane yield for the lime-treated chicken feathers where also significantly higher, 52%, than for the untreated (Tukeys test p=0.05).

---

1 pH was here analyzed using lacmus paper
2 Easy available VFA content, extraction method described above in section 4.2.2
The yields of the pretreated samples were higher already after 5 days, which indicates that steam explosion and lime treatment makes anaerobic digestion of the chicken feathers faster. This was statistically verified for steam exploded feathers at 165°C (Tukeys test p=0.5). The methane yield of steam exploded feathers at 165°C was 403 Nl CH₄/kg VS substrate, 82% of the theoretical methane yield of chicken feathers which is 490 Nl CH₄/kg VS substrate (Kashani, 2009). The methane content in the produced biogas was 59-61%.

5.4 BE 4; steam exploded wheat and maize

5.4.1 Steam explosion of lignocellulosic rich substrates

Steam exploded wheat straw, maize silage and wheat silage are shown in Fig. 5.9. Steam explosion made the plant substrates into a brown muck with the scent of burned sugar. Some fibers could still be seen in the muck and they had the same length as the pieces of substrate before treatment. Steam explosion increased homogeneity, decreased particle size and increased the density of the substrates.

![Figure 5.9](image)

**Figure 5.9:** In this picture you can see how maize silage (1), wheat silage(2) and straw (3) changes after treatment by steam explosion. (a) is before treatment and (b) is after.

The changes in characteristics of the substrates after steam explosion are presented in Table 5.7. The most significant change is the difference in TS, especially in the case of straw. When steam exploding straw for some reason some water did stay in the substrate. According to Pål Jahre Nilsen at Cambi, steam exploded straw is normally dryer. The VFA content got a bit lower after steam explosion probably because some volatiles went away with the steam. This would according to Pål Jahre Nilsen not have happened in a large scale THP, where the steam would have stayed in the system and the VFA would have become a part of the substrates sooner or later. In the pilot plant the steam was not circulated and not re-used.

In the VFA analysis of the condensate only the content of acetic acid could be detected, 5.4 g acetate /kg VS for maize silage. Calculated from the theoretical methane yield of
acetic acid this makes a theoretical loss of 21 Nl CH\textsubscript{4}/kg TS substrate (6\% of the total methane yield). Acetate has a boiling point of 118°C and should therefore evaporate in the steam at the temperatures used in the tests (180-200°C).

Table 5.7: Results from the substrate analysis for extruded and untreated maize silage and straw.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>pH</th>
<th>TS</th>
<th>VS</th>
<th>tot.e.a.VFA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g TS/kg ww</td>
<td>g VS/kg TS</td>
<td>g VFA/kg TS</td>
</tr>
<tr>
<td>Untreated maize silage</td>
<td>3.7</td>
<td>330</td>
<td>960</td>
<td>6</td>
</tr>
<tr>
<td>Steam exploded maize silage</td>
<td>4.1</td>
<td>240</td>
<td>960</td>
<td>5</td>
</tr>
<tr>
<td>Untreated wheat silage</td>
<td>4.0</td>
<td>450</td>
<td>910</td>
<td>8</td>
</tr>
<tr>
<td>Steam exploded wheat silage</td>
<td>4.0</td>
<td>190</td>
<td>910</td>
<td>5</td>
</tr>
<tr>
<td>Untreated straw</td>
<td>4.4</td>
<td>840</td>
<td>940</td>
<td>3</td>
</tr>
<tr>
<td>Steam exploded straw</td>
<td>4.4</td>
<td>780</td>
<td>950</td>
<td>2</td>
</tr>
</tbody>
</table>

According to analysis of the Italian maize silage by the German laboratory the total amount of acetate was 17.5g/kg which was 6.2g acetate/kg VS, thus a loss of 5.4g acetate/kg VS is not unrealistic. At steam explosion in a pilot plant the loss in methane yield is normally 5-15\% according to Pål Jahre Nilssen at Cambi. The analysis of the condensate water was only done for maize silage. When only acetate may contribute to a loss of 6\% is it not unlikely that all VOC together make up for a loss of methane yield of 15\%. Therefore is a minimum compensation of 5\% and a maximum compensation of 15\% made for the biogas production potential results to compensate for lost VFAs for maize silage and wheat silage.

5.4.2 Biogas production potential of steam exploded maize silage

After 3 days, the steam exploded maize silage had significantly, 14\%, higher methane yield than the untreated straw or 41-67\% higher if compensating for the lost VFA (Fig. 5.10)(Tukey test $P < 0.05$). Thus, steam explosion makes maize silage degrading faster.

At the end of incubation, after 44 days, the methane yield was highest for the untreated maize silage irrespective of compensation or not for VFA loss. This shows that steam explosion of maize silage decreases the total methane yield. This could be verified statistically (Tukeys test $p < 0.05$). The theoretical methane yield for maize silage is approximately 442 Nl CH\textsubscript{4}/kg VS substrate (Bauer et al., 2010). Steam exploded maize silage gave after 44 days 317 Nl CH\textsubscript{4}/kg VS substrate which is 72\% of the theoretical yield. The methane content of the produced biogas was about 53\%.
### Biogas production potential of steam exploded wheat silage

After 3 days, the steam exploded wheat silage had a 20% higher methane yield than the untreated control or 26-38% higher if compensating for the lost VFA (Fig. 5.11). This indicates that steam exploded wheat silage is digested faster than untreated. This could be statistically verified if compensating for lost VFA (Tukeys test $p < 0.05$). The content of the produced biogas was about 53%.

**Figure 5.10:** Methane yield of untreated and steam exploded (THP) maize silage after compensation for negative control and with a minimum* and maximum** compensations for VFA loss.

<table>
<thead>
<tr>
<th></th>
<th>Untreated</th>
<th>THP maize</th>
<th>THP maize*</th>
<th>THP maize**</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 days</td>
<td>63</td>
<td>88</td>
<td>93</td>
<td>102</td>
</tr>
<tr>
<td>11 days</td>
<td>118</td>
<td>167</td>
<td>175</td>
<td>192</td>
</tr>
<tr>
<td>33 days</td>
<td>347</td>
<td>296</td>
<td>311</td>
<td>341</td>
</tr>
<tr>
<td>44 days</td>
<td>365</td>
<td>305</td>
<td>320</td>
<td>351</td>
</tr>
</tbody>
</table>

**Figure 5.11:** Biogas yield and methane yield of untreated and steam exploded (THP) wheat silage at 200°C during 10 min. The error bars shows the standard deviation within the replicates.

At the end of incubation, after 44 days, the methane yield was 11% higher for the steam exploded wheat silage than the untreated (17-28% if compensating the lost VFA). It seems that steam explosion increases the total methane yield of wheat silage, but this could only be statistically verified not even if compensating for the lost VFAs (Tukeys test $p < 0.05$).
5.4.4 Biogas production potential of steam exploded straw

After 3 days, the steam exploded wheat straw had a 62% higher methane yield than the untreated (Fig.5.12). Thus, steam exploded wheat straw is significantly faster degraded than untreated (Tukeys test $p < 0.05$). However at the end of the incubation, the methane yield was highest for untreated straw, 8% higher than treated. Thus, steam explosion does not increase the total methane yield of straw.

![Figure 5.12: Biogas and methane yield of untreated and steam exploded (THP) straw at 200°C during 10 min. The error bars shows the standard deviation within the replicates.](image)

The theoretical methane yield for straw is approximately 440 Nl CH$_4$/kg VS substrate (Bauer et al., 2010) and steam exploded straw gave after 44 days 205 Nl CH$_4$/kg VS substrate, less than half of the theoretical yield. The methane content of the produced biogas was 53% for the untreated and 55% for the steam exploded straw.

5.5 Controls for the batch experiments

Figures of the methane production in all controls of all batch trials are presented in Appendix B (Fig. B.1 and B.2) The biogas production of the triplicates of all the controls except the positive control of batch trial 1 followed each other. The difference in batch trial 1 is probably due to inexperiences during the first trial. The blank controls are gradually descending like they should since no methane gas is produced in a bottle with only water.

The positive controls are showing methane production in all four batches. After 44 days with the same inoculum the yield for the same positive control ranges between 270 and 340 Nl CH$_4$/kg VS for batch 2, 3 and 4. BE 1 which was stopped after 31 days had already reached a methane yield of 350 Nl CH$_4$/kg VS substrate. This shows signs of a better biogas production with the inoculum used during trial with inoculum from Nykvarn sewage plant. The theoretical methane yield of the positive control is 418 Nl CH$_4$/kg VS. The differences between the positive controls in the different trials makes it hard to compare the results between the trials. The reason why the positive controls differs is probably because of the inoculum. The inoculum for batch trials 2, 3 and 4 were
all taken from Falkenberg biogas plant, but with weeks between and since the inoculum consists of living bacterias it could change a lot over time. Fresh samples of inoculum where collected 1-3 days before every batch experiment.

The negative controls with only inoculum from Falkenberg biogas plant produced gas with a methane content of 65-70%. This is a high methane content and tells us that the sludge from Falkenberg biogas plant still had organics available for anaerobic digestion left after the biogas process, possibly a high content of VFAs and that the anaerobic digestion therefore still was ongoing. The gas produced from the inoculum from Nykvarn sewage plant had a lower methane content of 45%.

5.6 Economics

5.6.1 Economics of dewatering

During the manure separation field test in Haverbeck two major groups of dewatering equipment were demonstrated: decanter centrifuges and screw presses. Approximate data gathered from the companies from the field test are summarized in table 5.8. The economical values of these equipments are compared with splitbox Agri, the equipment used in this master thesis. As can be seen Splitbox Agri has the highest cost per treated ton manure when the equipment is used at its maximum capacity. Splitbox Agri has a higher energy demand and lower capacity. However in the Splitbox Agri, struvite is precipitated. Struvite has a economical value and can be sold. A Splitbox Agri, cost approximately 2.5 million SEK, the operational costs are about 175 kSEK/year, energy demand is 75 MWh/year and it has a maximum capacity of about 15 000 ton manure/year according to Jan Broberg of Splitvision.

Table 5.8: Approximate prizes and data for different pretreatment systems based on data gathered from the companies showing their equipment at the manure separation field test in Haverbeck and from Splitvision. ND- stands for no dewatering and shows the approximate prize of transporting untreated manure 15 km.

<table>
<thead>
<tr>
<th></th>
<th>Screw press</th>
<th>Centrifuge</th>
<th>Splitbox</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prize, million SEK</td>
<td>0.2-0.5</td>
<td>5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Capacity ton/ year</td>
<td>4000-8000</td>
<td>8000</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Operational costs kSEK/year</td>
<td>20-40</td>
<td>250</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Energy demand kW</td>
<td>5-15</td>
<td>10-11</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Cost SEK /ton raw manure</td>
<td>2.5-5</td>
<td>15</td>
<td>45.7</td>
<td></td>
</tr>
<tr>
<td>Cost incl. transport 15 km SEK/ton</td>
<td>15-25</td>
<td>22</td>
<td>55-62</td>
<td>60</td>
</tr>
</tbody>
</table>

In table 5.9 the economics for two scenarios using a Splitbox Agri for dewatering of cow manure is given. In both scenarios the maximum capacity of the equipment, 15000
ton/year is used, since these amounts of manure are not unusual for a larger cattle farm in Sweden according to Jonas Simonsson, Falkenberg Biogas. The difference between the two scenarios is the distance between the farm and the biogas plant which is 15 km in scenario 1 and 37 km in scenario 2. The methane yields used for the calculations were based on the yields achieved in the batch digester experiments after 31 days, 250 Nl CH4/kg TS substrate for untreated and 180 Nl CH4/kg TS substrate for dewatered manure.

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure, ton ww</td>
<td>15 000</td>
<td>15 000</td>
</tr>
<tr>
<td>Distance to the farm, km</td>
<td>15</td>
<td>37</td>
</tr>
<tr>
<td>Utilization of Splitbox</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Cost of dewatering, SEK/ton</td>
<td>45.7</td>
<td>45.7</td>
</tr>
<tr>
<td>Cost of dewatering, SEK/MWh</td>
<td>236.9</td>
<td>236.9</td>
</tr>
<tr>
<td>Extra costs sek/a</td>
<td>685</td>
<td>685</td>
</tr>
<tr>
<td>Surplus CH4 yield Gwh/a</td>
<td>-1.3</td>
<td>-1.3</td>
</tr>
<tr>
<td>Surplus revenue, SEK/a</td>
<td>-106</td>
<td>694</td>
</tr>
<tr>
<td>Surplus result, kSEK/a</td>
<td>-791</td>
<td>8.4</td>
</tr>
<tr>
<td>Payback time, year</td>
<td>-</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 5.9: Economics calculated for a farm situated 15 resp. 37 km from a biogas plant investing in a Splitbox Agri, dewatering equipment. Extra costs are the operational costs and investment costs for a splitbox agri. Surplus revenue are the revenue from surplus methane yield, struvite and revenues from lower transportation costs.

For a farm producing 15000 ton stable cow manure/year on a distance of 15 km from a biogas plant dewatering with Splitbox Agri equipment is not a profitable option. When the farm is situated more than 37 km away from the biogas plant is it cheaper to dewater the manure with a a Splitbox Agri prior to transport than to transport the manure untreated. This does, however, not have to imply that dewatering makes it profitable to use manure so far away from the biogas plant.

5.7 Economics of extrusion

An extruder from Promeco costs approximately 4 million SEK according to Paolo Rebai at Promeco. According to him the operational costs when running the equipment at maximum capacity are around 10% of the investment or 4.7 SEK/ton. The capacity is around 70 000 ton ww per year and the energy demand is 150-180 kW. One of the aims of this report was to investigate if it would be economically beneficial to install an extruder on the reference plant. To analyze these three scenarios were established.
Table 5.10: Economics calculated for three different scenarios with an extruder. The first and second scenario illustrates two cases for the reference plant. The last scenario illustrates a case, where the extruder is used at its maximum capacity. Extra costs are the operational cost and capital investment for a extruder and surplus revenue is the revenue from the surplus methane yield.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize silage, ton ww</td>
<td>12 500</td>
<td>12 500</td>
<td>70 000</td>
</tr>
<tr>
<td>Horse manure, ton ww</td>
<td>11 500</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Utilization of extruder, %</td>
<td>34</td>
<td>18</td>
<td>98</td>
</tr>
<tr>
<td>Cost of extrusion, SEK/ton</td>
<td>52</td>
<td>87</td>
<td>26</td>
</tr>
<tr>
<td>Cost of extrusion, SEK/MWh</td>
<td>61</td>
<td>79</td>
<td>24</td>
</tr>
<tr>
<td>Extra costs, kSEK/a</td>
<td>1 235</td>
<td>1 085</td>
<td>1 837</td>
</tr>
<tr>
<td>Surplus CH4 yield, GWh/a</td>
<td>2.6</td>
<td>1.3</td>
<td>7.2</td>
</tr>
<tr>
<td>Surplus revenue, kSEK/a</td>
<td>1 720</td>
<td>840</td>
<td>4 705</td>
</tr>
<tr>
<td>Annual result, kSEK</td>
<td>485</td>
<td>-244</td>
<td>2 868</td>
</tr>
<tr>
<td>Payback time, year</td>
<td>3.4</td>
<td>9.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The calculations are based on the assumption that the methane yield of maize silage could be increased from 281 to 310 Nl CH₄/kg TS substrate while for straw from 179 to 226 Nl CH₄/kg TS substrate by extrusion and horse manure from 161 to 203 Nl CH₄/kg TS substrate. These yields are based on the results from the batch experiments. The methane yields after 31 days of incubation were used, since the retention time for the reference biogas plant is around 30 days. The economy would be different for a biogas plant with longer retention time since the yields for untreated and treated substrates differ more at 30 days than at 44 days.

If the reference plant gets horse manure with straw as bedding material extrusion could be an economical beneficial option. Calculations based on a substrate usage of 12 500 ton ww of maize silage and 11 500 ton ww of horse manure makes an annual profit of 485 000 SEK. If the reference plant gets horse manure with another bedding material or if the straw in the horse manure is not affected by extrusion as the straw was in the batch experiment, only maize silage should be pretreated. However then the use of an extruder at the reference plant is not profitable (scenario 2). If the extruder can be used at its maximum capacity pretreating maize silage, then it would make an annual profit of 2.9 million SEK (scenario 3).
5.8 Economics of steam explosion

A large scale THP unit costs around 50-70 million SEK and the operational costs are approximately 2-2.5% of the investment according to Pål Jahre Nilssen at Cambi. The capacity can be 10 000-70 000 ton TS/year. One of the aims of this report was to investigate if it would be economically beneficial to install an THP unit on the reference plant. To analyze this four scenarios were established.

Table 5.11: Economics calculated for 4 different scenarios using steam explosion: The first, second and forth scenarios illustrates three cases for the reference plant. The third scenario illustrates a case, where the THP is used at its maximum capacity. Extra costs are the operational cost and capital investment for a THP and surplus revenue is the revenue from the surplus methane yield.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feathers, ton ww(^1)</td>
<td>5 000</td>
<td>5 000</td>
<td>0</td>
<td>5 000</td>
</tr>
<tr>
<td>Horse manure, ton ww</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11 500(^2)</td>
</tr>
<tr>
<td>Wheat silage, ton ww</td>
<td>0</td>
<td>12 500</td>
<td>66 000</td>
<td>0</td>
</tr>
</tbody>
</table>

**THP with 100% heat re-utilization\(^3\)**

| Utilization of THPr, % | 6     | 25    | 99    | 17.5  |
| Cost of THP, SEK/ton   | 2 628 | 751   | 199   | 796   |
| Cost of THP, SEK/MWh   | 1 944 | 554   | 147   | 941   |
| Extra costs, kSEK/a    | 13 138| 13 138| 13 138| 13 138|
| Surplus CH\(_4\) yield, GWh/a | 2.1 | 6.0 | 27.3 | 3.5 |
| Surplus revenue, kSEK/a | 3 505 | 6 048 | 46 268 | 4 440 |
| Annual result, kSEK    | -9632 | -7090 | 287   | -8697 |
| Payback time, year     | 31    | 13    | 1.4   | 21    |

**THP with no heat re-utilization**

| Cost of THP, SEK/ton   | 2 675 | 943   | 450   | 985   |
| Cost of THP, SEK/MWh   | 1 979 | 696   | 332   | 1 165 |
| Extra costs, kSEK/a    | 13 374| 16 508| 29 687| 16 258|
| Annual result, kSEK    | -9 869| -10 461| -16 261| -11 817|
| Payback time, year     | 35    | 52    | -     | -     |

\(^1\)If feathers are used instead of maize silage

\(^2\)The used yield for steam exploded straw is a hypothetical yield based on earlier published results.

\(^3\)If all heat from steam explosion is used to heat other substrates. No extra energy needed.
The calculations were based on the assumption that the methane yield could be increased from 170 to 405 Nl CH\(_4\)/kg TS for feathers and 250 to 325 Nl CH\(_4\)/kg TS for wheat silage after pretreatment with steam explosion. These yields are based on the yields achieved after 26-33 days in the batch experiments. In earlier studies, 20-30% increase in methane yield with straw was reported (Bauer et al., 2009), (Bauer et al., 2010) and (Chen et al., 2005). Calculations using these data were therefore also made for comparison: i.e. 200 to 250 Nl CH\(_4\)/kg TS in scenario 4. The maize silage yield was not increased by steam explosion and was therefore not included.

The reference biogas plant would only use less than a fifth of the THP-unit capacity. No matter if calculations are made where all heat created can be used and no extra energy is needed for the steam explosion, the investment of a THP unit is still not profitable. If the THP unit is used at its maximum capacity and all heat is re-used, the investment makes a profit of 0.3 million SEK/year. Thus, for a very large biogas plant treating a lot of substrates hard to digest like wheat silage or feathers, a THP unit could be economically beneficial.
5.9 Answers to the research questions posted for this master thesis

5.9.1 Methane yield and rate of degradation

Does pretreatment by extrusion or/and steam explosion increase the total methane yield for lignocellulose-rich substrates like maize silage and straw?

Does it increase the rate of anaerobic digestion of the same substrates?

To answer this question fully larger laboratory experiments with more replicates would have been needed. Maize silage has a heterogenous composition, which make it hard to take out representative samples in the size needed for a bottle batch experiment. Because of this and because of the few replicates, no statistical verified answers to this question could be given.

The results seen in section 5.2.3 indicates however that extrusion at least increases the methane yield of straw. The analyzed changes in the characteristics of this substrate: less fibers, less lignin, smaller particle size after extrusion also point towards the fact that this pretreatment increases straws availability to anaerobic digestion and as a result of this also its methane yield.

The difference between the THP pilot plant used in the tests and a large scale THP plant, when keeping VFAs in the process or letting them disappear in the condensate water made it hard to evaluate this equipment. As much as 15% of the methane yield could have been lost in the THP pilot plant in form of VFAs. If compensating for this an increase in the total yield of wheat silage could be statistical verified. It seems justified to make such a compensation for maize and wheat silage.

Extrusion significantly increases the speed of anaerobic digestion of straw (Tukeys test $p < 0.05$). Extrusion also seemed to increase the rate of degradation of maize silage, but this could however not be verified statistically.

Steam explosion significantly increases the speed of anaerobic digestion of straw and maize silage (Tukeys test $p < 0.05$). It seems that it also increased the rate of anaerobic digestion of wheat silage, but this could however not be verified statistically.

Does pretreatment by lime treatment or/and steam explosion increase the total methane yield for chicken waste feathers? Does it increase the rate of anaerobic digestion of the same substrates?

Both lime treatment and steam explosion of chicken waste feathers significantly increased the total methane yield of chicken waste feathers (Tukeys test $p < 0.05$). Steam explosion at 165°C increased the yield close to the maximum theoretical yield. Steam explosion significantly increased the rate of anaerobic digestion of waste chicken feathers (Tukeys test $p < 0.05$). It seems that lime treatment also increased the rate of anaerobic digestion of feathers.
How is the methane yield of manure affected by dewatering with a Splitbox Agri?

The methane yield of solid manure dewatered with a Splitbox Agri is significantly lower per TS and VS, but significantly higher per wet weight compared to untreated manure (Tukeys test $p < 0.05$).

What are the benefits and drawbacks of using extrusion as pretreatment, could it be a profitable option for the reference plant?

The most important benefit of using extrusion as pretreatment is that it makes degradation faster, which allows smaller plants at a lower capital investment to produce the same amount of biogas as a large plant without extruder. Extrusion could probably also increase the total yield for many substrates. An extruder is a relatively cheap equipment and economical calculations seen in section 5.7 shows that a relatively small increase in methane yield is needed to cover the costs of the pretreatment. The equipment could after some changes be used automatically at the biogas plant and no more work should be needed to feed the extruder than was needed before to feed the biogasplant with substrates.

A point to be considered is that when extruding of dry substrates like straw dust is created which affects the working environment negatively and which leads to a loss of substrate. When extruding wet materials condensate water is instead formed which might make the metal parts inside the extruder to rust. When extruding maize silage and straw, gravel and stones could easily come along into the machine. This could wear out the parts in the extruder fast and could at worst make the equipment out of order. However, most parts in the extruder are changeable and these costs are covered in the economical calculations.

Another point to be considered is that the temperature seems to substantially affect the outcome of the pretreatment and the temperature is not easily adjustable. The temperature depend on how tight the exit hole of the extruder is and how hard and wet the extruded material is. It cannot be adjusted in a control system on a monitor like for the steam explosion, changing temperature takes time, when a operator needs to screw the hole tighter or looser by hand. This is hard to make perfect and could probably not be done in an easy way at changes of substrate compositions. However if the substrate comes from one silo, the substrate composition won’t change at all for month.

If the reference plant gets horsemanure with straw as bedding material, extrusion could be an interesting option. The results from this experiment show that this option is profitable. To just use the extruder for pretreatment of maize silage is not enough to make this pretreatment option profitable. Extrusion might also increase the yield and rate of degradation of other substrates which are not investigated in this report but could be interesting to look into if this option is chosen.
What are the benefits and drawbacks of steam explosion as pretreatment, could it be a profitable option for a biogas plant like the reference plant?

One great benefit of steam explosion is that it could make chicken waste feathers available as a substrate. Feathers without pretreatment are only partly degraded and end up in the biofertilizer, which not is popular among the farmers. Chicken feathers are a very cheap substrate that usually comes with a gate fee and according to the results it has a high methane yield. Steam explosion also increases the rate of anaerobic digestion of straw and maize silage and like the extruder allows smaller biogas reactors with the same biogas production as a larger one. It is easy to control the THP unit and it is easy to change temperature and pressure to optimize the process for different substrates. THP diminishes need for further hygienisation but the substrate needs to be cooled down after treatment before fermentation preferably with a heatexchanger to be able to use the energy.

One drawback is that steam explosion has a high demand of energy for steam production. However this also creates a lot of waste heat that could be used later in the biogas process. Thus, the economy of THP depends on a good concept for heat recovery. The most THP systems available on the market today comes with heatexchangers and are designed to have a good heat recovery.

The largest drawback of steam explosion is that a THP unit is very expensive. It costs about ten times as much as an extruder. This also makes operational costs high, when worn out parts needs to be changed. The high pressure and steam makes high operational risks. However, due to its high capacities it may be a beneficial economical investment for a very large biogas plant with a lot of substrates hard to digest like feathers and possibly also for straw. But for a plant of the size of the reference plant it is not a profitable option.

What are the benefits and drawbacks of lime treatment, could it be a economically beneficial option for a biogas plant like the reference plant?

There is no ready to use equipment for lime treatment on the market. All parts needed can be found, but the design of the process still needs to be made and to be evaluated. Lime is relatively cheap, but needs to be handled with caution. It could cause corrosion damages if exposed to moisture and it easily creates a dust which forces workers handling the lime to wear mask. A pretreatment, where the feathers needs to be boiled under 30 min could be fairly energy demanding. The large profits gained when making chicken waste feathers a possible substrate might make up for the high energy demand and the problems of lime handling.

During the experiments the feathers where not fully degraded after lime treatment. They would therefore not be suitable as a substrate because feather-parts would end up in the biofertilizers and the farmers do not want feather-parts on their fields. The results showed a significant increase in methane yield and it would be interesting to see if this pretreatment could be optimized for further degradation. It is not unlikely that this could be done based on the results of previous investigation of lime treatment by Coward-Kelly.
et al. (2006) and Kashani (2009). Lime treatment is not recommended for the reference plant. Further investigation of lime treatment is needed to fully explore its potential.

**What are the benefits and drawbacks of dewatering, could it be a profitable option for the reference plant?**

The greatest benefit of dewatering is the reduced cost of transportation due to the reduced volume. If a TS content of 30% is achieved, which was achieved after dewatering with the Splitbox Agri, the volume and cost of transport is reduced by 3 times (TS of dewatered manure is 8-12%). The dewatered manure seen in the manure separation field test in Haverbeck had reduced odour, which is a great benefit.

Drawbacks are lost biogas potential, when some of the organics end up in the water phase. The natural microflora in the manure could be affected by dewatering and some of the minerals in manure could also be lost.

Splitbox Agri, the only dewatering equipment evaluated entirely in this study, had relatively high operational and capital expenditures. Economical calculation for the dewatering equipment showed that the investment was not profitable for a farm situated on a distance of 15 km away from the biogas plant. In cattle rich areas like the area around the reference plant enough cattle to feed a normal size biogas plant with manure can be found within 15-20 km of distance. Therefore, investment of a Splitbox Agri is not profitable for a farmer connected to the reference plant. It is important to point out that these calculations are based on methane yield of dewatered solid manure, the conclusion might be different for liquid manure.

Some of the other equipment for dewatering evaluated in this study had lower operational cost and might therefore be more profitable. To verify this the methane yields of manure dewatered by these equipments are needed.

**Can new substrates like horse manure and feathers become possible for anaerobic digestion after a pretreatment equipment is installed?**

Steam explosion enables feathers and both steam explosion and extrusion enables straw and probably therefore also horse manure to become suitable as substrates for biogas production. This way the yield and rate of degradation is increased and the material is probably pulverized so much that the mechanical problems discussed in the introduction would no longer be a problem: straw or feathers getting stuck in pipes, creating floating layers in the reactor and preventing good stirring in the reactor. Feathers were almost fully degraded in this study which makes the digestate a suitable fertilizer.
Chapter 6
Conclusions

Pretreatment by extrusion increased the rate of degradation of straw and showed possibilities of increasing the total yield from straw. It made the substrate more available to anaerobic digestion because it increased the total accessible area for enzymes and bacteria. It seemed that extrusion also increased the rate of degradation of maize silage, but this could not be statistically verified.

Since extrusion is a relatively cheap pretreatment method, a small increase in methane yield could easily make the investment profitable for a biogas plant in the size of the reference plant. A pretreatment of 11500 ton horse manure with straw as bedding material and 12500 ton maize silage makes a profit of around 500 000SEK/year.

Pretreatment by steam explosion of straw, maize silage and chicken waste feathers increased the rate of degradation of the substrates. It increased the total methane yield of chicken waste feathers and after THP pretreatment at 165°C for 10 minutes were the feathers almost fully degraded by anaerobic digestion in 26 days. It is hard to know if the methane yield of maize silage, straw or wheat silage is increased by steam explosion out of the results in this trial, since it was hard to estimate how much VFAs that were lost in the pilot plant. VFAs would not have been lost in a large scale plant.

A THP unit is relatively expensive and has high operational costs. Steam explosion was therefore not a profitable option for the reference plant, a plant pretreating 11500 ton horse manure and 5000 ton feathers. The THP unit would have a high capacity and might therefore be a profitable option for a larger biogas plant running on a lot of recalcitrant substrates like feathers.

Dewatering of cow manure with a Splitbox Agri decreased the manure’s methane yield per kg TS, but increased its methane yield per kg wet weight. This made the substrate better for transportation. The money saved by lower transportation costs did, however, not cover the investment and the operational costs of a Splitbox Agri when the distance between the farm and the biogas plant was less than 40km. The distance between the biogas plant and farmer is normally much shorter.

A Splitbox Agri has relatively high operational costs and is relatively expensive. De-
canter centrifuges and screw presses have much lower costs per ton treated manure and might therefore make a more profitable option. To investigate this further methane yields for manure dewatered with such equipment are needed.

The only pretreatment technique that can be recommended for the reference plant after this study is extrusion. The rest of the evaluated pretreatment methods either need to be investigated further or have already in this study failed to be profitable options for this plant. For all pretreatment methods including extrusion further experiments are needed where the pretreated substrates are digested in a larger system, i.e. pilot plant and where the pretreated substrates are mixed together with the other substrates to be sure that the results are the same in a large scale biogas plant like the reference plant under normal conditions.
Bibliography


Cementa. 2010 (september). Pressrelease.


Appendix A

statistical analysis

Table A.1: Abbreviations used in the tables in this appendix and their meaning.

<table>
<thead>
<tr>
<th>Statistical abbreviations</th>
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</tr>
<tr>
<td>p1</td>
</tr>
<tr>
<td>p2</td>
</tr>
<tr>
<td>s</td>
</tr>
<tr>
<td>DF</td>
</tr>
<tr>
<td>k</td>
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<tr>
<td>m1</td>
</tr>
<tr>
<td>m2</td>
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<table>
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</tr>
<tr>
<td>d</td>
</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>E80</td>
</tr>
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<td>E100</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>s</td>
</tr>
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</tr>
<tr>
<td>s180</td>
</tr>
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<td>s200</td>
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Table A.2: Tukeys test with 95% confidence, the parameters used in the calculations and if one yield is significant higher that is showed under h. m1 and m2 stands for the meanvalue of the yield for different treatment. Abbreviations are explained above in Table A.1.

<table>
<thead>
<tr>
<th>days</th>
<th>yield</th>
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<th>p2</th>
<th>s</th>
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<th>k</th>
<th>N</th>
<th>q0.05</th>
<th>V</th>
<th>m1</th>
<th>m2</th>
<th>m2-m1</th>
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<tr>
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<td>d</td>
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<td>4</td>
<td>2</td>
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<td>28</td>
<td>57</td>
<td>127</td>
<td>70</td>
<td>p2</td>
</tr>
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<td>31</td>
<td>TS</td>
<td>u</td>
<td>d</td>
<td>19</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3.93</td>
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<td>179</td>
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<td>VS</td>
<td>u</td>
<td>d</td>
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<td>4</td>
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<td>3</td>
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<td>47</td>
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<td>98</td>
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**Table A.3:** Tukeys test with 95% confidence, the parameters used in the calculations and if one yield is significant higher that is showed under h. m1 and m2 stands for the meanvalue of the yield for different treatment. Abbreviations are explained above in Table A.1.

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Appendix B

Methane production

B.1 Controls for batch trial 1 and 2

Figure B.1: Accumulated methane in controls of BE1 and BE2.
B.2 Controls for batch trial 3 and 4

Figure B.2: Accumulated methane in controls of BE3 and BE4.
### B.3 Maize silage

**Figure B.3:** Accumulated methane in batches of maize silage.
B.4 Wheat straw

Figure B.4: Accumulated methane in batches of wheat straw.
B.5 Feathers

Figure B.5: Accumulated methane in batches of feathers.