System analysis of de-watering process for treating biogas digestate

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Abstract

Due to increasing production of biogas for transportation and other purposes, generation of biogas digestate is also increased. Biogas digestate is considered as an organic fertilizer which can potentially replace mineral fertilizer used for agricultural purpose as they contain rich soil and plant nutrient. Processing and logistics of the biogas digestate became a challenging opportunity due to presence of higher water content in the raw biogas digestate that is obtained from wet anaerobic digestion process. Many research groups and organizations are involved in designing a sustainable processing mechanism for biogas digestate so that they can be marketable and commercially available as bio-fertilizers. Among various identified processing options, de-watering is an important and mandatory process (solid-liquid separation) involved in full scale biogas digestate processing. This work is focused in systemic assessment of the environmental impacts associated with biogas digestate de-watering process using Life Cycle Impact Assessment (LCIA) methodology. Various operational options are considered for the de-watering process and analyzed accordingly. A comparison from environmental and economical perspective is made within the operational options to find out which one can be efficiently used.

**Key words:** Biogas digestate, Organic fertilizer, Life cycle analysis, De-watering.
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## Contents

1. Biogas digestate: a convenient truth about the by product ......................................................... 5  
   1.1 Aim and Objective ..................................................................................................................... 7  
2. Biogas digestate: a potential bio-fertilizer .................................................................................... 7  
   2.1 Digestate from biogas plant ...................................................................................................... 7  
   2.2 Processing of biogas digestate .................................................................................................. 10  
   2.3 Overview of biogas digestate processing technologies ............................................................. 13  
3. Life Cycle Impact Assessment of biogas digestate de-watering system ....................................... 15  
   3.1 Goal and Scope definition .......................................................................................................... 15  
   3.2 Studied system and boundaries .................................................................................................. 16  
   3.3 Data collection .......................................................................................................................... 19  
   3.4 Impact Categories ..................................................................................................................... 20  
   3.5 Inventory Analysis .................................................................................................................... 20  
4. Impacts analysis of the digestate de-watering system .................................................................. 21  
   4.1 Impacts due to Energy Consumption ...................................................................................... 22  
   4.2 Impacts due to Polymer Consumption .................................................................................... 23  
   4.3 Overall Impact Analysis ........................................................................................................... 24  
5. Possible findings from the Impact Analysis .................................................................................. 27  
6. Economical Analysis of the digestate de-watering system ......................................................... 30  
7. Concluding Discussions and Recommendations ........................................................................... 31  
8. References ...................................................................................................................................... 33  
9. Appendix A ..................................................................................................................................... 35  
10. Appendix B .................................................................................................................................... 40  
11. Appendix C .................................................................................................................................... 43  
12. Appendix D .................................................................................................................................... 45  
13. Appendix E .................................................................................................................................... 47  
14. Appendix F .................................................................................................................................... 49
1. Biogas digestate: a convenient truth about the by product

Production of biogas from wet waste is considered as a renewable source of energy from environmental aspects as it is carbon-di oxide neutral [10]. Anaerobic digestion (AD) in biogas plant is a well advanced and proven process where the organic matters are decomposed by the micro-organism in the absence of oxygen to produce biogas and wet digestate [1]. The biogas can be burned to produce heat and electricity, or it can be upgraded and compressed so that it can be used as transportation fuel.

The wet digestate is rich in plant and soil nutrients depending on the feedstock characteristic and can be used as bio-fertilizer via appropriate processing techniques. Use of biogas digestate as bio-fertilizer can possibly minimize the usage of mineral fertilizers, which will directly decrease the environmental impacts associated with life cycle of mineral fertilizers. The main barrier in using biogas digestate directly as bio- fertilizer is due to the reason that the digestate produced in the wet AD process contains higher amount of water which creates problem in logistics and nutrient availability. The distribution of nutrients, particularly nitrogen, Phosphorous and Potassium, in the digestate is mostly in dissolved and suspended form, hence processing of digestate to concentrate these nutrients could e a way of improving its fertilizing value and converting it to more a marketable bio-fertilizer product [10].

Identification and assessment of technological pathways for treating biogas digestate is being studied and researched in many institutions globally. There are also many successful cases where biogas digestate is treated and used as bio-fertilizers in full scale agricultural practices, replacing the mineral fertilizers [7]. Biogas Research Center at Linköping University (Sweden) is currently researching in this area in order to find a feasible solution to treat biogas digestate and produce bio-fertilizer for farming which complies with the Swedish policies and regulations (SPCR 120).

**Biogas Research Center (BRC)**

BRC is a center of excellence in biogas research funded by the Swedish Energy Agency, Linköping University and a number of external organizations with one-third each. BRC has a very broad interdisciplinary approach, bringing together biogas-related skills from several areas to create interaction on many levels – between industry, academia and society, between different perspectives, and between different disciplines and areas of expertise. BRC consist of eight projects which focus on improving existing biogas processes and systems as well as to achieve biogas solutions in new sectors and enable the use of new substrates [2]. BRC project.8 (DP8-Systems and technology for effective use of biofertilizers) deals with different possibilities to develop the treatment and management of biogas digestate in order to strengthen the total economics of biogas plants. Kemira Oyj and Svensk Biogas AB are partners with BRC who are also involved in this project.
**Svensk Biogas AB**

The Svensk biogas AB in Linköping was started with the aim of treating organic waste in southeastern Sweden. The biogas produced is upgraded and primarily used as transportation fuel for urban city buses thereby reducing the local, regional and global emissions from urban transport sector. The plant was commissioned in 1997 and is currently producing 100000 MWh of upgraded biogas annually. The biogas plant consist of four digesters (3 x 3800 m³, 1 x 6000 m³ capacity) and receives around 85000 tons of substrate per year. The substrate includes slaughterhouse waste, domestic organic waste and waste products from the food industries. The annual production of biogas digestate is around 81000 tons [3]. The digestate is stored in an open tank before being transported to the surrounding farmland. The digestate is certified according to SPCR 120, and currently about 30 farmers are using it in their culture [3]. The characteristic of the biogas digestate obtained from Svensk Biogas AB [17] is shown in table 1:

**Table 1: Characteristic of Biogas digestate produced from Svensk Biogas AB [17]**

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Nitrogen (N)</td>
<td>5.4 kg/m³</td>
</tr>
<tr>
<td>N- Ammonia</td>
<td>3 kg/m³</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>1.2 kg/m³</td>
</tr>
<tr>
<td>Phosphorous (P)</td>
<td>0.5 kg/m³</td>
</tr>
<tr>
<td>Dry Matter</td>
<td>4.5 %</td>
</tr>
</tbody>
</table>

**Kemira Oyj**

Kemira Oyj is a global, over two billion euro water chemistry company serving customers in water-intensive industries. During its 90 years of history, Kemira has gained deep knowledge and understanding in the water treatment industry. Kemira offers water quality and quantity management improving its customer’s energy, water, and raw material efficiency. Kemira has developed a wide range of leading technologies and chemical products that today serve the water treatment industries. Kemira headquartered in Helsinki is present in 40 countries, with around 5,000 employees and 71 sites [4].

Kemira is providing solution for de-watering process in waste water sludge and biogas digestate processing. Kemira’s broad experience in de-watering technology enables it to offer a sustainable way for biogas digestate processing. The improved dewatering system which is being developed and to be marketed by Kemira, considerably reduces the amount of polymers to be added in the process and also to a greater extent decreases the digestate volume to be handled by removing solid organic matter and phosphorous [4]. The separated solid fractions are rich in plant nutrients (N, P, and K) which can be used as organic fertilizer for farming. The liquid fraction contains nitrogen and potassium can be either used as organic fertilizer or can be taken for further treatment (Nutrient recovery).
Currently Bioga Research Center (BRC) and Kemira are conducting pilot plant study in this improved de-watering system which treats biogas digestate produced from Svensk Biogas plants. This report is associated with BRC project.8, which is focused in environmentally assessing and evaluating this de-watering system.

1.1 Aim and Objective

The main aim of this study is to analyze the environmental performance of biogas digestate de-watering system using Life Cycle Impact Assessment (LCIA) methodology. There are several indicators and tools for analyzing and evaluating the environmental performance of process/product (e.g. Material Flow Analysis (MFA), Life Cycle Life Cycle Impact Assessment (LICA), and Ecological Footprint, etc.). Among this, Life Cycle Impact Assessment (LCIA) is a well proven method to evaluate the possible utilization of resources and environmental performance of a process/product throughout its life cycle. However, LCA consumes lot of time and effort, still it is considered as a proven standardized tool and an assessment method to evaluate the environmental impacts of a product/ process. The studied de-watering system involves chemical and mechanical process for treating the wet raw biogas digestate. Two options are considered in this de-watering system: with and without digestate conditioning process (Kemira KemiCond®). Both the options are viable for treating digestate but when it comes to complying with Swedish policies and regulation which determines the usage of treated biogas digestate as bio-fertilizers, there are certain restrictions. With reference to this factor, the objective of this report is to perform a comparative analysis of these two options from system perspective view and to find which option highly complies with the Swedish policies and regulation for using processed biogas digestate as bio-fertilizer. Each option is evaluated with three possible mechanical separation (centrifuge, screw press and belt press) technologies to separate the solid from liquid in the treated digestate mixture.

2. Biogas digestate: a potential bio-fertilizer

2.1 Digestate from biogas plant

Biogas plants have started operating in great numbers throughout the world promoting renewable energy. Methane production by anaerobic digestion has been recognized as an efficient and proven way to reduce greenhouse gases according to the Kyoto protocol, which is also a critical factor that supports upcoming of the biogas plants [5]. Sweden has a tremendous development when it comes to production of biogas and its utilization as vehicle fuel. During the past decade in Sweden, the number of biogas plants and their capacity has increased to a greater extent. But still the demand for biogas is greater in many parts of Sweden. The production of organic wastes
and byproducts from biofuel sector enhanced the establishment of large scale biogas plants in Sweden. Biogas production by wet anaerobic digestion of the organic waste is not only a sustainable way to produce bio-energy, but also converts the biomass resources to nutrient-rich end product namely biogas digestate [5]. Biogas digestate is basically a by-product from biogas production which has an opportunity to contribute to the total economy of the biogas life cycle. These digestate contains a larger amount of mineral nitrogen (N) in the form of ammonium which is readily available for plants. It also contains other macro and micro nutrients which are essential for the growth of plants. Biogas digestate also used as soil conditioners as they can improve the physical, chemical and biological properties of soil [5]. The nature and quality of digestate is highly depended on the feedstock characteristics, type of conversion technology and also the efficiency of the digestion process used to produce biogas. A good digestate will be stabilized with and low in odour. A poorly digested product will contain readily degradable organic material, however it has risks of further degradation with release of odour during storage or after application to land [5].

The biogas digestate which provides guarantee of digestate quality independently and those accredited by the corresponding nation’s bio fertilizer certification scheme are termed as bio-fertilizer [21]. Biogas digestate is an alternative to mineral fertilisers, and using them as bio-fertilizer will improve the sustainability of cropping systems, also offsets the finances on purchased fertilizer [10]. The biogas digestate as a substitute to manufactured mineral fertilizers closes the natural nutrient and carbon cycle of the entire biogas production process (Figure 1).
Figure 1: Overall system for sustainable production of biogas from waste [23]

The raw digestate obtained from the digester will be either in solid (slurry) form or liquid form. Based on the dry matter content they are classified as liquid and the solid digestate. Dry matter (DM) content is defined as the total solids present in a compound or mixture excluding water. The solid digestate contains more than 15% DM content, while the liquid digestate contains less than 15% DM [23]. Solid digestate are cost effective for transporting to larger distances when compared to the liquid digestate and also it can be composted with other organic residues [6]. The value of biogas digestate as an alternative to the mineral fertilizer is highly based on the effectiveness of AD on nitrogen availability and also the effect of co-digestion on nutrient content. The micro and macro nutrients present in the feedstock are also available in the digestate after the digestion. During the AD process, certain bio-chemical reactions occur which modifies the nutrient structure in the feedstock and make it available for crops [10]. For example, the AD process coverts the organic nitrogen into ammonium. Therefore, amount of nitrogen in digestate is the same as in the feedstock, but the proportion of nitrogen in the form of ammonium is greater [6]. The averaged biogas digestate composition obtained from wet AD process is shown in table 2 which is gathered from different studies.
Apart from nutrients presented in the above table, traces of some microelement like copper, zinc, cadmium, mercury, lead are also present in small fractions. The amount of digestible organic solids that are fed inside the digester per unit time (Organic loading rate) and the average time that the digestible organic solids remains inside the digester (hydraulic retention time) are the major operational parameters which affects the quantity and quality of digestate characteristic [8]. The more the organic loading rate and less the hydraulic retention time, then the digestate will have more de-mineralized organic matter, which is not economic. Longer retention time leads to more effective AD process consuming most of the organic matters and the digestate contains less organic solids [8]. Hence there should be an optimal balance in the organic loading rate and the hydraulic retention time for producing a quality digestate which can be used as bio-fertilizer. As a fertilizer, biogas digestate are transported from the biogas plant to the farmlands where the crops receives majority of essential nutrients and the soil fertility is conserved.

### 2.2 Processing of biogas digestate

Wet AD mechanism involves addition of large amount of water for digestion process and hence the biogas digestate produced will contain more liquid (90-98%) and less DM (2-8%) [10]. Most of these liquid digestate are transported directly from biogas plants to farmlands via trucks, where they are directly applied on farming lands using conventional technologies. Application of liquid digestate in agriculture land is a well-known and proven technology [8]. However, to safeguard the groundwater resources the nutrients present in the soil needs to be evaluated firstly and the legal limits of maximum allowable nutrient loads should be followed. Particularly the European Nitrate Directive 91/676/CEE [9] limits the annual loads of nitrogen that can be applied on farming fields since higher load of nitrogen compound creates big hurdle in agricultural practice. The storage, logistics and application of the liquid digestate are very expensive. Due to these factors, development of appropriate processing techniques and volume reduction options for raw biogas digestate are gaining more importance. Biogas digestate processing involves similar kind of technological pathway for treating wastewater sludge. Biogas digestate are processed depending upon the local needs and specific purpose.
The main purposes for treating biogas digestate are as follows:

- To increase the nutrient value of the digestate;
- Treating digestate and converting them to bio-fertilizers thereby creating new markets scenario;
- Reducing the operating and logistic cost of the digestate handling.

The digestate processing can be categorized into partial processing (simple volume reduction) and complete processing (separation of digestate into solid fibers, mineral nutrients and clean water) from technical point of view [10]. Partial processing of biogas digestate (Fig. 2) involves the phase separation of digestate (Solid-liquid separation) and elimination of P$_2$O$_5$ using simple and normal technologies. Flocculants and digestate conditioning chemicals are added to the raw digestate to agglomerate the solid particles forming larger flocs. The separation is done by various mechanical processes (centrifuge, screw press etc) [10].

![Diagram of Partial processing of biogas digestate](image)

*Figure 2: Partial processing of biogas digestate [11]*

Complete processing of biogas digestate (Fig. 3) involves phase separation and elimination of P$_2$O$_5$ and Nitrogen using various technologies that require larger amount of chemicals and energy. Processing costs are usually high and there will also higher investment costs due to
appropriate machinery. A complete processing starts with solid-liquid separation like the partial processing [10].

**Figure 3: Complete processing of biogas digestate [11]**
2.3 Overview of biogas digestate processing technologies

The following processing options as shown in table 3 can be possibly used in treating biogas digestate [12].

### Table 3: Biogas digestate processing options [12]

<table>
<thead>
<tr>
<th>Processing option</th>
<th>Type of Processing</th>
<th>DM content in the products (%)</th>
<th>Solid fertilizer</th>
<th>Liquid fertilizer</th>
<th>Compost</th>
<th>Pellet Fertilizer (N,P,K)</th>
<th>Process Water</th>
<th>Waste Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional digestate management (CM)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>De-Watering (DW)</td>
<td>Partial Processing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Composting (CO)</td>
<td>Complete Processing</td>
<td>-</td>
<td>2.5</td>
<td>65</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Belt Dryer (BD)</td>
<td>Complete Processing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drum Dryer (DD)</td>
<td>Complete Processing</td>
<td>-</td>
<td>2.5</td>
<td>-</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Solar Drying (SD)</td>
<td>Partial Processing</td>
<td>70</td>
<td>2.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thermal concentrations (TC)</td>
<td>Complete Processing</td>
<td>25</td>
<td>3.5</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Physical Chemical treatment (PT)</td>
<td>Complete Processing</td>
<td>25</td>
<td>5.8</td>
<td>-</td>
<td>-</td>
<td>7.2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In conventional digestate management (CM) the untreated biogas digestate is stored in a digestate storage tank for a time period and then transported to farmlands by trucks and spread on farmlands using conventional methods for spreading liquid manure [12].

De-watering (DW) involves separation of the solids from the liquid fraction of biogas digestate. This involves both chemical and mechanical process. Chemicals and polymers are added to enhance the separation and separated by mechanical process (Centrifuge, belt press etc). The separated solid cake has higher dry matter content which can be directly used as fertilizer without any further processing. Sometimes, these separated solids are further treated to concentrate the dry matter content. Efficiency of de-watering depends upon the nature of the digestate and the
characteristics of residual particles following the anaerobic digestion process. For example, cellular level particles making up the dry matter content of digestate will not be separated efficiently, while undigested plant residues which are large in size can be separated efficiently. Hence the origin and quality of the digestate highly influence the de-watering process. The separated liquid contains majorly dissolved nitrogen and potassium, which is transported to the farmlands and spreaded over the farmlands using conventional methods or taken to further processing (Nutrient recover) [12].

Composting (CO) generally has three stages: mechanical pre-treatment, composting and manufacturing of the soil product. De-watering of biogas digestate into solid and a liquid phase is done in mechanical pre-treatment. Polymer is added to the digestate to increase the separation rate. The separated liquid is generally used for fertilizing purposes in the farmlands. The separated solid cake is dumped in heaps to undergo proper composting for 10 weeks. Closed windrow composting is done with occasional mixing for aeration. Drainage water is collected and recycled back to moisten the compost matter through the closed loop drainage system. After composting the heaps are moved to open storage boxes [12].

In the belt dryer (BD) process, the water content of the digestate is reduced to 20% by mixing the fresh digestate with already dried material. The hot air with a maximum temperature of 85 °C is blown over the substrate in the dryer. Then the dried digestate is conveyed to the pelletizing plant. To achieve optimal pellet consistency starch and lime flour are added. These pellets are used for fertilizing purposes in agriculture, landscaping and horticulture [12].

In the drying drum (DD) process, the biogas digestate is mechanically pre-treated and then it is continuously applied as a thin film on the rotating drum. The drum is rotated and heated from inside which makes the product to get dried on the surface of the drum. After drying the dried digestate is conveyed to the pelletizing plant [12].

The solar dryer (SD) reduces the water content of digestate by drying under direct sun light. Digestate is dried in solar-powered greenhouse-dryer covered with transparent polycarbonate sheets. Before drying, the digestate is mechanically pre-treated and the separated solid cake and liquid is taken for solar drying process [12].

The biogas digestate is separated into solid and liquid fractions using decanter before vaporization starts in the thermal concentration (TC) process. The solid cakes are directly applied on the farm without any further processing, while the separated liquid is vaporized to separate into specific ingredients and water. The separated liquid is heated up by hot steam and then boiling sulphuric acid is added to remove CO₂ and pH is increased (Acidic). This also converts ammonia into ammonium. As a result of the increase in pH value, gaseous losses of nitrogen are completely reduced. The CO₂ emission during the concentration process will be reduced by the
using antifoaming agent. Concentrated high nutrient content and condensed steam will be the outputs of concentration process [12].

In physical–chemical processing option (PT), the digestate is mechanically pre-treated where the separated solid cakes are transported to farmlands and used as fertilizers. The separated liquid is treated by ultra filtration which separates the substrate into permeate and retentate. Permeate is water with low-molecular substances and a retentate with the remaining concentrated high molecular substances which can be further treated by reverse osmosis to produce clean water. Retentates from ultra-filtration and reverse osmosis are rich in nutrients and used as fertilizer [12].

This study focuses on digestate de-watering system. Biogas digestate from Svensk biogas plants contains less DM (4.7%) and more liquid, hence it is important to separate the solid from liquid for efficient use and also to reduce the volume of digestate. The improved de-watering system which is being developed and to be marketed by Kemira reduces the volume of digestate to a greater extent by concentrating the solids and separating them from liquid. Chemicals and polyelectrolyte are added to increase the solid capture and to activate the digestate. The activated digestate is fed into a mechanical separator where solids are separated from liquid.

3. Life Cycle Impact Assessment of biogas digestate de-watering system

3.1 Goal and Scope definition

The main goal of this LCA study is to assess the environmental impacts associated with two options for improved biogas digestate de-watering system which is being developed and to be marketed by Kemira that treats digestate from Svensk biogas plants. The analyzed two de-watering system options (Option A&B) are studied in laboratory scale by Kemira and BRC. The two options are formulated by optimizing the addition of Kemira polymers and chemicals which seems to have direct impact on the effectiveness of the de-watering system and also the environment. Each de-watering option is analyzed with three mechanical separation techniques (Centrifuge, Screw Press and Belt press). LCA is conducted for six cases (two de-watering system option, each with three separation process) and analyzed in this study.

The selected functional unit (FU) of this study will be “Environmental impacts of treating 1 tonne of biogas digestate”. The advantage of this FU is that it serves as a functional equivalence to adequately compare the two options for a biogas digestate de-watering system studied in this report. The DM content in the raw and treated biogas digestate is also considered while performing the comparative analysis and to find which one is much efficient from product perspective.
3.2 Studied system and boundaries

To better describe and quantify the environmental impact of the biogas digestate de-wathering options and to provide essential recommendations, the de-wathering system options are categorized as Option A and B as per the Kemira polymers used and inclusion of KemiCond process. The description of the options is given in table 4.

**Table 4: Options for de-watering the digestate**

<table>
<thead>
<tr>
<th>Mechanical Separation Technique</th>
<th>Options for de-watering</th>
<th>Options for de-watering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifuge separator</td>
<td>A1</td>
<td>B1</td>
</tr>
<tr>
<td>Screw Press separator</td>
<td>A2</td>
<td>B2</td>
</tr>
<tr>
<td>Belt press separator</td>
<td>A3</td>
<td>B3</td>
</tr>
</tbody>
</table>

*Figure 4: System boundaries for the De-watering system options for treating biogas digestate*
**Kemira KemiCond® Process:**

Option B contains a specialized process called KemiCond. This process is a patented process developed by Kemira. It is used for conditioning the waste water sludge improving the effectiveness of sludge dewatering and also simultaneously hygienizes the sludge [13]. The de-watering system which involves KemiCond process consumes less polyelectrolyte compared to the de-watering system without KemiCond. KemiCond process starts with addition of sulphuric acid to raw sludge to make it acidic (pH<5). Dissolution of the inorganic salts (iron phosphates and calcium carbonates) takes place in the acidic medium thereby reducing the volume of sludge. In the next step, hydrogen peroxide is added to the acidified sludge which initiates the oxidation process. During this phase, re-precipitation of dissolved phosphorus occurs and the DM content is increased. Extracellular polymeric substances (EPS) are also oxidized, which improves the efficiency of dewatering and handling properties of the sludge. Addition of Hydrogen peroxide also reduces the odour and hygienizes the sludge [13]. KemiCond is already a proven process in the waste water sludge de-watering technology as it is operational in Oulu municipal waste water treatment plant (Oulu MWWTP) (Check Appendix F) [18]. Since biogas digestate has similar properties to the waste water sludge and biogas de-watering is an emerging opportunity, Kemira is now considering the use of KemiCond process in its lab scale biogas digestate de-watering system (Only in option B). A de-foaming agent manufactured by Kemira is added along with the sulphuric acid to prevent the foam formed during the acidification. Fe (II) Product which is a flocculant is added along with hydrogen peroxide, which activates the digestate mixture for flocculation process. Sodium hydroxide (buffer) is added to the oxidized digestate in order to normalize the pH (pH between 6 to 8) before starting the flocculation process. All these chemicals are produced by Kemira and used in this system. Details of chemicals added in KemiCond process is given in Appendix A.

**Flocculation Process:**

Flocculation of the solid particles present in the digestate mixture is achieved by addition of suitable polymers which are manufactured by Kemira. During this process the solid particles in the digestate agglomerate to form heavier particles which can be easily separated in the separation equipments. Kemira polymer 1 is used as flocculant in option ‘A’, whereas Kemira polymer 2 is used in option ‘B’ [17]. Description of the Kemira polymers used in given in Appendix A.

**Solid-Liquid separation technique:**

There are several solid-liquid separation techniques which could be used in the biogas digestate processing. However the accurate data availability regarding the separation efficiency and energy consumption for the separation equipments used in biogas digestate de-watering is very limited. In this study, Centrifuge, Screw Press and belt press are considered as the separation equipments as there are good data availability for these equipments which made this study easier.
Centrifuge separator is a high speed mechanical device which uses centrifugal force to separate fine solids and liquid in a mixture. Generally, polyelectrolyte is added to flocculate very fine particles before centrifuging. The amount of solids in feed, characteristics of feed, type of polymer used and feed rate influences the efficiency of separation and the performance of centrifuge. Centrifuge separator generally achieve a separation efficiency of greater than 95%, producing a separated solid that consist DM in the range of 18% to 35%, and a liquor of less than 0.3% DM [14].

Screw press separator takes the liquid out from the feed mixture by compressing them in a gradually decreasing screw channel between a screw shaft and screen mantle. The amount of solids in feed, characteristics of feed, type of the screen used and operational pressure are the major factors that influences the efficiency of the separation in a screw press. Screw Press separator can achieve 30–38% DM in the separated solid fractions. Screw press separator also tends to have solids-capture efficiency between 10% and 40% depending on the feed characteristics [14].

Belt press separator work in a similar way to screw presses, where the feed mixture is compressed between two tensioned belts which are passed through decreasing diameter rolls to squeeze out water. These tend to have higher separation efficiency and are often used to produce a cake output, rather than a fibre (DM) output [14].

**Option A (Kemira polymer 1 + Mechanical Separation)**
Option A1 uses Kemira polymer 1 and operates without KemiCond process. Flocculation occurs due to the addition of Kemira polymer 1. Then the agglomerated digestate is fed into the centrifuge separator which separates the solid from the liquid. In option A2, screw press separator is used instead of centrifuge, whereas remaining operation is same like option A1. Option A3 uses belt press separator for solid–liquid separation, whereas all other operation remains same to option A1.

**Option B (KemiCond + Kemira polymer 2 + Mechanical Separation)**
In option B1, KemiCond process is used to condition the digestate and then Kemira polymer 2 is added to flocculate the solid particles. Then the digestate is fed into centrifuge separator for separating the solids from the liquid. Option B2 contains all the operation similar to option B1, except that the centrifuge separator is replaced by screw press separator. In option B3, all the operation is similar to option B1, except that belt press separator is used in the place of centrifuge separator.
The materials added and the type of mechanical equipment used in each option is shown in table 5.

**Table 5: Amount of chemicals and polymer added along with the selection of separation equipment in the two biogas digestate de-watering options**

<table>
<thead>
<tr>
<th>options</th>
<th>KemiCond (kg / ton of dry solids)</th>
<th>Kemira Polymer 1 (kg / ton of dry solids)</th>
<th>Kemira Polymer 2 (kg / ton of dry solids)</th>
<th>Separation equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H₂SO₄ (97%)</td>
<td>H₂O₂ (100%)</td>
<td>Kemira defoamer</td>
<td>Fe (II)</td>
</tr>
<tr>
<td>A1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1</td>
<td>250</td>
<td>30</td>
<td>4.8</td>
<td>276</td>
</tr>
<tr>
<td>B2</td>
<td>250</td>
<td>30</td>
<td>4.8</td>
<td>276</td>
</tr>
<tr>
<td>B3</td>
<td>250</td>
<td>30</td>
<td>4.8</td>
<td>276</td>
</tr>
</tbody>
</table>

*Note: The ‘✓’ mark indicates that those process are considered in the system*

The data in the above table is taken from lab scale experimentations. The chemical and polymer consumption will be reduced when scaling up, for instance Kemira defoamer addition will be reduced by the factor of 4 when using in large scale. This study includes the environmental impact of all associated materials and energy flows used within the system boundary (fig.4). LCA of mechanical separator is not included in the study. Swedish electricity mix is the only source of energy considered here which is consumed by various unit processes (mixers and pump) within the system. Direct emissions from digestate due to mixing and processing are not accounted. Economical costs for transportation, disposal and hygienisation effects have not been considered in this study.

### 3.3 Data collection

In reality, this type of biogas digestate de-watering options doesn’t exist in large scale. Hence this LCA study is totally based on laboratory setup of Kemira and also based on various literature studies. Due to confidentiality, LCA data associated with the Kemira polymers and chemicals used in the de-watering systems are obtained from literatures and Ecoinvent 2.0 database. Ex: The LCA data of NaOH is taken from Ecoinvent database. A visit is made to the biogas digestate de-watering laboratory setup by Kemira at Linkoping University. The functioning of the system is observed and various associated experimental data are collected which are used in this study. A site visit is made to Oulu MWWTP operated by Kemira, in order to understand the functionality of KemiCond Process. This plant involves the KemiCond process for sludge conditioning and various data regarding the KemiCond process is collected which can be used in further studies. These data can be considered in the further analysis while scaling up this laboratory scale setup of the de-watering system and also upon the assumption that these data are
compatible for treating biogas digestate in large scale. The energy consumption for the separator
equipments are calculated with reference to literatures studies (table 7.).

3.4 Impact Categories
SimaPro Software (Version 7.3.3) is used to calculate the impacts associated with the studied de-
watering systems. EPD (Environmental Product Declaration) 2008 method is selected to assess
the life cycle impacts of the systems. EPD method is developed in accordance with the
international standard ISO 14025, which helps in calculating the impact categories for making a
standard EPD reports. The impact categories analyzed are global warming potential (GWP),
eutrophication potential (EP), photochemical oxidation potential (POP), ozone depletion potential
(ODP) and acidification potential (AP).

3.5 Inventory Analysis
Amount of sulphuric acid, hydrogen peroxide, Kemira defoamer, Fe (II) product, sodium
hydroxide, Kemira polymer 1 and Kemira polymer 2 consumed in the studied system are
obtained from the laboratory experimentation (Table. 5). The data used to calculate the LCA of
above mentioned chemicals and polymers are shown in Appendix A. Assuming that the density
of biogas digestate is similar to waste water slurry, energy consumption of the mixers and the
pumps used in the system are calculated accordingly. From the Ecoinvent data, the energy
consumption used by the mixer is approximately 0.4 kWh per 1 ton slurry. The energy
consumption for pumping slurry in a pipeline from housing to storage is in the range of 0.5 kWh
per 1 ton slurry [19]. Swedish electricity mix data are used in this study. These two data are used
in this study and shown in table 6.

<table>
<thead>
<tr>
<th>Table 6: Electrical energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy used</strong></td>
</tr>
<tr>
<td>Electricity for stirring 1 ton of digestate</td>
</tr>
<tr>
<td>Electricity for pumping 1 ton of digestate</td>
</tr>
</tbody>
</table>

The characteristic of input (raw biogas digestate) and output (separated fractions) is also
considered in this study. The main reason for considering this is

- The quality and quantity of the output separated solid cake and liquid obtained from the
  mechanical separator is an important factor for evaluating the performance of the system
  [19].
- The output obtained from the separator is aimed to be used as bio-fertilizers complying
  with the Swedish Bio-fertilizer scheme; hence the characteristic in output should be known [21].
The output dry matter characteristics obtained from the mechanical separation equipment and its energy consumption is collected from several studies [15] and given in table 7.

**Table 7: Characteristic of raw digestate and separated fractions from the separator along with its electrical consumption [15]**

<table>
<thead>
<tr>
<th>Technology</th>
<th>DM content in the raw digestate (%)</th>
<th>DM content in separated solid (%)</th>
<th>Electricity consumption (kWh/ton)</th>
<th>DM content in separated liquid (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>4.5</td>
<td>18</td>
<td>30</td>
<td>1.8</td>
</tr>
<tr>
<td>Screw Press</td>
<td>4.5</td>
<td>25</td>
<td>40</td>
<td>0.24</td>
</tr>
<tr>
<td>Belt Press</td>
<td>4.5</td>
<td>21</td>
<td>25</td>
<td>0.08</td>
</tr>
</tbody>
</table>

4. **Impacts analysis of the digestate de-watering system**

Using the Life cycle inventory data (Appendix A), the two options are modelled (Appendix B). The results of the analysis per functional unit (FU) for Global warming potential (GWP), Eutrophication potential (EP), Ozone layer depletion potential (ODP), Photochemical oxidation potential (POP) and Acidification potential (AP) are shown in table 8.

**Table 8: LCA results for option A and B**

<table>
<thead>
<tr>
<th>Digestate De-watering Options</th>
<th>Separator options</th>
<th>DM obtained in separated solid fraction (%)</th>
<th>Global warming Potential (kg CO₂ eq* FU⁻¹)</th>
<th>Eutrophication Potential (kg PO₄ eq* FU⁻¹)</th>
<th>Ozone layer depletion potential (kg CFC-11 eq* FU⁻¹)</th>
<th>Photochemical oxidation potential (kg C₃H₄ eq* FU⁻¹)</th>
<th>Acidification potential (kg SO₂ eq* FU⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kemira Polymer 1 + Flocculation</td>
<td>A1 Centrifuge</td>
<td>18</td>
<td>2.08</td>
<td>0.001</td>
<td>4.6E-8</td>
<td>0.0004</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>2.60</td>
<td>0.003</td>
<td>7.2E-8</td>
<td>0.0007</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>A2 Screw Press</td>
<td>25</td>
<td>1.92</td>
<td>0.0006</td>
<td>3.7E-8</td>
<td>0.0004</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>2.01</td>
<td>0.0009</td>
<td>4.2E-8</td>
<td>0.0004</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>A3 Belt Press</td>
<td>21</td>
<td>1.9</td>
<td>0.0006</td>
<td>3.6E-8</td>
<td>0.0003</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>1.9</td>
<td>0.0006</td>
<td>3.7E-8</td>
<td>0.0004</td>
<td>0.001</td>
</tr>
<tr>
<td>KemiCond + Kemira Polymer 2 + Flocculation</td>
<td>B1 Centrifuge</td>
<td>18</td>
<td>5.1</td>
<td>0.05</td>
<td>1.09E-6</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>5.7</td>
<td>0.06</td>
<td>1.2E-6</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>B2 Screw Press</td>
<td>25</td>
<td>4.9</td>
<td>0.04</td>
<td>1.07E-6</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>5.0</td>
<td>0.05</td>
<td>1.08E-6</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>B3 Belt Press</td>
<td>21</td>
<td>4.8</td>
<td>0.04</td>
<td>1.07E-6</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>4.9</td>
<td>0.05</td>
<td>1.08E-6</td>
<td>0.02</td>
<td>0.2</td>
</tr>
</tbody>
</table>
4.1 Impacts due to Energy Consumption

The only source of energy involved in both the options is electricity. Swedish electricity mix is considered in the study. A comparative analysis of Global warming potential (GWP) in kg CO₂ equivalents per functional unit as resulting from the energy consumption in the different digestate de-watering options is shown in fig.5.

![Graph showing GWP resulting from energy consumption in the digestate de-watering system](image)

**Fig 5: GWP resulting from Energy consumption in the digestate de-watering system**

*% represents the DM content in the separated solid fractions from the separator

It is observed that the Centrifuge separator has the highest GWP profiles as they consume higher electrical energy among other separation equipments. Belt press has the lowest GWP, however they can retain a maximum of 25% DM in the separated solids. Screw Press shows a GWP profile lower than centrifuge and could be considered as a good option as they can retain up to 40% DM in the separated solid fraction. Eutrophication potential (EP) in kg PO₄ equivalents per functional unit for the studied digestate de-watering is shown in Fig.6 and it has similar pattern of GWP profile.
Photochemical oxidation potential (POP), ozone depletion potential (ODP) and acidification potential (AP) due to energy consumption in the digestate de-watering system have the same pattern like Global warming potential (kindly refer Appendix C).

### 4.2 Impacts due to Polymer Consumption

As per Swedish Bio-fertilizer Certification scheme SPCR 120, the separated solid fraction from the digestate de-watering system can be used as a bio-fertilizer for farming only if it has no polymer content [21]. However it is still can be debated upon this issue as it is under examination [22]. Hence the minimum the addition of polymer in the digestate de-watering system the maximum the chances that the separated solid fractions can get the Bio-fertilizer labelling as per SPCR 120 regulations and can be marketed. Therefore polymer addition in the digestate de-watering system plays a vital role from market and environmental perspective. GWP and EP resulting from the addition of polymer in the digestate de-watering system are shown in Fig 7a and 7b.
From both the profile it is evident that Option B consumes less Kemira polymer compared to Option A, hence Option B could be an efficient option for treating the biogas digestate. Photochemical oxidation potential (POP), ozone depletion potential (ODP) and acidification potential (AP) due to Kemira polymer consumption in the digestate de-watering system have the same pattern like Global warming potential (kindly refer Appendix D).

**4.3 Overall Impact Analysis**

Contribution of the each material and energy consumed in the both options towards the environmental impact is shown from Fig 8-10. Kemira polymer 1 is the major contributor to the GWP in Option A, whereas Fe (II) Product has the highest share in the GWP profile of Option B. Electricity consumption is majorly influences EP in Option A. The EP profile of Option B shows that Fe (II) Product is the highest contributor among other materials.
Fig 8. Environmental Impact Analysis of Digestate De-watering system using Centrifuge Separator [*% represents the DM content in the separated solid fractions from the separator]

From fig 8, it is evident that in option A (18% DM) using centrifuge separator, Kemira polymer 1 is the highest contributor to the global warming potential, ozone depletion potential and photochemical oxidation potential categories. In option A (30%DM), electricity contributes much to ozone depletion potential, photochemical oxidation potential, acidification potential and eutrophication potential categories. In both the cases (18% and 30% DM) electricity has the highest share in acidification potential and eutrophication potential categories.

In both the cases of option B using Centrifuge separator, Fe (II) product has the highest share in global warming potential and eutrophication potential categories. Whereas, Sulphuric acid is the highest contributor to photochemical oxidation potential and Acidification potential categories. Kemira defoamer has the major share in ozone depletion potential category in both the cases. It can be also seen that from both the cases of option B, Kemira polymer 2 and NaOH share is very minimal in all impact categories.
Figure 9 depicts that in both the cases of option A using screw press separator, Kemira polymer 1 has the highest share in global warming potential, ozone depletion potential, photochemical oxidation potential and Eutrophication potential categories. Both the cases of Option B using screw press separator resembles the impact category pattern of both the cases of option B using Centrifuge Separator.
In both the cases of option A using Belt Press Separator, Kemira polymer 1 has the highest shares in all the impact categories. Both the cases of Option B using the belt press separator have the similar impact categories pattern of option B using Centrifuge separator.

5. Possible findings from the Impact Analysis

The overall environmental performance of the two options for the biogas de-watering process is depicted in previous chapter. Polymer addition plays a critical role in selection of the options. Phosphorus in the raw digestate is present in the form of tiny solids which are suspended in the liquid. The characteristic of these tiny solid phosphorous substances will be like largely colloidal, amorphous solids where magnesium and calcium are bound to phosphate. Due to this physical form of phosphorous it is difficult to remove it with screens, hence polymers are added to agglomerate the tiny particles to form a heavier solid particle and settle them down, which also increases the performance of the de-watering system [20].

KemiCond process reduces the addition of Kemira polymer, however it involves other chemicals: sulphuric acid, hydrogen peroxide, Kemira defoamer, Fe (II) product and Sodium Hydroxide. The increase of overall all impact categories for option B, compared to option A is due to inclusion of KemiCond process (Fig 12). Overall eutrophication potential (EP), photochemical
oxidation potential (POP), ozone depletion potential (ODP) and acidification potential (AP) of the digestate de-watering system options follows the same pattern as GWP profile (kindly refer Appendix E). The polymer content in the separated solid fractions obtained from the de-watering system can be effectively reduced by KemiCond process. As per SPCR 120, any additive used in the digestate processing system must be free from negative effects on the digestate or the soil quality [21]. According to the certification system, the quantity of the polymer must be negligible in the treated digestate in order to label them as certified Bio-Fertilizer [22]. This means that addition of polymers in the digestate de-watering process must be replaced with another alternative. If polymers cannot be used in the digestate de-watering process then the possibilities to optimize the DM content in the raw digestate will be limited [22]. Also, the limited possibilities to adjust DM content and reduce the volume of the digestate will have a serious negative impact on the whole digestate processing system. The authorities have not handled the issue before and have no further information. Hence this issue is still under debate and researches are been performed to analyze the effect of polymer in soil as well as to environment [22]. Hence Option B has can be a best option for treating the biogas digestate which to an extent favors the certification system. KemiCond process retains almost all suspended soils in the solid cake within small fraction of time [13]. Hence option B is more time saving, when compared to option A.

![Graph](image_url)

**Fig 11. GWP of Digestate De-watering system options.**
Fig 12. EP of Digestate De-watering system options.

The DM content of separated solid cake from the mechanical separators is also considered in this study which is used to determine the technical performance of the digestate de-watering system. Separated solid cake with more than 25% DM is preferable for better stocking and transportation [18]. The separated liquid should have less suspended solid contents if they are taken for further processing, since higher amount of suspended solids can cause damage and fouling to the membranes in downstream processes [6]. The application of phosphorous to soil is restricted to 65-95 kg P2O5/hectare and it will further get reduced in the upcoming year which creates a limited possibility for marketing phosphorous for direct agricultural use [10]. Due to this reason, the separated liquid fraction which has less phosphorous content, thereby forming a low phosphorous but nitrogen rich fertilizer. Hence depending on the separation efficiency and availability of the nutrients in the treated digestate, its value is determined. The comparison of the operational parameters and separation efficiencies for Belt press, Screw Press and Centrifuge are taken from various literatures and summarized in table 9 [16].
Table 9: Characteristics and Separation Efficiencies of the mechanical separators used in the digestate de-watering system [16].

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Input DM (%)</th>
<th>Output DM (%)</th>
<th>Energy used (kWh/ton)</th>
<th>Separation Efficiency (%)* DM</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Volume Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt Press</td>
<td>3 – 7</td>
<td>21 – 25</td>
<td>0.08 - 0.12</td>
<td>65</td>
<td>32</td>
<td>29</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>Screw Press</td>
<td>1-16</td>
<td>25 – 40</td>
<td>0.24 – 1.1</td>
<td>20-65</td>
<td>5-28</td>
<td>7-33</td>
<td>5-18</td>
<td>5-25</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>1.7 – 8.1</td>
<td>18 – 30</td>
<td>1.8 - 7</td>
<td>54-68</td>
<td>20-40</td>
<td>52-78</td>
<td>5-20</td>
<td>13-29</td>
</tr>
</tbody>
</table>

*Percentage of component in total raw digestate input that was partitioned to solid fraction

It can be seen that belt press and screw press option are more efficient (less energy consumption and commendable separation efficiency) when compared to centrifuge separator.

6. Economical Analysis of the digestate de-watering system

It is very important to evaluate the options to find which is more feasible from economical point of view. Table 10 gives the cost of the materials consumed in the both the options and it seems option B is more economical. Economical costs for transportation, disposal and hygienisation effects have not been considered in this study.

Table 10: Economic analysis of materials used in digestate De-watering options [17].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cost (€/kg)</th>
<th>Option A (€)</th>
<th>Option B (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kemira polymer 1</td>
<td>3.2</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Kemira polymer 2</td>
<td>1.1</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Sulphuric Acid</td>
<td>0.15</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>Hydrogen peroxide</td>
<td>0.6</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Kemira defoamer</td>
<td>4</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Fe (II) product</td>
<td>0.09</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>NaOH</td>
<td>0.3</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1.4</strong></td>
<td><strong>4.6</strong></td>
</tr>
</tbody>
</table>
Fig 12. Economic analysis of Digestate De-watering system options.
*% represents the DM content in the separated solid fractions from the separator

7. Concluding Discussions and Recommendations

The goal of the study was to quantify the life cycle environmental profile of two options for biogas digestate de-watering process. This study is also associated with BRC project no.8 (DP8) which deals with different possibilities to develop the treatment and management of biogas digestate in order to strengthen the total economics of biogas plants.

From the life cycle impact assessment results, belt press and screw press option showed the best environmental performances compared to centrifuge operated systems. Centrifuge separator used in all the options is more energy demanding which are the previous discussions. Centrifuge operated de-watering system has higher life cycle environmental impacts due to higher energy consumption, this make them not a good option for treating biogas digestate. It is observed that KemiCond process reduces the polymer addition by 82%. This will be helpful in producing separated solid fractions from the digestate de-watering system which will have very lower polymer content thus to an extent complies with SPCR 120 regulation. Also the KemiCond process reduces the time of de-watering process as it retains most of solids in the digestate which makes the separation easier [13]. Hence option B will consume less time compared to option A. Screw press and belt press options proves to be the best separation techniques in the de-watering of biogas digestate since it consumes less energy and also produces dry matter content >25% in
the separated solid fractions, which makes it easily stackable and transportable. Option A proves to be more economical however when taking into account of other factors as mentioned above, Option B can be opted.

This study has evaluated the biogas digestate de-watering system exclusively from environmental and economical perspective. All the data used in the study is taken from lab setup experimentation. However in real size application, chemicals and polymer consumption in the de-watering process will be reduced, for example Kemira defoamer addition will be reduced by factor of 4. Environmental profile is not only the essential aspects but also technological and socio-political aspects need to be taken into account for proper holistic analysis of biogas digestate processing options and decision making. From technological perspective, treatment efficiency is highly based on the quality and composition of processed biogas digestate and also the performance of the mechanical separator. Total solids, pH and fiber fractions present in the raw biogas digestate and the type of polymer added influences the performance of the mechanical separator. Ex: screw press can retain particles of size greater than 1 mm in diameter, whereas centrifuges can retain particles greater than 0.02mm in diameter [15]. Polymer characteristic and its function are also important parameters to be considered which makes the de-watering process more efficient and economical. In future study, selection of biogas digestate de-watering system should be developed including the above mentioned aspects.
8. References


[17] Interview with Kemira executives on 2nd October, 2013

[18] Site visit to Oulu MWWTP operated by Kemira Oyj on 22nd October, 2013


http://www.sp.se/sv/units/certification/product/Documents/SPCR/SPCR120.pdf

[22] Accessed online on November 15th, 2013

9. Appendix A

Sulphuric acid
Amount of Sulphuric acid required = 250 kg/ ton of dry solids in biogas digestate (refer table.5)
Amount of dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)
Amount of sulphuric acid added in option B = 11.25 kg

The GWP is taken from the data sheet provided by Kemira [17-18]. Data used for calculating the impacts associated with production of Sulphuric Acid are taken from Ecoinvent 2.0 Database modeled in Simapro Software.

Table A1: Impacts related to Sulphuric acid

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg Sulphuric acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>0.113</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>1.8E-8</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.000681</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.0133</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.00034</td>
</tr>
</tbody>
</table>

Hydrogen Peroxide
Amount of hydrogen peroxide required = 30 kg / ton of dry solids (refer table.5)
Amount of dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)
Amount of hydrogen peroxide added in option B = 1.35 kg

The GWP is taken from the data sheet provided by Kemira [18-19]. Data used for calculating the impacts associated with production of Hydrogen Peroxide are taken from Ecoinvent 2.0 database and modeled in Simapro Software.

Table A2: Impacts related to Hydrogen peroxide

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg Hydrogen peroxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>0.459</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>1.3E-7</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.00107</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.00314</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.00168</td>
</tr>
</tbody>
</table>
**Kemira defoamer**
Amount of Kemira defoamer required = 4.8 kg / ton of dry solids (refer table.5)
Amount of dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)
Amount of Kemira defoamer added in option B = 0.216 kg

Due to non availability of data, it is assumed that Kemira defoamer is similar to polypropylene glycol copolymers. Data used for calculating the impacts associated with production of propylene glycol are taken from Ecoinvent 2.0 database and modeled in Simapro Software.

**Table A3: Impacts related to Kemira defoamer**

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg Kemira defoamer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>4.04</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>3.09E-6</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.00395</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.014</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.0131</td>
</tr>
</tbody>
</table>

**Fe (II) Product**
Amount of Fe (II) Product required = 276 kg / ton of dry solids (refer table.5)
Amount of dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)
Amount of Fe (II) Product added in option B = 12.42 kg

GWP is taken from Kemira data sheet [18]. Due to non availability of data, it is assumed that Fe (II) Product is similar to Iron (III) chloride. Data used for calculating the impacts associated with production of Iron (III) chloride are taken from Ecoinvent 2.0 database and modeled in Simapro Software.

**Table A4: Impacts related to Fe (II) Product**

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg Fe (II) Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>0.13</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>1.74E-9</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.000366</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.00362</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.00292</td>
</tr>
</tbody>
</table>
**Sodium Hydroxide**

Amount of NaOH Product required = 2.2 kg / ton of dry solids (refer table.5)

Amount of dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)

Amount of Fe (II) Product added in option B = 0.1 kg

Data used for calculating the impacts associated with production of sodium hydroxide are taken from Ecoinvent 2.0 database and modeled in Simapro Software.

**Table A5: Impacts related to Hydrogen peroxide**

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg NaOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>1.39</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>0</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.00054</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.00632</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.000401</td>
</tr>
</tbody>
</table>

**Kemira polymer 1**

Kemira polymer 1 is particularly effective in primary clarification, sludge thickening and sludge/biogas digestate dewatering applications.

Amount of Kemira polymer 1 used = 9.7 kg / ton dry solids in biogas digestate [refer table.5]

Amount of dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)

Amount of Kemira polymer 1 added to 1 ton biogas digestate = 0.4365 kg

Due to non availability of data, the composition of a flocculant [20-21] is taken as the composition of Kemira polymer 1. The environmental impacts are calculated from the composition of Kemira polymer 1 as shown below [20-21]. The energy used for manufacturing and transporting the Kemira polymer 1 is not included while making the inventory

**Table A6: Raw material data related Kemira polymer 1**

<table>
<thead>
<tr>
<th>Polymer raw material</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citric acid</td>
<td>3%</td>
</tr>
<tr>
<td>Acrylamide</td>
<td>25%</td>
</tr>
<tr>
<td>Ethoxylated alcohols</td>
<td>4%</td>
</tr>
<tr>
<td>Water</td>
<td>68%</td>
</tr>
</tbody>
</table>
GWP is taken from data sheet given by Kemira data sheet [18]. Data from Ecoinvent 2.0 database is used for calculating the impacts associated with production of Kemira polymer 1. The impacts are modeled in Simapro Software.

**Table A7: Impacts related to Kemira polymer 1**

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg of Kemira polymer 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>4.15</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>7.29E-8</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.000779</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.00195</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.000713</td>
</tr>
</tbody>
</table>

**Kemira polymer 2**

Amount of Kemira polymer 2 used in option B = 1.8 kg / dry ton solids in biogas digestate [refer table 5]

Dry solids present in 1 ton of biogas digestate = 0.045 ton (refer table 1)

Amount of Kemira polymer 2 added in option B = 0.081 kg

Due to non availability of data, it is assumed that the composition of a flocculant [20-21] is same as Kemira polymer 2. The energy used for manufacturing and transporting the Kemira polymer 2 is not included while making the inventory. GWP is taken from Kemira data sheet [18]. Data from Ecoinvent 2.0 database is used for calculating the impacts associated with production of Kemira polymer 2. The impacts are modeled in Simapro Software. The energy used for manufacturing and transporting the Kemira polymer 2 is not included while making the inventory.

**Table A8: Impacts related to the Kemira polymer 2**

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kg of Kemira Polymer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential (GWP 100)</td>
<td>kg CO₂ eq</td>
<td>3.29</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>7.29E-8</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>0.000779</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.00195</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.000713</td>
</tr>
</tbody>
</table>
Electricity
The electricity consumed in both the options are assumed to be of Swedish mix electricity. The impacts associated with Electricity used in the system is taken from Ecoinvent 2.0 Data base and modeled in Simapro Software.

Table A9: Impacts from Energy consumption

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Unit</th>
<th>For producing 1 kWh Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential</td>
<td>kg CO₂ eq</td>
<td>0.101</td>
</tr>
<tr>
<td>Ozone layer depletion (ODP) potential</td>
<td>kg CFC-11 eq</td>
<td>5.07E-9</td>
</tr>
<tr>
<td>Photochemical oxidation potential</td>
<td>kg C₂H₄ eq</td>
<td>4.42E-5</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>kg SO₄ eq</td>
<td>0.000413</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>kg PO₄ eq</td>
<td>0.000275</td>
</tr>
</tbody>
</table>
10. Appendix B

**Option A1: Kemira Polymer 1 + Centrifuge**
Amount of raw digestate treated = 1 ton (Functional Unit)
Amount of Solids in raw digestate = 0.045 ton (Refer table 1)
Amount of Kemira polymer 1 added to 1 ton biogas digestate = 0.0004365 ton (Appendix A)
Amount of digestate entering Centrifuge = 1.0004365 ton
Electricity consumed for stirring = 0.4 kWh
Electricity consumed for pumping = 0.5 kWh
Electricity consumed by Centrifuge for treating 1 ton digestate and producing 18% DM in separated solid = 1.8 kWh
Electricity consumed by Centrifuge for treating 1 ton digestate and producing 30% DM in separated solid = 7 kWh
Total Electricity Consumed for producing 18% DM in separated solid = 2.7 kWh
Total Electricity Consumed for producing 30% DM in separated solid = 7.9 kWh

**Option A2: Kemira Polymer 1 + Screw Press**
Amount of raw digestate treated = 1 ton (Functional Unit)
Amount of Solids in raw digestate = 0.045 ton (Refer table 1)
Amount of Kemira polymer 1 added to 1 ton biogas digestate = 0.4365 kg (Appendix A)
Amount of digestate entering Screw Press = 1.0004365 ton
Electricity consumed for stirring = 0.4 kWh
Electricity consumed for pumping = 0.5 kWh
Electricity consumed by Screw Press for treating 1 ton digestate and producing 25% DM in separated solid = 0.24 kWh
Electricity consumed by Screw Press for treating 1 ton digestate and producing 40% DM in separated solid = 1.1 kWh
Total Electricity Consumed for producing 25% DM in separated solid = 1.14 kWh
Total Electricity Consumed for producing 40% DM in separated solid = 2.0 kWh

**Option A3: Kemira Polymer 1 + Belt Press**
Amount of raw digestate treated = 1 ton (Functional Unit)
Amount of Solids in raw digestate = 0.045 ton (Refer table 1)
Amount of Kemira polymer 1 added to 1 ton biogas digestate = 0.0004365 ton (Appendix A)
Amount of digestate entering belt Press = 1.0004365 ton
Electricity consumed for stirring = 0.4 kWh
Electricity consumed for pumping = 0.5 kWh
Electricity consumed by belt Press for treating 1 ton digestate and producing 21% DM in separated solid =0.08 kWh
Electricity consumed by belt press for treating 1 ton digestate and producing 25% DM in separated solid =0.12 kWh
Total Electricity Consumed for producing 21% DM in separated solid = 0.98 kWh
Total Electricity Consumed for producing 25% DM in separated solid = 1.02 kWh

**Option B1: KemiCond+ Kemira Polymer 2 + Centrifuge**

Amount of raw digestate treated = 1 ton (Functional Unit)
Amount of Solids in raw digestate = 0.045 ton (Refer table 1)
Amount of sulphuric acid added = 0.01125 ton (Appendix A)
Amount of hydrogen peroxide added = 0.00135 ton (Appendix A)
Amount of Kemira defoamer added = 0.000216 ton (Appendix A)
Amount of Fe (II) product added = 0.01242 ton (Appendix A)
Amount of NaOH added = 0.0001 ton (Appendix A)
Amount of digestate entering the flocculation process = 1.1 ton
Amount of Kemira polymer 2 added to 1.1 ton biogas digestate = 0.0001 ton (Appendix A)
Amount of digestate entering centrifuge = 1.1 ton
Electricity consumed for stirring = 0.44 kWh
Electricity consumed for pumping = 0.55 kWh
Electricity consumed by Centrifuge for treating 1.1 ton digestate and producing 18% DM in separated solid =2 kWh
Electricity consumed by Centrifuge for treating 1.1 ton digestate and producing 30% DM in separated solid =8 kWh
Total Electricity Consumed for producing 18% DM in separated solid = 3 kWh
Total Electricity Consumed for producing 30% DM in separated solid = 9 kWh

**Option B2: KemiCond+ Kemira Polymer 2 + Screw Press**

Amount of raw digestate treated = 1 ton (Functional Unit)
Amount of Solids in raw digestate = 0.045 ton (Refer table 1)
Amount of sulphuric acid added = 0.01125 ton (Appendix A)
Amount of hydrogen peroxide added = 0.00135 ton (Appendix A)
Amount of Kemira defoamer added = 0.000216 ton (Appendix A)
Amount of Fe (II) product added = 0.01242 ton (Appendix A)
Amount of NaOH added = 0.0001 ton (Appendix A)
Amount of digestate entering the flocculation process = 1.1 ton
Amount of Kemira polymer 2 added to 1.1 ton biogas digestate = 0.0001 ton (Appendix A)
Amount of digestate entering centrifuge = 1.1 ton
Electricity consumed for stirring = 0.44 kWh
Electricity consumed for pumping = 0.55 kWh
Electricity consumed by screw press for treating 1.1 ton digestate and producing 25% DM in separated solid = 0.3 kWh
Electricity consumed by screw press for treating 1.1 ton digestate and producing 40% DM in separated solid = 1.2 kWh
Total Electricity Consumed for producing 25% DM in separated solid = 1.29 kWh
Total Electricity Consumed for producing 40% DM in separated solid = 2.19 kWh

Option B3: KemiCond+ Kemira Polymer 2 + Belt Press

Amount of raw digestate treated = 1 ton (Functional Unit)
Amount of Solids in raw digestate = 0.045 ton (Refer table 1)
Amount of sulphuric acid added = 0.01125 ton (Appendix A)
Amount of hydrogen peroxide added = 0.00135 ton (Appendix A)
Amount of Kemira defoamer added = 0.000216 ton (Appendix A)
Amount of Fe (II) product added = 0.01242 ton (Appendix A)
Amount of NaOH added = 0.0001 ton (Appendix A)
Amount of digestate entering the flocculation process = 1.1 ton
Amount of Kemira polymer 2 added to 1.1 ton biogas digestate = 0.0001 ton (Appendix A)
Amount of digestate entering centrifuge = 1.1 ton
Electricity consumed for stirring = 0.44 kWh
Electricity consumed for pumping = 0.55 kWh
Electricity consumed by belt press for treating 1.1 ton digestate and producing 21% DM in separated solid = 0.1 kWh
Electricity consumed by belt press for treating 1.1 ton digestate and producing 25% DM in separated solid = 0.13 kWh
Total Electricity Consumed for producing 21% DM in separated solid = 1.09 kWh
Total Electricity Consumed for producing 25% DM in separated solid = 1.12 kWh
11. Appendix C

Impacts due to electricity consumption

**Fig C1**: ODP resulting from Energy consumption in the digestate de-watering system
*% represents the DM content in the separated solid fractions from the separator

**Fig C2**: POP resulting from Energy consumption in the digestate de-watering system
*% represents the DM content in the separated solid fractions from the separator
Fig C3: AP resulting from Energy consumption in the digestate de-watering system
*% represents the DM content in the separated solid fractions from the separator
12. Appendix D

Impacts due to polymer consumption

**Fig D1:** ODP resulting from Kemira polymer consumption in the digestate de-watering system

**Fig D2:** POP resulting from Kemira polymer consumption in the digestate de-watering system
Fig D3: AP resulting from Kemira polymer consumption in the digestate de-watering system
13. Appendix E

Overall Impact Analysis

**Fig E1: ODP of Digestate De-watering system options.**

**Fig E2: POP of Digestate De-watering system options.**
Fig E3: AP of Digestate De-watering system options.
14. Appendix F

Site visit to Oulu MWWTP

Fig F1. Sulphuric acid and Hydrogen Peroxide storage tanks at Oulu MWWTP

Fig F2. Acidification tank in the KemiCond Process at Oulu MWWTP
Fig F3. NaOH storage tank in KemiCond process at Oulu MWWTP

Fig F4. Oxidation tank in KemiCond process at Oulu MWWTP