Lappeenranta-Lahti University of Technology LUT
LUT School of Engineering Science
Chemical Engineering
Chemical and Process Engineering

Master's Thesis

Armi Rissanen

Study on different effluent treatment sludge utilizing methods in pulp and paperboard mills

Examiners: Professor Tuomas Koiranen
D. Sc. Eeva Jernström

Advisor: M. Sc. Juha Oksanen

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
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Armi Rissanen

Tutkimus sellu- ja kartonkitehtaiden jätevesilietteiden hyötykäyttömahdollisuuksista

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TkT Eeva Jernström

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Tässä diplomityössä tutkittiin lietteiden käsittelyprosesseja Stora Enson Suomen tehtailla yhdessä niiden tyypillisten hyötykäyttömahdollisuuksien kanssa. Kolme tehtaista otettiin tarkempaan tapaustutkimukseen, jossa lietteiden käsittelyprosessit yhdessä hyötykäytön kanssa arvioitiin perustuen lietteiden tyypillisiin ominaisuuksiin sekä tehtyyn teoreettiseen tutkimukseen aiheesta.

Tapauskohtainen tieto kerättiin tehtailta haastatteluiden avulla. Tehdastutkimuksia varten lietenäytteitä kerättiin ja lietteiden ominaisuuksia analysoitiin erilaisin analyysimenetelmin. Jokaiselle tapaustutkimustehtaalle tehtiin SWOT-analyysi.

Jokaisessa tehtaassa lietettä hyötykäytetään joko kokonaan tai suurimmalta osin energiantuotannossa. Tapaustutkimuksen perusteella Imatran ja Varkauden tehtaiden lietteet ovat potentiaalisia niin energia- kuin maanparannushyötykäytössä, kun taas Sunilan tehtaan liete soveltuu parhaiten energiantuotantoon. Jokainen tehdas pystyy parantamaan lietteidensä energiahyötykäyttöä kehittämällä lietteenkäsittelyprosessiaan. Tätä varten on tulevaisuudessa tehtävä tarkka tapauskohtainen tutkimus parhaasta mahdollisesta lietteidenkäsittelytekniikasta huomioiden tehdaskohtaiset lietteiden ominaisuudet.

ABSTRACT

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Study on different effluent treatment sludge utilizing methods in pulp and paperboard mills

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86 pages, 21 figures, 21 tables

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Keywords: wastewater treatment, sludge, utilization

In this master's thesis, sludge treatment processes along with typical utilization applications at Stora Enso mills in Finland were studied. Three of the Stora Enso's mills were taken into more detailed study, in which their sludge treatment processes and utilization uses were evaluated based on their typical sludge characteristic and theoretical study on this matter.

Case by case information from the mills was gathered by interviews. For study of mill cases, sludge samples were gathered from each mill and different characteristics were analysed by using multiple different analytical methods. A SWOT analysis was performed for sludge utilization uses in each case mill.

Each mill utilizes either totally or mostly in energy recovery. Based on the study, sludge from Imatra Mills and Varkaus Mill are potential raw material for soil improvement and in energy recovery, whereas Sunila Mill could be used in energy recovery. Each Stora Enso mill could improve their energy recovery processes by improving their sludge treatment processes. Improvements requires further case by case study on most suitable technology available in terms of each mill's sludge characteristics.

Contents

1. Introduction

Efficient wastewater treatment is crucial to any industry in the terms of circular economy and in the legislation point of view. As fresh water is essential for life, water is also an important raw material in pulp and paperboard industry. Therefore, industries are obligated and highly motivated to maintain the clean freshwater resources by investing in their wastewater treatment processes.

However, the endless resources of clean fresh water is not something taken for granted. In environmental challenges such as this, circular economy is one conceptual tool to promote sustainable production and consumption. In circular economy, linear process models in traditional industries are transformed into circular models. In other words, in linear process model raw material is transferred roughly into product and waste. In circular model, the concept of 'waste' does not exist. Instead, each waste stream is considered as a potential raw material source, which leads to the cycle of materials. (Korhonen et al. 2017) Since environmental issues are in high concern worldwide, promoting the aims of circular economy is good for industry brand as well as it might secure endless raw material sources. Therefore, circular economy approach is popular within industries along with politics.

While clean water is achieved in wastewater treatment processes at pulp and paper industries, effluent treatment sludge is being produced as a side product. In the eyes of the law, sludge is considered as a waste in Finland (Virolainen 2017). On the other hand, in the terms of circular economy, each side stream is considered as potential raw material source. Not to mention, since each mill is slightly different in their process design and in raw materials used, wastewater treatment processes and sludge treatment processes vary case by case. In pulp and paperboard industry, challenge is to balance between these points of views in design of sludge treatment processes.

1.1. Objectives

This master's thesis consists of two main issues: literature part and study of mill cases. In literature part, the aim is to answer, how effluent treatment sludge is being formed in wastewater treatment process, what are the typical sludge characteristics and how these sludges can be processed along with their potential utilization uses.

In study of mill cases, sludge treatment processes along with their typical characteristics are taken into more detailed study in Stora Enso mills in Finland. Case by case information from the mills is gathered by interviews. Based on the gathered knowledge, each mill’s sludge treatment process is presented and briefly evaluated based on the theoretical study on this matter.

Three of the Stora Enso’s mills were taken into case evaluation. Selected mills was located in Imatra, Sunila and Varkaus. In case evaluation, each mill’s typical sludge characteristics are taken into more detailed study in terms of sludge treatment process and sludge utilization. In order to perform valid evaluation on the sludge characteristics, sludge samples are gathered from each case mill. From these samples, most important sludge characteristics in the terms of sludge utilization possibilities are being analysed. These characteristics are efficient heating value, chemical content and ash content, for instance. Analysed characteristics are evaluated in the terms of sludge treatment processes, sludge utilization possibilities and based on the available literature, studies and legislation on this matter.

According to the case study, a SWOT analysis is performed for each mill. Based on the SWOT analysis and theoretical study on this matter, suggestions are made, if found necessary. Nevertheless, potential sludge utilization possibilities for each mill are being studied and compared to their current situation.

LITERATURE STUDY

2. Wastewater treatment process

In a pulp-based industry, water is present in multiple essential parts of the process, such as dilution and different purification methods. Approximately 15 m^3 water is required to air dry ton of pulp. (KnowPulp 2020) Therefore, a significant amount of wastewater is produced and processed daily. For instance, Stora Enso Imatra Mills produces roughly 180 thousand cubic metres of process water discharge daily (Stora Enso Annual Report 2019).

Typical wastewater treatment process has three main process units: primary, secondary, and tertiary treatment processes, (Eckenfelder 2000) from which tertiary treatment process is not always used in pulp and paper industries. In this following chapter, the main structures of wastewater treatment process in pulp and paper industries are presented briefly along with their treatment process residues, sludges.

2.1. Pre- and primary treatment process

In order to prepare wastewater for biological treatment, wastewater is treated in primary process. Along with secondary treatment process, most of the nontoxic wastewater is handled in primary treatment process. (Eckenfelder 2000)

Before the primary treatment, wastewater is pre-treated in mixing basin. On daily basis, a wastewater treatment plant has hour-to-hour variations both in concentrations and flows. By mixing basin, these variations are levelled out in order to stabilize further treatment process. In most of the cases equalization can also serve as neutralization as differences in pH levels neutralize each other. Variations in flows are also managed by a spill basin and source control. (Eckenfelder 2000)

In the primary treatment, most of the solid waste is removed. Large waste particles can easily be removed by screening. Grit is removed from wastewater as it is allowed to settle at the bottom of grit chamber. (EPA 2004)

At this point, wastewater still contains fine, suspended solids along with inorganic and organic matter, (EPA 2004) which are removed by sedimentation.

In sedimentation, wastewater is directed in a sedimentation tank, in which suspended solids settle on the bottom of the tank gradually by coagulation and precipitation. (EPA 2004) Wastewater flow through screening, grit chamber and sedimentation tank is presented in Figure 1.

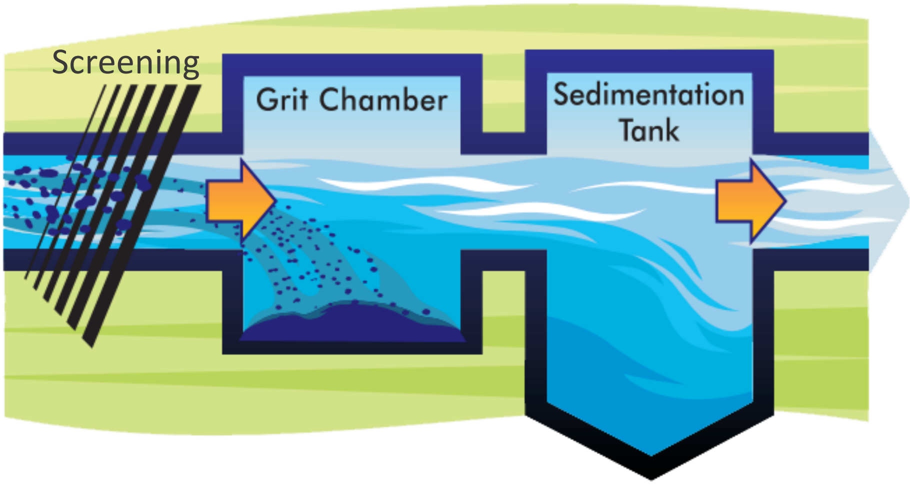

Figure 1. Wastewater flow through screening, girt chamber and sedimentation tank. (EPA 2004, page 11, modified)

In the wastewater treatment, suspended solids are considered as one of the major pollutants. Sedimentation processes are often rather effective for removing these. However, in order to design such a process successfully, characteristics of suspended solids, such as particle size, specific weight and hydrophilicity/hydrophobicity, have to be known. In some cases, apt characteristics can increase chance of particles being lifted by air bubbles. Therefore, unfit process design can lead to such lifting power that small and difficult-to-settle particles are being buoyed to the liquid surface, which decreases process efficiency. (Nemerow 2007)

Along with sedimentation, flotation and filtration are used to remove oils and suspended solids from the wastewater. Oils can also be removed by a gravity oil separation in wastewater pre-treatment. (Eckenfelder 2000) From tanks, separated solids and other discharge, in other words primary sludge, are removed by pumping (EPA 2004). Pre- and primary treatment technologies are presented in Figure 2.

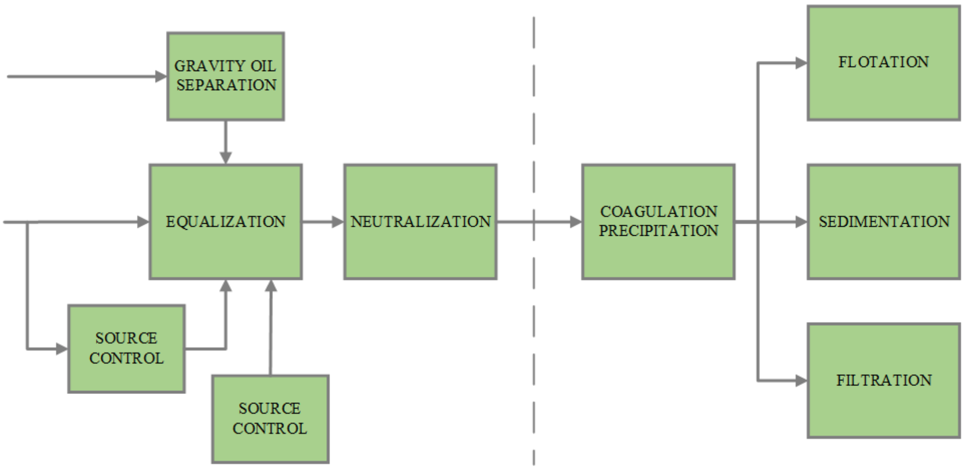

Figure 2. Pre-treatment technologies on the left and primary treatment technologies on the right. (Eckenfelder 2000, Figure 3.1, modified)

2.2. Secondary treatment process

After the primary treatment process, effluents contain different soluble organic compounds. In order to remove organic matter from wastewater, a secondary treatment process, also known as biological treatment, is required. (Eckenfelder 2000)

In biological treatment, microorganisms are harvested into purification as they use organic matter in effluent as nutrition. The basic principle of biological treatment methods is following

$$carbonaceous\ matter + \ with\ or\ without\ O_2 \xrightarrow{microorganisms} CO_2 + H_2O + \ biomass + \ byproducts + \text{energy}$$

. (KnowPulp 2020)

While various technologies for the biological treatment methods exist, activated sludge process and trickling filtration are presented from aerobic treatment methods as it follows. In pulp and paperboard industry, aerobic treatment methods are more commonly used than anaerobic methods in wastewater treatment due to their rather effortless implementation (KnowPulp 2020). Anaerobic wastewater treatment is presented briefly along with selected two aerobic technologies.

2.2.1. Activated sludge process

In an activated sludge process, effluent is treated with microorganisms in aerobic conditions. Activated sludge process is presented in Figure 3.

Effluent enters in an aeration tank, in which air is introduced either by porous diffusers, surface aerators or by bubbling compressed air with open-ended pipes. Main differences in these aeration technologies are the efficiency of oxygen transfer and maintenance. For example, porous diffusers generate smaller bubbles, which have more efficient oxygen transfer. However, in a presence of fine dust particles, they clog up more easily than open-ended pipes, which increases the maintenance costs. (Nesaratnam 1998)

A concentrated biomass, the activated sludge, is presented in the aeration tank along with air. The microorganisms in the activated sludge degrade the organic material in the wastewater also as new cells are being formed. After the residence time, effluent and sludge enters in the sedimentation tank, in which sludge settles at the bottom as final effluent exits from the top. Some of the sludge is returned in the aeration tank as activated sludge. The surplus sludge, also known as biosludge, is pumped at the bottom of sedimentation tank for further processing. (Nesaratnam 1998)

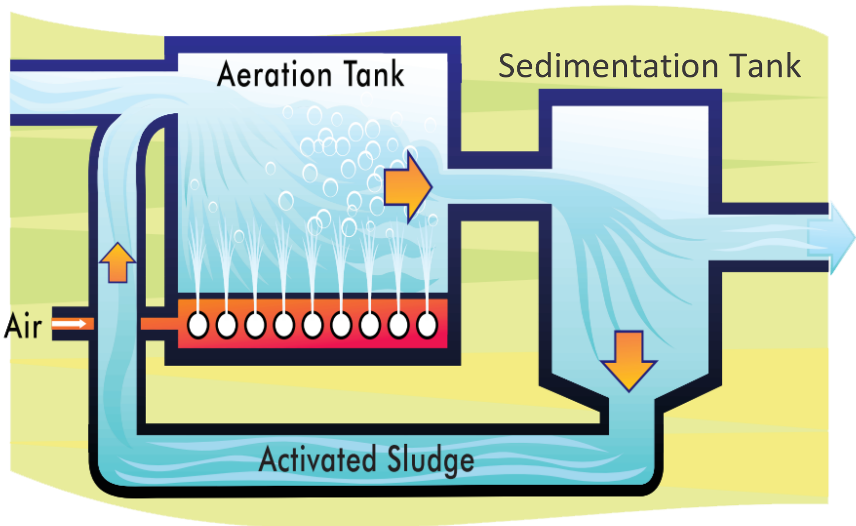

Figure 3. Activated sludge process, (EPA 2004, page 13, modified) in which air is introduced by using open-ended pipes.

The activated sludge process techniques are desired due to their relatively small process unit size and generally odour-free process, when operated correctly.

However, due to the high energy demand of aeration system, the activated sludge processes are more costly. Also, the microorganisms are relatively sensitive for changes in process conditions. (EPA 2004)

2.2.2. Trickling filtration

Trickling filtration, despite its' name, bases on oxidation, not filtration. In trickling filtration, effluent is directed through a ventilated bed media. Bed media is sprayed evenly with a rotating effluent distributor. As the effluent trickles down through the bed, the organic matter in effluent comes in contact with the biological film of bacteria in which oxidation takes place. After oxidation, treated effluent is collected with an underdrainage system. (Wang et al. 2009) Remain biological matter is washed through the filter media in a sedimentation tank, from which formed biosludge is directed to further processing. (Nesaratnam 1998)

In comparison with equivalent activated sludge system, trickling filter treatment method requires more land area and it can clog due to microbial growth. However, trickling filters have relatively low operating costs. (KnowPulp 2020) Cross-section of typical trickling filtration equipment is presented in Figure 4.

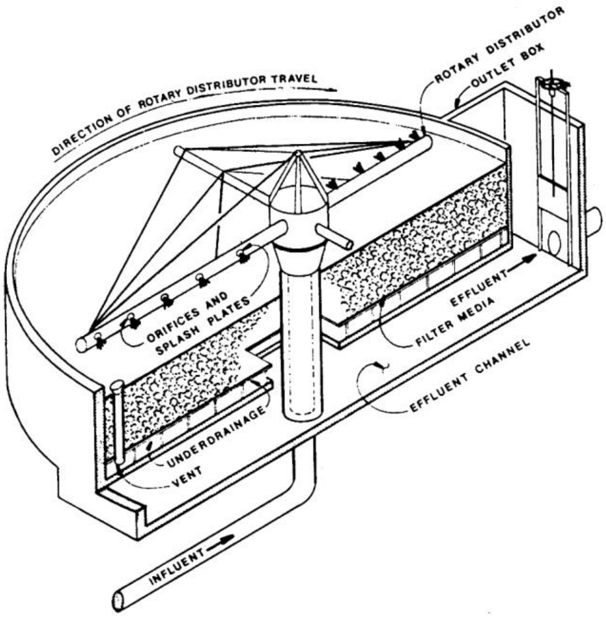

Figure 4. Cross-section of typical trickling filtration equipment. (Wang et al. 2009, Figure 9.3)

2.2.3. Anaerobic wastewater treatment

Wastewater can be treated anaerobically in lagoons. In anaerobic conditions, molecular oxygen is absent in process. Nevertheless, the quantity of organic matter is decreased as microorganisms utilize the alternative sources of oxygen as methane carbon dioxide is being produced. Alternative oxygen sources are located in nitrates and sulfates, for instance. (Muthu 2018)

In comparison with the aerobic wastewater treatment, the anaerobic wastewater treatment could be considered more ideal. Both have a capacity to decrease waste, but the anaerobic wastewater treatment has byproduct, methane, which can be significant resource. (Muthu 2018) In other words, anaerobic treatment could be utilized in a biofuel production. This varied approach would increase process efficiency and decrease the need of fossil fuels.

2.3. Tertiary treatment process

Different pollutants can be toxic either for biota or humans. Therefore, the appropriate concentration levels of priority pollutants, such as heavy metals, biocides and metalloids, are strictly defined and controlled by legislation. (Bonilla-Petriciolet et al. 2017) In some cases, effluent can still contain pollutants after secondary treatment process. If so, a tertiary treatment process is required, which is uncommon in pulp and paper industries.

Tertiary treatment processes can remove specific types of residuals, but they are not pollutant-specific. For example, organic pollutant dichlorophenol can be removed by ozonation, but it will remove most of the other organic compounds as well. For not being pollutant-specific, treatment costs highly increase as well as it makes the tertiary treatment process inefficient. (Eckenfelder 2000)

Depending on desired residual, technologies for tertiary treatment vary. However, most of the treatment processes involve advanced physical-chemical separation, such as activated carbon adsorption, ion exchange or advanced filtration by membranes. (Mareddy 2018) Due to required advanced technology, tertiary treatment processes can be highly expensive for large wastewater quantities.

(Eckenfelder 2000) In tertiary wastewater treatment processes, tertiary sludge is being produced. From tertiary treatment technologies, activated carbon adsorption and membrane filtration are presented as it follows.

2.3.1. Activated carbon adsorption

In the effluent treatment, adsorption is widely used due to its' cost-effectiveness and technical suitability for various cases. In activated carbon adsorption, activated carbon is used as adsorbent. Among with activated carbon, a wide range of absorbents exist for different applications. For instance, activated zeolites, clays and polymeric resins can be applied in adsorption processes. (Jana et al. 2018) Different adsorption mechanisms exist, from which the basic principle of multilayer adsorption is presented in Figure 5.

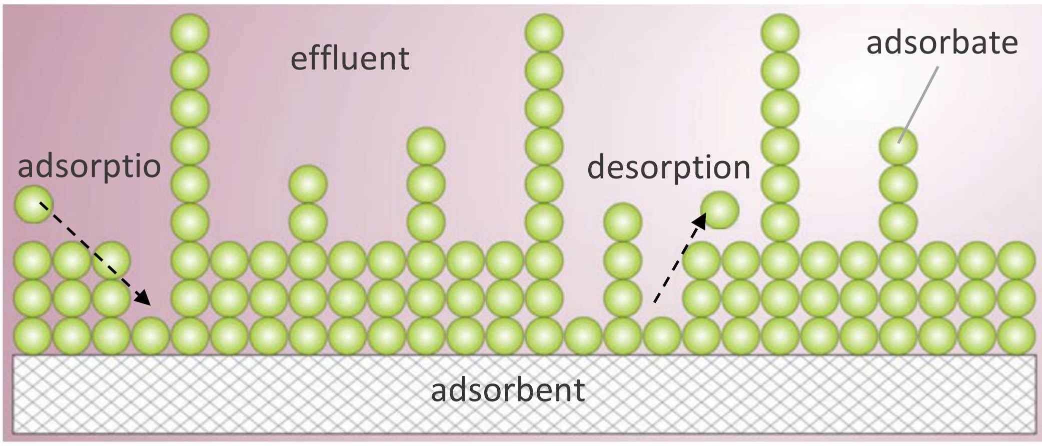

Figure 5. The basic principle of multilayer adsorption mechanism. (Gupta 2018, Figure 2.6, modified)

As adsorbent, activated carbon is classified as natural material, which is processed to develop its' structure and properties. Activated carbon is one of the most preferred choice of adsorbent material, since it is rather easy to apply in industrial scale processes and it often provides the best efficiency in pollutant removal. Also, activated carbon is suitable for various contaminants, such as heavy metals, phenolic derivates and radionuclides. However, these adsorption systems are rather expensive due to high material costs. (Crini & Lichtfouse 2018) One of the greatest advantages of adsorption is the reusability of adsorbents. With suitable desorption process, most of the adsorbents, including activated carbon, can be regenerated. (Jana et al. 2018)

2.3.2. Membrane filtration

In the wastewater treatment, filtration is commonly used technology in tertiary treatment processes. However, traditional granular filtration is facing competition as membrane technology is establishing its' place as a considerable choice.

The aim of filtration is to purify effluent from microorganisms and other particles based on physicochemical processes. In comparison, the aim in traditional granular filtration and in membrane filtration is same. However, in physicochemical processes, filtration conditions and filter media structures are very different between these two. (Howe et al. 2012)

In traditional filtration, a filter media is typically very thick, and it is made of granular material. In membrane filtration, effluent is filtered through thin synthetic filter media, which width is typically less than 1 mm and contains tiny pores. In other words, granular filtration relies on the depth of filter media as the membrane filtration rely on straining. As various membrane materials exist, right material is selected based on the wanted contaminants and process conditions. (Howe et al. 2012)

In order to process same quantity of wastewater than traditional granular filtration plant, the membrane filtration plants require 100 times larger filter area. However, these plants are often smaller because packing density is significantly higher. If the land area is limited or expensive, these compact membrane installations have their advantages. (Howe et al. 2012)

One of the disadvantages is membrane fouling, which can be cause of pore blocking or cake formation, for example. If the resistance in membrane increases too high, water will no longer flow through in wanted rate. Even though these problems can often be avoided with frequent cleaning and backwashing, it is not very cost effective and sometimes pores can be damaged permanently. (Howe et al. 2012)

3. Sludges and their typical characteristics

In this chapter, typical sludge fractions and their characteristics in pulp and paper industries are presented. Dry content, efficient heating value and chemical content are being discussed in characteristics. It is worth noting, that effluent treatment sludge characteristics are individual for each pulp and paper mill depending on their manufacturing processes and their wastewater treatment plants (Bajpai 2015).

Based on the information presented before, three main sludge fractions in wastewater treatment processes are being reread as it follows. Three sludge fractions are primary sludge, biosludge and tertiary sludge.

Primary sludge is produced in the primary wastewater treatment stage. In the primary treatment stage, sludge is produced when mostly inorganic solids settle at the bottom of the sedimentation tank from which sludge is being pumped in further processing. Flotation is also used in primary wastewater treatment, but sedimentation is more common.

Biosludge is produced in the secondary wastewater treatment stage, also known as biological wastewater treatment stage, as discussed before. In secondary wastewater treatment stage, soluble organic compounds and matter are separated from the effluent with microorganisms. When microorganisms use organic matter in effluent as nutrition, mostly organic sludge is being formed along with few other by-products, such as carbon dioxide. Biosludge can also be referred as a secondary sludge.

Tertiary sludge is produced in tertiary wastewater treatment stage, in which toxic pollutants and other residuals are being separated. Separation often requires advanced physical-chemical separation.

While tertiary sludge and other sludges, such as bark sludge, exist, in pulp and paperboard industry, primary sludge and biosludges are the main sludge fractions. Therefore, these two are in the main focus in this thesis.

3.1. Dry content

In sludge utilization, especially in energy recovery, dry content is one of the essential sludge characteristics. Due to sludge characteristics and differences in each process design, effluent treatment sludge has its' own typical dry content after each wastewater treatment process. In sludge pretreatment before utilization, the one of the main aims is to increase dry content in sludge.

After wastewater treatment, the dry content of sludge is relatively low. Typical dry content for primary sludge varies approximately from 5 to 6 % after primary treatment. Biosludge can be thickened to dry content of approximately 3 % in secondary treatment, but if secondary sludge is thickened in the same settling tank than primary sludge, from 4 to 5 % dry content can be achieved. (Wang et al. 2007)

As well as other characteristics, dry content of sludge also varies between different mills. Listing of typical dry content values for sludges from different forest industry mills are presented in Table 1. Dry content can be increased with multiple different dewatering technologies, which will be discussed in detail in Chapter 5.

Table 1. Typical dry content values for sludges from different forest industry mills. (Wang et al. 2007, Table 8) Values are referred to sludges before dewatering.

Sludge source	**Dry content, %**
Board mills	2 – 10
Chemical pulp	1 – 10
Deink pulp	3 – 10
Ground wood	2 – 5
Paper mills	1 – 5

3.2. Chemical content

As sludge utilization possibilities are concerned, studying the chemical content of sludge is of high importance. For instance, heavy metals and other chemical elements along with ash content, or in other words residues after burning, are in the main focus.

3.2.1. Heavy metals

Heavy metal concentrations of sludge are the main concern in sludge utilization. According to study by Berninger (2018), cadmium concentration is the main issue in soil improvement applications. Sludges from pulp and paper mills can easily contain such high concentration of cadmium that it exceeds the limit. Heavy metal content in forest industry primary sludge is presented in Table 2.

Table 2. Heavy metal content in primary sludge from forest industry. (Alakangas 2000, Table 94) Content is informed in mg per one kilogram of dry sludge.

Heavy metal	**Content, mg/kg**
Cd	0.0 – 2.5
Cr	-
Cu	3.4 – 3.1
Hg	0.0 – 0.2
Ni	7.0 – 26.7
Pb	0.0 – 15.5

3.2.2. Other chemical elements

Chemical content mainly determines the processability of sludge rather than utilization possibilities of it. For example, due to their hydrous nature, effluent treatment sludges from pulp and paper mills are often rather difficult to dewater. (Bajpai 2015) As other characteristics, chemical content also varies between different forest industries. For instance, according to study, sludges from pulp mill contain more sulphur compounds than sludges from paper mills. (Scott et al. 1995)

Since pulp and paper mill sludges are high in fibre and contains a lot of organic matter, most of the chemical content is carbon and oxygen (Alakangas 2000). General chemical content in primary sludge and biolsudge is presented in Table 3.

Table 3. Chemical content in primary sludge and in biosludge. (Alakangas 2000, Table 93) Percentage is presented in dry sludge.

Chemical element	Primary sludge, %	Biosludge, %
C	44	47
H	6	5.2
S	0.1	1.2
N	0.4	1.6
O	25	30

3.2.3. Ash

Along with other chemical substances, the ash content of sludge is in high interest. In other words, ash content is considered as the mineral content of sludge, which is seen as residue after burning. Typical ash content of primary sludge is approximately 50 to 60 % in paper industry whereas in pulp mill, ash content varies from 5 to 20 %. For biosludge, typical ash content is approximately from 16 %. (Alakangas 2000)

Ash content differences in sludge from different mills can be explained by the raw material choice, for instance. According to study, mills that use virgin wood as raw material, have lower ash content in the sludge than mills who uses recycled paper as raw material. Ash content is increased mainly due to fillers, such as clay or calcium carbonate, which are used in paper manufacturing. (Scott et al. 1995)

3.3. Heating value

In energy recovery applications, the heating value of sludge has shown its' importance to pulp and paperboard industry. In order to design efficient energy production process, the heating value of sludge has to be known. From sludge characteristics, dry content and ash content influence on the heating value, for instance.

Dry content of sludge is directly related to the efficient heating value and to the efficiency of energy recovery. In order to support the burning process, the efficient heating value of fuel must be at least 5 MJ/kg, which requires dry content from 30 to 50 %, depending on boiler technology used. With typical moisture content, for primary sludge efficient heating value is approximately from 4 to 6 MJ/kg and for biosludge efficient heating value is roughly 0 MJ/kg. Therefore, in most of the cases, sludge requires support for fuel, such as bark. In practise, effluent treatment sludge is always burned along with bark and other woody waste in boilers. (Alakangas 2000)

Along with dry content, the ash content of sludge is directly related to the heating value. For instance, according to study, effluent treatment sludges with high ash content have only approximately 60 % of the low-ash sludge's efficient heating value. For example, sludge from deinking mill with 14 % ash content has efficient heating value of 12.2 MJ/kg, but sludge from a pulp mill with 4.9 % ash content has efficient heating value of 21.5 MJ/kg. (Scott et al. 1995) Visualized relations between sludge's heating value as a function of moisture content for different ash content values is presented in Figure 6. Good to note, that these heating values have been determined for sludge in its' initialization moisture, not for 100% dry sludge. As is presented in figure, when the moisture and ash contents are at their lowest, the heating value is on its' highest.

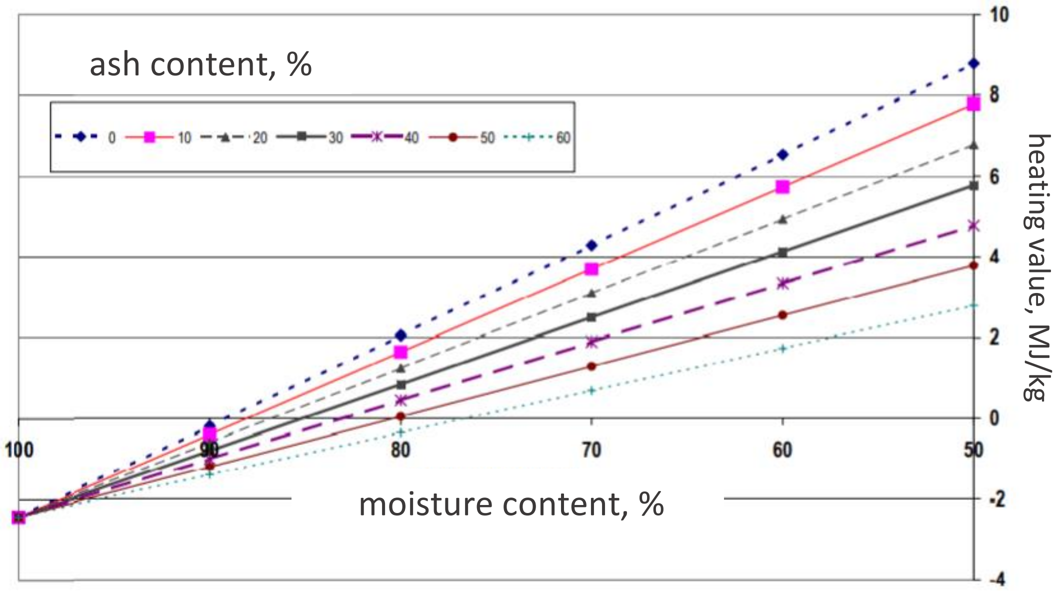

Figure 6. Sludge's heating values as a function of moisture content for different as content values. (Alakangas 2000, Figure 20, modified)

4. Sludge unit operations

As sludge leaves from wastewater treatment process, it contains significant amount of water. Before sludge can be utilized in any application at pulp and paperboard industry, sludge needs to be pretreated. Most of the sludge unit operations are about dewatering or improving dewatering of sludge. Sludge unit operations are thickening, conditioning, dewatering and drying. Since hygienisation is essential for utilizing sludge as soil improvement, it is presented as unit operation in this context as well.

4.1. Thickening

Thickening is a mechanical primary stage in pre-dewatering sludge. In thickening, the volume of residuals is significantly reduced. Most common technologies used are gravity thickeners and rotary sludge thickeners. (EPA 2003) In pulp and paperboard industry, gravity thickeners are most popular ones.

4.2. Conditioning

Water ponds within cell structures is why sludge is difficult to dewater. In order to increase the water repulsion of sludge in dewatering, conditioning is required. In conditioning, sludge can be treated physically or chemically. (KnowPulp 2020) Conditioning unit is commonly located right before the dewatering unit.

4.3. Dewatering

Sludge dewatering serves a lot of different aims. For instance, the cost of waste disposal is directly related to the volume of waste. In dewatering, the volume of waste that requires handing is determined. (Bajpai 2015) As a result, significant cost saving can be achieved with sufficient dewatering. Also, in dewatering, free liquids are being removed, which simplifies further waste handling and optimizes following processes. (Wang et al. 2007) Therefore, in sludge pretreatment, dewatering is considered the most essential unit operation. (Bajpai 2015)

As discussed before, sludge characteristics influence on dewaterability of sludge and the characteristics differs in each mill. Also, other dewatering methods are more efficient to some of sludges than others. Therefore, it is impossible to determine only one efficient method for sludge dewatering. Instead, each mill and their effluent treatment sludge need to be studied as their own case.

However, some basic guideline for dewaterability of different sludges exist. Primary sludges, which are high in fibre (> 20 %) and low in ash (< 30 %), are the easiest to dewater. On the other hand, secondary sludges, also known as biosludges, have higher resistance for dewatering. In the case of combined sludges, in which primary and biosludges have been mixed, dewaterability is directly related to the percentage of biolsudge in the mix: higher the percentage, higher the dewaterability resistance. (Bajpai 2015)

4.4. Drying

In dewatering, water is separated from sludge mechanically. In drying, remaining water, especially the in-cell water, is separated thermally. Dry content achieved in dewatering sludge can be appropriate for some of sludge utilization cases, but not for material or energy recovery. Therefore, drying increases its' importance in sludge pretreatment. (Bajpai 2015) Different technologies for sludge drying exist, such as fluidized bed dryers, rotary dryers and multiple heart dryers. (Bajpai 2007)

4.5. Hygienisation

In order to utilize sludge in agricultural and soil improvement applications, sludge hygienisation is prescribed by law in Finland (MMM, decree 24/11 2011). Therefore, in some of the sludge pretreatment cases one of the main objectives is to get rid of pathogenic organisms. This can be done either by increasing temperature with a thermophilic digester or by combustion. Hygienisation can also be done chemically by lime stabilization or by Kemicond treatment, for instance. (Berninger 2018)

5. Technologies used in sludge unit operations

In sludge unit operations, different technologies are required. As presented before, sludge unit operations are thickening, conditioning, dewatering and drying along with hygienisation. In following chapters, the most common technologies used in sludge treatment processes at pulp and paperboard industry are presented.

5.1. Gravity thickener

Gravity thickeners, circular tanks with slowly rotating rake mechanisms, can be implemented in clarifiers, in which approximately 2 % dry content can be achieved. As the rake mechanism rotates, it brakes junctions between sludge particles. By this, sludge volume can be decreased even down to 10 % of its' original volume as sludge settles in the bottom. (Bajpai 2015) Gravity thickener is presented in Figure 7.

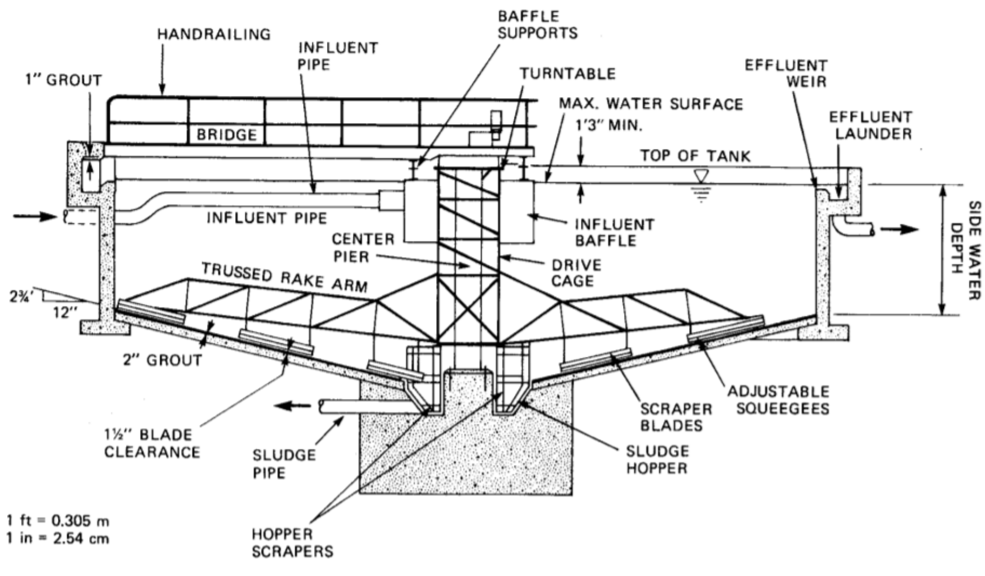

Figure 7. Gravity thickener. (EPA 2003, Figure 1)

More efficient thickening could be achieved, if thickening was implemented in a flotation unit. With flotation unit, 4 % dry content could be achieved. However, even more efficient thickening can be performed by a gravity table or a belt thickener. For example, with belt thickener, dry content could be increased even up to 15 %. In comparison, the gravity thickeners have low operating costs as well as they offer simplified machinery with minor operator attention to it. Also, energy consumption is low in gravity thickeners, but the land area required is higher. (Bajpai 2015) Performance of different pre-watering devices used in thickening is presented in Table 4.

Table 4. Performance of different pre-watering devices used in thickening. (Bajpai 2015, Table 4.1)

Equipment	**Expected dry content** (%)
gravity thickener	< 3
rotary sludge thickener	4 – 10
dissolved air flotation clarifiers	3 – 6
gravity tables	4 – 10

5.2. Physical and chemical conditioning

In physical conditioning, sludge is treated with relatively high pressure and heat conditions. The most popular methods used are wet air oxidation and heat treatment, from which heat treatment is most common one. As effluent treatment sludge is heated, water bounds within cell structures break which makes dewatering significantly easier. (Bajpai 2015) Process conditions in wet air oxidation and heat treatment are presented in Table 5. As shown, process heat conditions are slightly higher in wet air oxidation than in heat treatment, but the process pressure conditions are significantly higher.

Table 5. Process conditions in wet air oxidation and heat treatment. (Bajpai 2015)

Physical conditioning method	**Pressure** (MPa)	**Heat** (°C)
heat treatment	1 – 2	180 – 200
wet air oxidation	8.3	230 – 290

In chemical conditioning, also referred as reactant treatment, the water repulsion of sludge is increased chemically. However, mechanism differs from physical treatment. As the chemicals react with sludge, instead of breaking water bonds within the cells, the stability of the flocs is destroyed, and small particles coagulate into larger ones. As the sludge contains mainly larger particles, it is easier to dewater. Along with sludge properties and process design local prices determines, which chemical is preferred. The flocculation of sludge is commonly done by adding polymers. (Bajpai 2015) In Stora Enso, chemical conditioning by adding polymers is preferred due to its' low cost and efficiency.

In comparison, physical conditioning increases dewatering efficiency better than chemical conditioning. However, due to high energy demand, costs in physical conditioning are higher. (Bajpai 2015) Therefore, chemical conditioning is more commonly used in pulp and paperboard industry than physical conditioning.

5.3. Belt filter press

In belt filter presses, conditioned effluent treatment sludge is first drained under gravity. After this, sludge is sandwiched between two filtering belts. As the belts are tensioned, water is squeezed out by the pressure and the cake of dewatered residuals is being formed. As the sludge cake leaves the system, belt is being washed continuously. (Wang et al. 2007) Typical belt filter press and its' working principle is presented in Figure 8.

In order to achieve higher solid content, vacuum boxes can be added in belt presses' free drainage zones. (Wang et al. 2007) With the belt filter presses, approximately 20 to 35 % of dry content is achieved with feed solid concentration from 2 to 5 %. (Bajpai 2015)

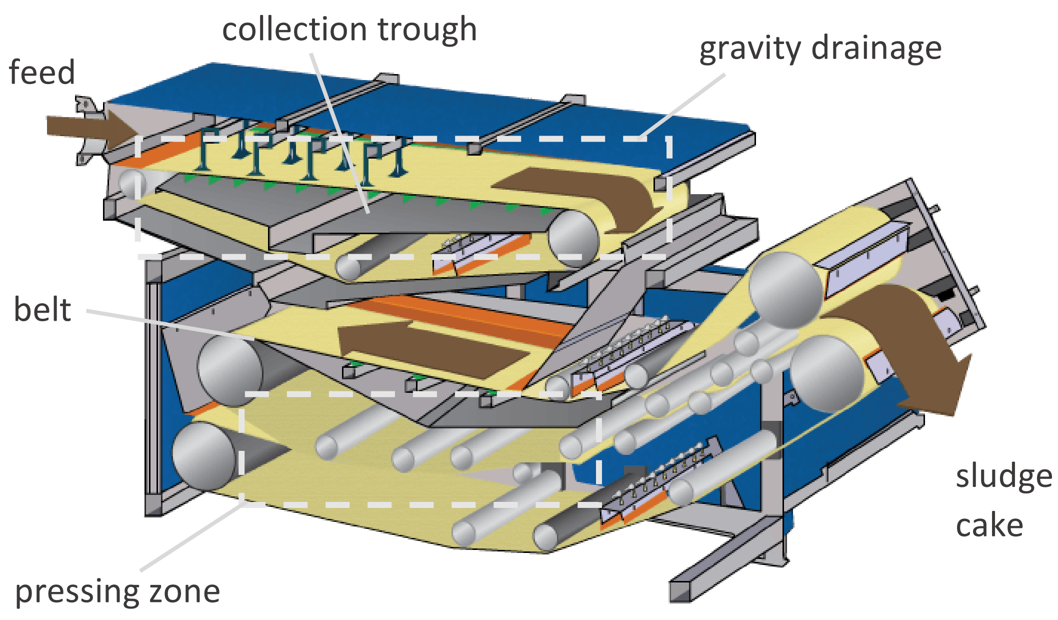

Figure 8. Belt filter press and its' basic working principle. (picture retrieved from frcsystems.com, modified)

The efficiency of belt filter presses is determined by three criteria: the dry content of dewatered sludge, sludge's lateral movement on the belt and solid recovery rate. According to studies, the performance of belt filter presses is related directly to belt speed, belt tension, feed solid concentration and input rate, for instance. (Olivier & Vaxelaire 2005)

Belt filter presses have relatively low energy consumption, approximately from 10 to 25 kWh per one tonne of sludge treated. Also, one of the main advantages is the simplicity and reliability of the technology used in these presses. However, if sludge moves excessively, solid recovery rate can be decreased, since it can cause overflow. (Olivier & Vaxelaire 2005) The belt maintenance causes few disadvantages. If any sharp objects are present, belt gets easily damaged. Also, the belt washing can require a lot of water as well as it can be time consuming. (Bajpai 2015)

5.4. Screw press

In screw presses, a gradual forced volume reduction is used in dewatering. As the screw rotates, force is created in tapered shafts. (Eckenfelder 2000) As the water dribbles for the whole length of screw shaft, dewatered sludge cake leaves at the end of screw. Back pressure is controlled by the control device. Screw press and its' basic working principle is presented in Figure 9.

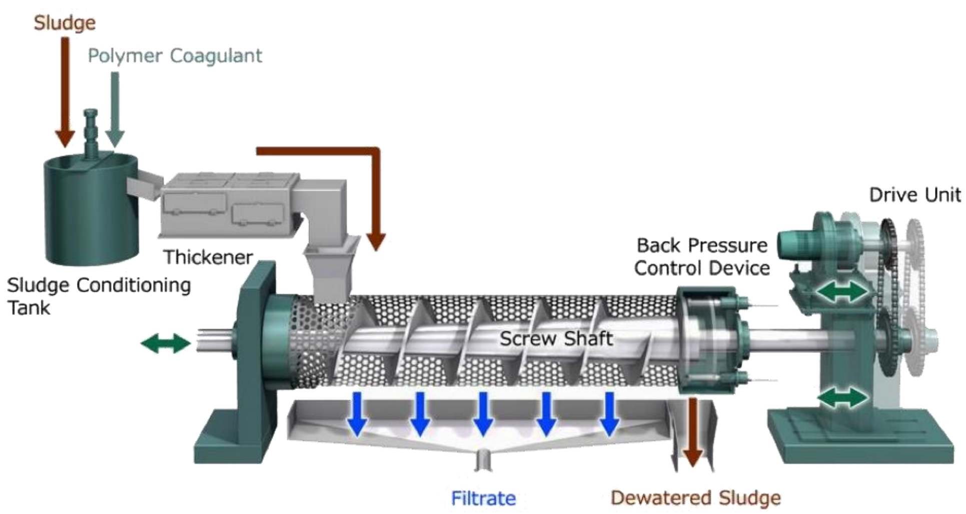

Figure 9. Screw press and its' basic working principle. (picture retrieved from viridis-engineering.com)

Effluent treatment sludges from pulp and paperboard industry contains a lot of fibres. For sludges such as these, screw presses are one of the most reliable dewatering tools. Even from 30 and up to 50 % of dry content can be achieved depending on sludge characteristics and conditioning. However, for primary sludges, screw presses have shown higher efficiency than for secondary sludges. Due to the slimy texture of secondary sludges, screw presses cannot operate well. On the other hand, energy consumption of screw presses is roughly same as belt filter presses, roughly from 10 to 30 kWh per one tonne of sludge treated, which is relatively low. (Bajpai 2015)

5.5. Decanter centrifuge

In decanter centrifuges, also known as solid-bowl centrifuges, water is separated from the solids by a centrifugal force. Decanter centrifuge consists two main parts: rotating decanter and rotating conveyor. Sludge slurry is fed from feed pipe and as the decanter rotates, conveyor rotates at faster or slower rate and transports sludge forward in pre-separation zone. Eventually, solids move to the decanter wall and forward out of the system through thickening chamber as removed water exit from the other end. Contacting can be implemented either by counter current or concurrent mode. (Wang et al. 2007f) With typical centrifuge, dry content from 25 to 35 % can be achieved whereas specific energy consumption varies from 20 to 60 kWh per tonne of sludge treated. (Bajpai 2015) Typical decanter centrifuge and its' working principle is presented in Figure 10.

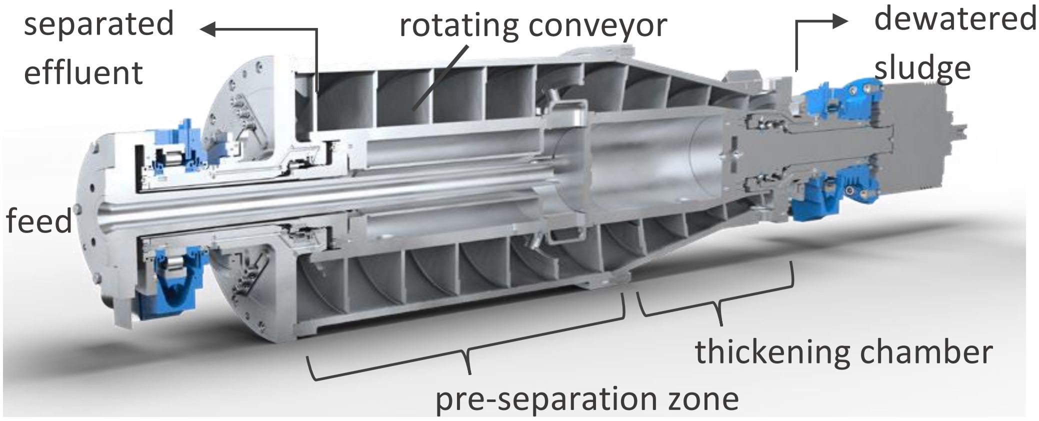

Figure 10. Decanter centrifuge and its' basic working principle. (picture retrieved from andritz.com, modified)

According to Wang et al. (2007), decanter centrifuges require little operator attention and they are adaptable for various processes. In conditioning, lower polymer dosage is required if decanter centrifuges are used in dewatering. However, decanter centrifuges are very noisy, and they have high wear and high maintenance costs.

Overall, decanter centrifuges are widely used due to their ability to achieve relatively high dry content. Dewatering efficiency is directly related to the conditioning and the sludge characteristics. Decanter centrifuges have shown higher efficiency in dewatering both primary and conditioned sludge, but with organic biosludge their operating performance suffers. (Bajpai 2015) As mentioned before, same issue has been witnessed with screw presses.

5.6. Rotary dryer

Rotary dryers structure is rather simple: a cylindrical shell which rotates upon bearings. The shell is inclined to the horizontal and feed, wet solid, is fed into upper end of the dryer. Due to the slope, rotation and head effect dried product exits from the lower end. (Mujumdar 2014) The simplified working principle of rotary dryer is presented in Figure 11.

In rotary dryers, the heat passes through drying agent. The contact between feed and drying agent can be either direct or indirect contact. In direct contact, drying agent is fed in the dryer with feed and heat is applied by steam or gas. In indirect contact, drying agent is fed into a drum jacket, for instance. Latter is better for substances in small particle size range. (Mujumdar 2014) For sludges, direct contact rotary dryers have shown to be more efficient. (Bajpai 2007)

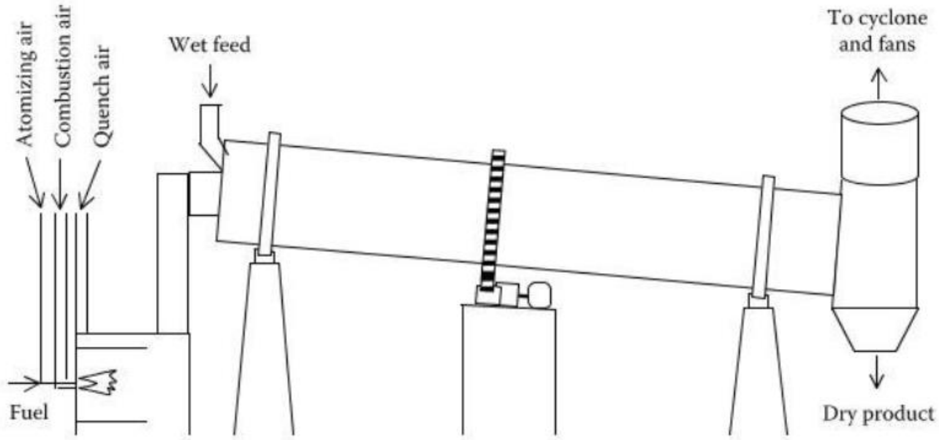

Figure 11. The simplified working principle of rotary dryers. (Mujumdar 2014, Figure 7.1)

5.7. Sludge drying beds

Sludge drying beds are used to dewater sludge both by evaporation and draining. Sludge beds consist of two layers: porous support structure and sludge layer. Further the support structure consists of sand layer, which is on top of layer of graded gravel of stone. Some of the water gets drained through the porous support structure and the drainage is collected with piping. The rest of the water is evaporated, as sludge layer's surface is exposed to the air. (Wang et al. 2007)

When wanted dry content is achieved, sludge is removed from the drying bed mechanically and manually, depending on the dry content. If dry content varies from 20 to 30 %, mechanical devices can be used. However, sludge cakes in 30 to 40 % of dry content requires manual removal. (Wang et al. 2007) The basic working principle of sludge drying beds is presented in Figure 12.

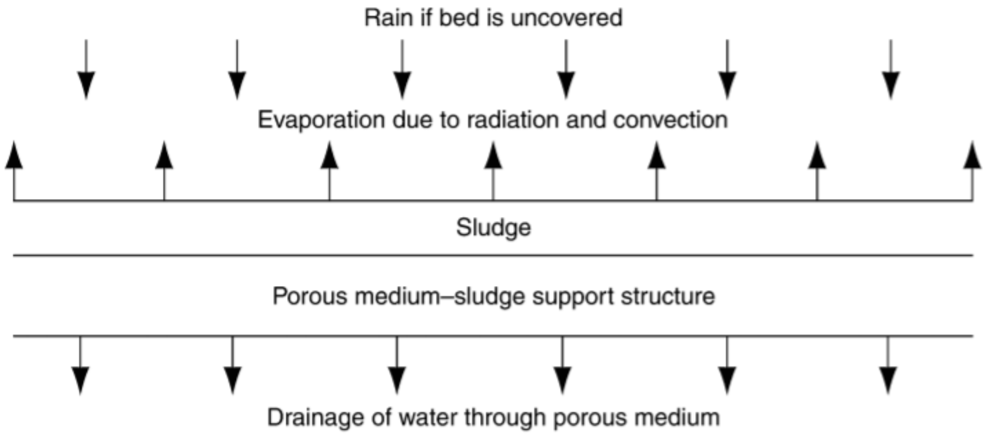

Figure 12. The basic working principle of sludge drying beds. (Wang et al. Chapter 13, Figure 1.)

Sludge drying beds requires small operator attention and operating skills, and the energy consumption is low. Also, they are less sensitive to sludge variability and if land area is already available, the lowest capital cost can be achieved. However, drying beds can be used only for stabilized sludges, they require a lot of land area and dry sludge removal is labour intensive as well as they are exposed to changing weather conditions. (Wang et al. 2007) In Finland, seasonal changes are radical, which is why sludge drying beds cannot operate evenly through whole year but could be considered in seasonal use.

Fluidized bed dryers could offer more steady operating conditions. Roughly the bed structure is same, but in fluidized beds, heat source within the bed is added. In fluidized bed hot air or steam, also known as fluid, is directed through straightening vane from the bottom of the bed. Fluid heats up the inert material, such as sand, which is in contact with the sludge. Due to the contact, which is constant with all sludge particles, sludge drying is enabled. (Bajpai 2007)

Fluidized beds and also rotary dryers could easily utilize waste heat from the mill. However, drying unit should be as close as possible to the heat source in order to minimize heat loss and sludge source as close as possible to drying unit in order to minimize sludge transportation costs. With existing mill environments, this can be impossible to arrange.

5.8. Thermophilic digester and sludge combustion

In thermophilic digester, effluent treatment sludge is treated in elevated temperature conditions as methane is being produced. (Zábranská et al. 2000) Processing temperature is approximately 55 °C, which is high enough for sludge hygienisation (Berninger 2018). As methane is being produced in thermophilic digestion, value is being added in the process as well as it offers an alternative source for biogas.

Along with thermophilic digestion, combustion can also be used in sludge hygienisation. If combustion process is well designed, temperature can increase up to 55 °C, which is sufficient for pathogens removal (Berninger 2018).

In Finland, sludge is often treated in mesophilic digester (Berninger 2018). In mesophilic digester, sludge is treated in lower temperature than in thermophilic digester. Process temperature is only approximately up to 37 °C in mesophilic digester, which is not high enough for removing all of the pathogens. (Zábranská et al. 2000) Therefore this treatment requires further sludge hygienisation.

5.9. Lime stabilization and Kemicond treatment

Along with increasing temperature, sludge hygienisation can be done chemically. The most popular chemical hygienisation methods are lime stabilization and so called Kemicond treatment method. (Berninger 2018)

In lime stabilization, CaO, also known as burnt lime, or $Ca(OH)_2$, also known as hydrated or slaked lime, is mixed with sludge. Hygienisation is based on increased temperature change and/or increased pH change. If lime stabilization is done with slaked lime, hygienisation is based only in the change of pH. In case of burnt lime, temperature is increased in along with pH change due to the chemical reaction. In addition, lime also binds water to itself and combustion of organic hazardous materials are put down. (Kykkänen et al. 2014) In paper and pulp industry, lime stabilization is commonly used due to its' efficiency and low cost.

In so called Kemicond method, sludge hygienisation is applied chemically by sulfuric acid and hydrogen peroxide. Pathogens are deactivated as the chemical treatment breaks down cell structures. Kemicond method also increases sludge dewaterability as cell structures are being destroyed. (Berninger 2018) As mentioned before, the main difficulties in sludge dewatering are caused by water within the cell structures. However, due to the acids and hazardous chemicals used in Kemicond method, process safety can cause major concerns if compared with lime stabilization.

6. Sludge utilization

As mentioned before, in the legislation point of view, effluent treatment sludge is considered as a waste in Finland. However, each side stream is needed to be evaluated as a potential raw material source in the terms of circular economy. As far as sludge utilization possibilities are considered, the aims of circular economy are fulfilled.

In order to process sludge for utilization purposes efficiently, processing facilities must have sufficient amount of storage as well as sludge transportation must be coordinated accordingly. This enables the possibility of steady process volumes and conditions in various situations. (Pöyry Environment Oy 2007) However, as discussed before, sludge is high in moisture content. According to estimated, economically reasonable transportation distance for industry sludges is approximately from 150 to 250 km. (Pöyry Environment Oy 2007) Therefore, sludge processing facilities must be located as near as possible to sludge source.

In this chapter, different sludge utilization possibilities are presented and briefly evaluated. Evaluation is based on reasonability in economical and energy efficient points of views. Along with different utilization possibilities, the legislation point of view is discussed.

6.1. Legislation

As mentioned before, utilizing sludge from wastewater treatment plant is prescribed by law in Finland. However, legislation mostly considers utilizing sludge in agricultural and soil improvement uses. Decrees in Finland dates back to European

Union directive 86/278/EEC, also known as Sewage Sludge Directive. This directive aims to regulate sludge utilization in agricultural uses in terms of preventing harm caused in soil or vegetation, for instance. (Tavazzi et al. 2012) However, decrees in Finland are significantly stricter than in other countries. In energy recovery utilization cases, emissions and legislation concerning them are in high interest.

As discussed before, in order to utilize sludge from wastewater treatment plant in agricultural and soil improvement uses, hygienisation is required. Along with hygienisation, maximum heavy metal content is prescribed in detail by law (MMM, decree 24/11 2011). Maximum heavy metal content for sludge utilized in agricultural uses are presented in Table 6. As discussed before, sludge from pulp and paper mills often exceed maximum cadmium content levels, which forbids soil improvement uses. However, there is significant differences in regulation limits even in Europe. In Finland, maximum cadmium content allowed is 1.5 mg per one kilogram of dry sludge, but same value in Germany is 10 mg per one kilogram of dry sludge and in Italy 20 mg per one kilogram of dry sludge, for instance. (Tavazzi et al. 2012)

Table 6. Maximum heavy metal content for sludge utilized in agricultural uses in Finland (MMM, decree 24/11 2011) Content is informed in mg per one kilogram of dry sludge.

Heavy metal	**Content, mg/kg**
As	25
Hg	1.0
Cd	1.5
Cr	300
Cu	600
Pb	100
Ni	100
Zn	1500

In energy recovery, emissions from sludge burning and emission limits are in high interest at pulp and paper industries. As effluent treatment sludge is being burned, emissions such as carbon monoxide, nitrogen oxide, sulphur dioxide and fine particulate matter are being released. However, emissions can vary seasonally due to changes in sludge characteristics (Nielsen et al. 2019) Each of these emissions mentioned have negative impact in the environment and in the health of human. Therefore, the National Emission Ceilings Directive have set national emission reduction commitments for member states of European Union regarding nitrogen oxides, sulphur dioxide, ammonia, fine particular matter and non-metane volatile organic compounds. In commitment, member states, such as Finland, are agreed to reduce health impacts of air pollution by half by 2030 in comparison with year 2005. (European Environment Agency 2020) Therefore, pulp and paperboard industry will have to prepare themselves in more strict legislation regarding emissions and take their energy recovery processes in close study.

6.2. Energy production

While economically reasonable sludge utilization possibilities are yet under study and some are applied in use, most of the sludge is used in energy production in pulp and paperboard industry. (Bajpai 2015) Despite its' popularity, in most cases sludge is not an ideal fuel for efficient energy production as it is.

Sludge utilization in energy production consist of three main stages: pretreatment, burning and disposal of residuals (Pöyry Environment Oy 2007). The pretreatment of sludge is applied in terms of dewatering and drying, as discussed before. Burning is implemented in boilers. Commonly in pulp and paperboard industry sludge is burned in bark boilers along with bark within mill premises. (Bajpai 2015) In some pulp mills, sludge can also be burned in recovery boiler along with black liquor in terms of chemical recovery (Bajpai 2017).

In order to achieve economically reasonable and energy recovery efficient sludge burning process, the heating value of sludge must be increased by increasing dry content of sludge. This can be done by investing in sludge dewatering or drying, for instance. However, optimal dry content varies case-by-case due to other variables, such percentages of other fuels. In addition, if dry content of sludge is increased excessively, other consequences, such as dusting, needs to be considered in process optimization. (Pöyry Environment Oy 2007) Before new investments can be made, costs and benefits must be evaluated carefully. If more energy is consumed in sludge dewatering and drying than what its’ gained in burning, new investments are not reasonable in the terms of energy recovery.

Along with energy, burning also produces some residuals, ashes, which can be either utilized or after stabilization disposed into landfill. According to the law in Finland, ash formed in sludge burning is not considered as soil improvement. Therefore, it cannot be used as fertilizer or as soil improvement on its’ own, but fractions, such as phosphorus, can be separated from ash and be used further as raw material in fertilizers. In addition, these ashes can be used in road construction or in cement manufacturing, for instance. (Pöyry Environment Oy 2007) Various utilization possibilities for sludge burning residuals add value in the burning process and decreases the need of costly waste disposal into landfills. In terms of circular economy, this is desired feature.

6.3. Soil improvement and agricultural uses

Pulp and paper mill sludge is high in fibre, but also in plant nutrients, such as nitrogen and phosphorus (Wang et al. 2007). According to study by Camberato et al. (2006), biosludge from pulp and paperboard mills is high in plant nutrients, whereas primary sludge is high in carbon, but low in plant nutrients. Overall, as soil improvement, both sludges seem to have their benefits and utilization potential.

According to study by Kinnunen et al. (2017), erosion can be reduced with soil improvement made from sludge. This increases the continence of water in soil. Same study also pointed out, that as the soil was treated with sludge, the amount of eroded phosphorous was significantly decreased. In eroded nitrogen, remarkable changes were not discovered. Sludge also increases organic matter in the soil, which is beneficial for vegetation in agriculture. Good to note, that as organic matter is added in the soil, it also works as significant carbon storage. (Kinnunen et al. 2007) In terms of sustainable and efficient agriculture, all these findings are remarkable.

As discussed before, in order to utilize sludge in agricultural and soil improvement uses, sludge hygienisation and maximum heavy metal concentrations are prescribed by law. Based on the information presented before, sludge hygienisation is easy to achieve with existing technology, but cadmium concentration is the main issue in agricultural applications, since sludges from pulp and paper mills can easily exceed the limit concentration. Since sludge characteristics varies, usability of each mill's sludges is needed to be evaluated case-by-case.

Despite sludge's good features in soil improvement and agricultural uses, this utilization possibility struggles with demand and possible negative approach. In Finland, most of the pulp and paper mills are concentrated within same area and/or in areas, which are located relatively far away from agriculture. Even though sludge could be processed within mill facilities for soil improvement uses, overall cost can increase unreasonably due to high transportation costs. Nevertheless, from a stand point of law, sludge is considered as a waste. Unfortunately, instead of considering waste as valuable resource, it can have negative approach within public eye.

6.4. Biogas

In recent years the need for non-fossil fuels in energy production has been increasing rapidly due to global warming. One of these fuels is biogas, also known as sustainably produced methane.

In biogas production, organic material in solid waste is converted into methane. Various different methods for biogas production exist. For instance, methane can be produced by anaerobic digestion or pyrolysis. (Wang et al. 2007) Here anaerobic digestion is presented as pyrolysis is discussed further on.

In aerobic digestion, sludge is decomposed by anaerobic bacteria in oxygen-free conditions. Depending on process design, retention time can vary between 15 to 60 days. End products are mainly methane, carbon dioxide and stable organic residues. Anaerobic digestion can be used for stabilizing sludge for soil improvement and agricultural uses, in which methane is valuable byproduct. Along with stabilization, dewaterability of sludge is improved and volume of waste is significantly decreased in anaerobic digestion, as the process itself does not require oxygen or significant amounts of additional nutrients. Anaerobic bacteria require inorganic nutrients, such as nitrogen and phosphorus, which are often available in wanted quantities in the sludge itself. (Wang et al. 2007)

Due to the high organic material content and high nutrient content, sludge is potential raw material for biogas production. In biogas production, sludge as raw material has relatively high production rate. According to study by Huopana et al. (2015), approximately from 60 to 65 % of volatile solids could be converted into methane. Also, since aerobic digestion is known method in sludge stabilization, practical experience has already been gained.

However, relatively high retention time, disposal of residues along with available facilities are one of main concerns in sludge utilization into biogas. While some of the residues could be utilized in agricultural and soil improvement uses, demand is yet slightly limited. Also, biogas production facilities should be located nearby sludge source since transporting sludge is costly and troubled due to high moisture content. This can cause issues within existing mill units. The amount of sludge that could be utilized in biogas production should be studied for each mill in economical point of view case-by-case.

6.5. Pyrolysis and hydrothermal carbonization (HTC)

Biochar is a product produced from biomass in aerobic or anoxic conditions. Pyrolysis and hydrothermal carbonization, also known as *HTC*, are both thermochemical conversion technologies for biochar production. (Yungui et al. 2016) For these technologies, sludge could be potential raw material option.

In pyrolysis, biomass is converted into biochar in an inert atmosphere and elevated temperatures. Process temperature range varies from 300 to 650 °C. Pyrolysis is well known for its' high yields and energy-efficiency. However, pyrolysis serves best for relatively dry biomass. (Hagner et al. 2018) In order to use sludge in pyrolysis efficiently, its' typical dry content needs to be increased.

For sludge, hydrothermal carbonization is more optimal due to relatively high moisture content. In HTC, wet biomass is converted to biomass under pressure at moderate temperature. Process pressure is typically under 50 bar and temperature range varies from 180 to 260 °C. In this process, water serves as carbonization medium. Produced biochar can be utilized in energy production, (Hagner et al.

2018) due to its' high heating value, or in adsorption as adsorbent, for instance (Yungui et al. 2016).

However, the lignocellulosic nature of pulp and paper mill sludge needs to be considered in HTC process design in terms of maximizing the yield. In order to degrade hemicelluloses, required temperature varies from 180 to 260 °C, but for cellulose, optimal process temperature varies from 240 to 350 °C. The most difficult to degrade is lignin, which requires process temperature from 280 to 500 °C. (Hagner et al. 2018)

In Finland, Stora Enso has experimental HTC plant starting in Heinola. In this plant, sludge is used as raw material in biochar production. Further on, produced biochar would be utilized in energy production within mill premises.

STUDY OF MILL CASES

7. Sludge treatment processes and annual characteristics in Finland

Stora Enso has several different types of mills globally in different locations (Stora Enso, 2020). In this thesis the focus is on eight different pulp-based mills located in Finland. Selected mills are in Oulu, Heinola, Uimaharju, Veitsiluoto, Anjalankoski, Sunila, Imatra and in Varkaus.

In following chapters, study of mill cases is presented. Sludge treatment process in each mill is presented along with their annual sludge characteristics, such as quality and quantity. Majority of the information is gathered by interviewing environmental specialist from each mill.

7.1. Imatra Mills

Imatra Mills belongs in Stora Enso's Packaging Materials division, which products are consumer board, pulp and plastic coating. Two individual production units, Kaukopää and Tainionkoski, form the total Imatra Mills. Annual production capacities are 1 155 000 tonnes of consumer board, 825 000 tonnes of pulp from Kaukopää production unit, 195 000 tonnes of pulp from Tainiokoski production unit and 285 000 tonnes of polymer coated board. (Stora Enso, 2020)

Despite of two individual production units, they share one wastewater treatment plant. In order to gather information from Imatra Mills, their two environmental specialists, Heini Mahlamäki and Teemu Klemetti, were interviewed.

7.1.1. Sludge treatment process

Imatra Mills produces approximately from 100 to 150 thousand wet tonnes of sludge annually. Approximately one third is biosludge and two-thirds is primary sludge. In Imatra Mills, biosludge is processed in two streams: roughly half of the biosludge is mixed with primary sludge, and another half is mixed with black liquor.

Composition of primary sludge and biosludge is first thickened with drum thickener. After this, composition is dewatered with screw press, with which approximately 30 % dry content is achieved. After dewatering, composition of primary sludge and biosludge is mixed with bark before utilization.

Second half of the biosludge is dewatered with decanter centrifuge. After dewatering, biosludge is mixed with black liquor before utilization. The flowsheet of the sludge treatment process in Imatra Mills is presented in Figure 13.

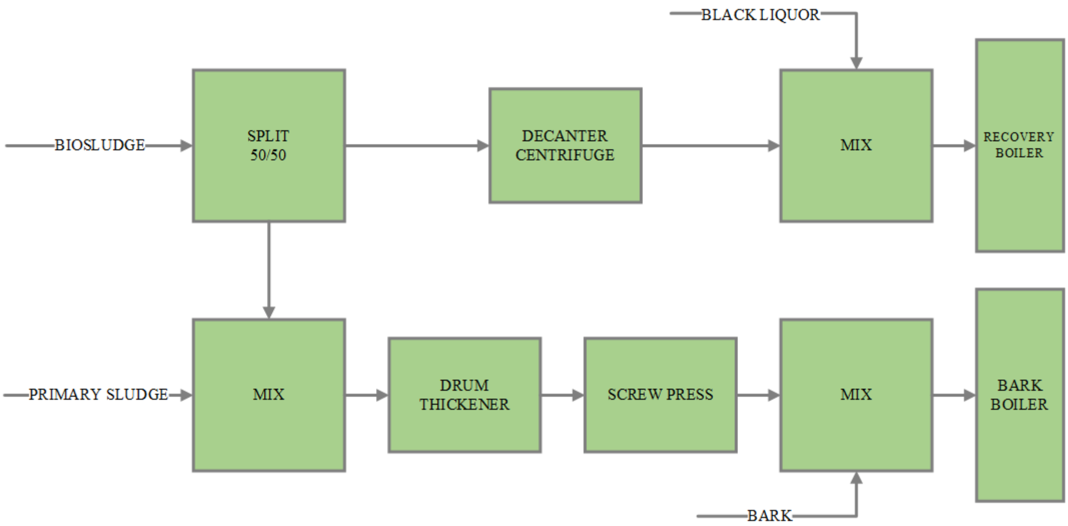

Figure 13. Sludge treatment process in Imatra Mills.

7.1.2. Sludge utilization

Most of the biosludge, primary sludge and bark composition are utilized in energy production in bark boiler. However, approximately 5 to 10 % of sludge is utilized in soil improvement applications. In chemical recovery composition of biosludge and black liquor is burned in recovery boiler.

As the sludge is burned in bark boiler, it decreases bark boiler capacity due to low heating value in sludge. Therefore, especially during winter Imatra Mills resorts to natural gas as support fuel in order to produce enough energy. Furthermore, as the bark is mixed with sludge, if there is delay in burning, bark starts to decompose, which decreases the heating value of bark.

Regarding bark boiler, Imatra Mills has had month long trial, in which bark boiler was operated only with bark. As a result, sulphur emissions of the bark boiler was significantly decreased and the boiler capacity was increased. However, ash from boiler lost its' concrete-like properties, which made it useless in land construction uses.

Imatra Mills is willing to utilize more sludge into soil improvement, but the mill location causes issues. Since Imatra Mills is located in area, which has a lot of pulp and paperboard industry, there is oversupply of sludge. Furthermore, cadmium levels in sludge may restrain the use in soil improvement applications.

7.2. Sunila Mill

Sunila Mill belongs in Stora Enso's Biomaterials division, and their main products are softwood pulp and lignin. They also produce tall oil and turpentine. Annual production rates are 375 000 tonnes of pulp and 50 000 tonnes of lignin. (Stora Enso, 2020) Manager of environmental affairs, Terttu Heinonen, was interviewed from Sunila Mill.

7.2.1. Sludge treatment process

In Sunila Mill, biosludge and primary sludge are being produced. Approximately 2000 dry tonnes of biosludge and 2300 dry tonnes of primary sludge are produced annually. In comparison with other mills, Sunila Mill is exceptional since biosludge is produced more than primary sludge.

In sludge treatment process at Sunila Mill, biosludge and primary sludge are mixed before dewatering. Dewatering is done with belt filter press, with which approximately 30 % dry content is achieved. Before utilization, sludge is mixed with bark. The flowsheet of the sludge treatment process in Sunila Mill is presented in Figure 14.

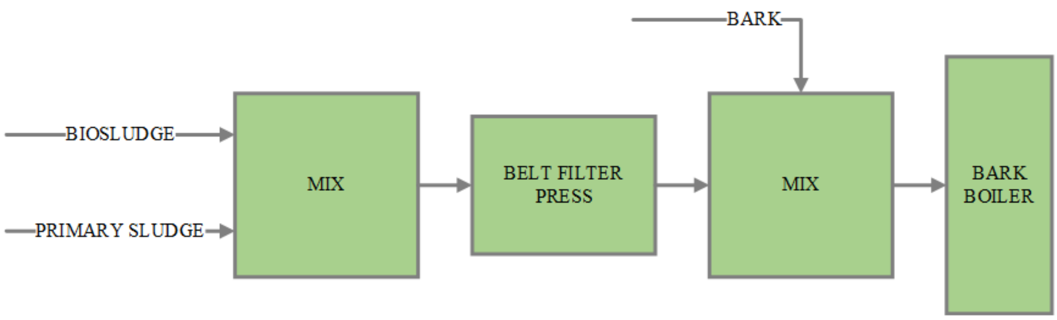

Figure 14. Sludge treatment process in Sunila Mill.

7.2.2. Sludge utilization

In Sunila Mill, all sludge is utilized in energy production. As the dewatered sludge is mixed with bark, it is burned in bark boiler, in which natural gas is used as support fuel, if needed. Primary sludge could be used as soil improvement, but primary sludge is needed to support dewatering biosludge.

However, cadmium content limits the utilization in soil improvement applications in Sunila Mill. Primary sludge is optimal for soil improvement, but biosludge on itself cannot be dewatered enough with belt filter press. Therefore, with existing dewatering equipment, it is not possible to burn only biosludge with bark.

7.3. Varkaus Mill

Varkaus Mill belongs in Stora Enso's Packaking Materials division, and they produce containerboard and pulp. Annual production rates are 390 000 tonnes of containerboard and 310 000 tonnes of pulp. In Varkaus Mill unit has also their own sawmill. (Stora Enso, 2020) These two production units together with local fishery share same wastewater treatment plant. From Varkaus Mill, two environmental specialists, Ulla-Maija Olander and Tenho Pakarinen were interviewed.

7.3.1. Sludge treatment process

Varkaus Mill has several different sludge fractions, which are biosludge, primary sludge and tertiary sludge along with the sludge from the fishery. Annually, 25 thousand wet tonnes of sludge is produced. From annual sludge quantity, approximately from 60 to 70 % is primary sludge, 5 % is biosludge and 20 % is tertiary sludge. Fishery produces approximately from 1 to 1.5 % of total sludge amount. All sludges are mixed before treatment.

In sludge treatment process at Varkaus Mill, preliminary water separation is done by gravity belt. The main dewatering is done by screw press, which can achieve approximately from 35 to 40 % dry content. However, in a case of screw press malfunction, sludge can be dewatered by two parallel belt filter presses. Dewatered sludge is mixed with bark before bark boiler. The flowsheet of the sludge treatment process in Varkaus Mill is presented in Figure 15.

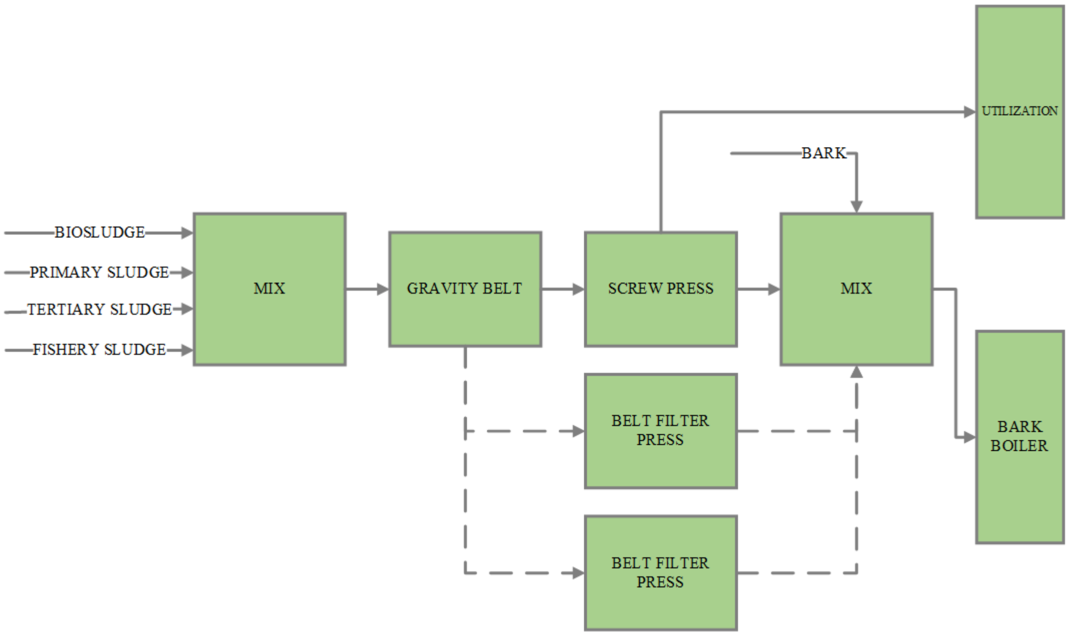

Figure 15. Sludge treatment process in Varkaus Mill. In a case of malfunction, sludge dewatering can be done with two belt filter presses.

Varkaus Mill is considering to invest in sludge dryer, which would utilize secondary heat in drying. Approximately 30 to 40 % of drying would be done by secondary heat, the rest with primary heat. This would increase the dry content from 30 % up to 40 - 60 %. Achieved dry content is rather optimal dryness for sludge. If the dry content increases too high, problems with sludge handling due to dust, for instance, might occur.

7.3.2. Sludge utilization

At the moment sludge is utilized in energy production in Varkaus Mill. Sludge is mixed with bark and burned in bark boiler, in which coal is used as support fuel, if needed. Regarding sludge utilization experimentation, Varkaus Mill has had various trial implementations. For instance, Varkaus Mill is going to use primary sludge in landscaping as they are building sound barrier around the mill area.

Primary sludge is also tested in agricultural uses as litter. Primary sludge utilized as litter have seemed to be beneficial. For example, in agriculture, primary sludge seems to work better as litter than peat or sawdust and it is easier to spread in fields afterwards. However, results of trial are still under study. In addition, primary sludge is also tested as support material in offal compost.

7.4. Anjalankoski Mills

Two individual production units, Anjala Mill and Ingerois Mill forms the total Anjalankoski Mills. Anjala Mill belongs in Stora Enso's Paper division, and they produce variety of different papers from mechanical pulp, such as book paper, magazine paper and improved newsprint. Annual production capacity of paper is 435 000 tonnes. Ingerois Mill belongs in Stora Enso's Packaging Materials division, and they produce folding boxboard. Annual production capacity of board is 290 000 tonnes. (Stora Enso, 2020)

Anjalankoski Mills have one wastewater treatment plant, which is shared by two individual production units. Environmental manager Heini Kukkonen was interviewed from Anjalankoski Mills regarding their sludge treatment process and sludge utilization.

7.4.1. Sludge treatment process

At Anjalankoski Mills, biosludge, primary sludge and bark sludge are being produced. However, occasionally tertiary sludge is also generated. If so, tertiary sludge is directed in the same processing stream with biosludge. Approximately 13 thousand dry tonnes of sludge is produced annually. From annual production, roughly 50 % is primary sludge, 25 % is biosludge and 25 % is bark sludge.

Before dewatering, different sludge fractions are mixed. Received sludge compound is either dewatered by belt filter press or first thickened before dewatering compound by screw press. Major part of biosludge is dewatered separately with decanter centrifuge. In dewatering, approximately 30 % dry content is achieved. After dewatering, sludge is transported either to boiler or in utilization. The flowsheet of the sludge treatment process in Anjalankoski Mills is presented in Figure 16.

Typical problems faced with sludge treatment are different odour related issues. Only after sludge is made hygiene for soil improvement applications, odour is disposed.

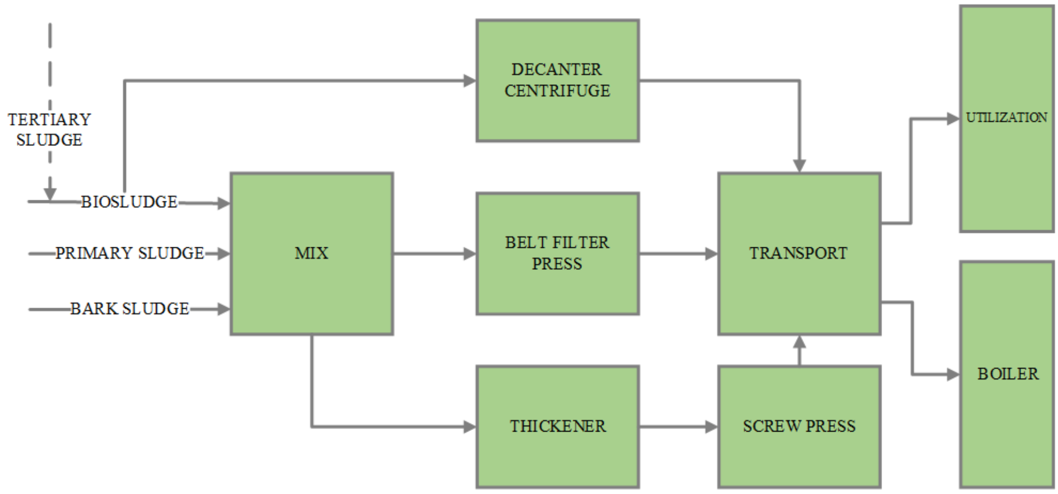

Figure 16. Sludge treatment process in Anjalankoski Mills. Occasionally produced tertiary sludge is directed in biosludge stream for further processing.

7.4.2. Sludge utilization

In Anjalankoski Mills, sludge is utilized in energy production and in soil improvement applications. Majority of sludge, approximately 90 %, is used in energy production and the rest is used in soil improvement applications. Sludge from Anjalankoski Mills is exceptionally good for soil improvement due to its' low cadmium content. Anjalankoski Mills would like to increase soil improvement utilization, but there is not enough demand for it.

7.5. Uimaharju Mill

Uimaharju Mill belongs in Stora Enso's Biomaterials division. Their products are softwood pulp and dissolving pulp. Annual production rate is 450 000 tonnes of pulp. Stora Enso has also a sawmill in Uimaharju, which is part of Biomaterials division. (Stora Enso, 2020) These two production units share same wastewater treatment plant. From Uimaharju Mill, environmental specialist Harri Lepistö was interviewed.

7.5.1. Sludge treatment process

In Uimaharju Mill, approximately 4000 wet tonnes of biosludge in 14 % of dry content and approximately 3300 wet tonnes of primary sludge in 47 % dry content are annually produced.

In sludge treatment process at Uimaharju Mill, primary sludge is dewatered by screw press and disc filter. Biosludge is dewatered with decanter centrifuge. After dewatering, primary sludge and biosludge are mixed with bark before utilization. Uimaharju Mill used to first mix biosludge and primary sludge before dewatering the mixture with belt filter press. After investing separate primary sludge and biosludge dewatering equipment, issues with released sulphur compounds in dewatering process have been decreased. The flowsheet of the sludge treatment process in Uimaharju Mill is presented in Figure 17.

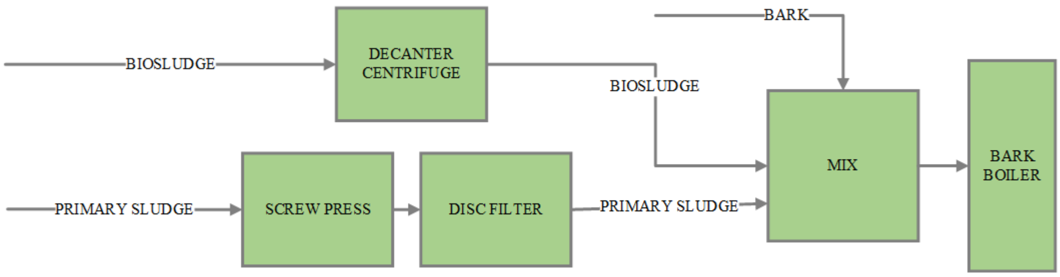

Figure 17. Sludge treatment process in Uimaharju Mill.

7.5.2. Sludge utilization

Sludge is totally utilized in energy production in Uimaharju Mill as sludge is burned in bark boiler. Uimaharju Mill have not had any major issues in sludge burning. However, sludge burning works in stable way if only the sludge is properly mixed with bark. If not, the boiler temperature might suffer and drop radically.

7.6. Veitsiluoto Mill

Veitsiluoto Mill belongs in Stora Enso’s Paper division, but including paper, they also have production facilities for pulp and sawn products. The paper products in Veitsiluoto are light-weight and medium-weight coated paper, and wood free uncoated paper. Annual production rates are 850 000 tonnes of paper, 380 000 tonnes of pulp and 200 000 m^3 of sawn timber. (Stora Enso, 2020) Pipsa Maikkula, the environmental specialist from Veitsiluoto Mill, was interviewed.

7.6.1. Sludge treatment process

In Veitsiluoto Mill, biosludge and primary sludge are being produced. Approximately 26 dry tonnes of sludge is produced annually, from which approximately 40 % is biosludge. In Veitsiluoto Mill, it is not economically reasonable to invest in dryer for biosludge alone. Therefore, biosludge is dewatered along with primary sludge with two parallel belt filter presses. Before dewatering primary sludge and biosludge are being mixed. With belt filter press, 27 % dry content is achieved before utilization. The flowsheet of the sludge treatment process in Veitsiluoto Mill is presented in Figure 18.

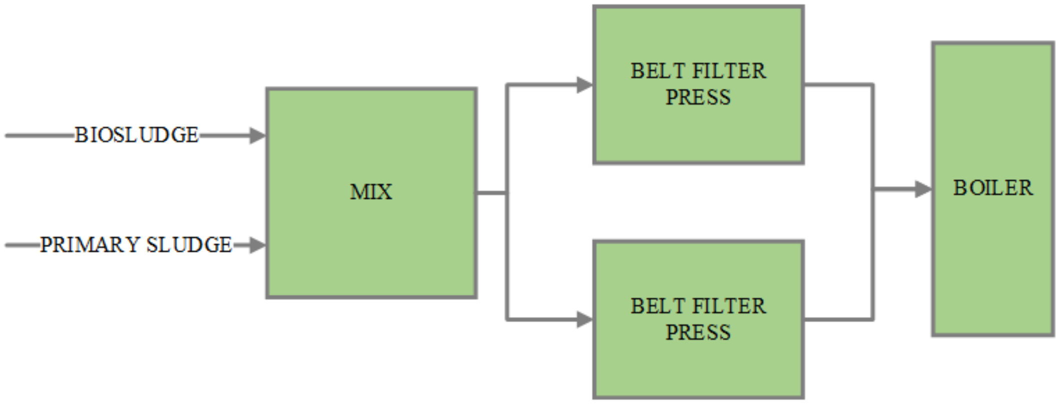

Figure 18. Sludge treatment process in Veitsiluoto Mill.

7.6.2. Sludge utilization

In Veitsiluoto Mill, sludge is mainly used in energy production. In energy production, sludge is burned in boiler along with wood waste and peat. Some of the sludge has also been used in landscaping. However, the landscaping utilization is forbidden by the end of year 2023. Therefore, in the future, all of the sludge is utilized in energy production.

7.7. Oulu Mill

Oulu Mill belongs in Stora Enso's Paper division, and at the moment they produce wood-free coated paper and bleached softwood pulp. Mill also has facilities for sheeting. Oulu Mill's annual production rates have been 1 080 million tonnes of paper and 360 tonnes of pulp. (Stora Enso, 2020)

In order to gather information from Oulu Mill, their environmental specialist Mervi Partanen was interviewed. However, needed to be noted, that at the moment Oulu Mill is living in the time of change, which is why current sludge fractions are unknown. According to Partanen, Oulu Mill's paper production will transfer totally into board production. After transition, Oulu Mill will be part of the Stora Enso's Packaging Materials division. Transition is expected to be ready at the late autumn in 2020.

7.7.1. Sludge treatment process

Currently in sludge treatment process at Oulu Mill biosludge and primary sludge are mixed and after dewatered with decanter centrifuge and further dried by belt filter press. After dewatering, sludge is mixed with bark before utilization. The flowsheets of the sludge treatment process in Oulu Mill before the transition are presented in Figure 19.

At the moment Oulu Mill have not highly invested in sludge drying since it has not been economically reasonable. As the board production starts, the amount of biosludge will increase significantly. Therefore, Oulu Mill will most likely have to invest in biosludge dewatering.

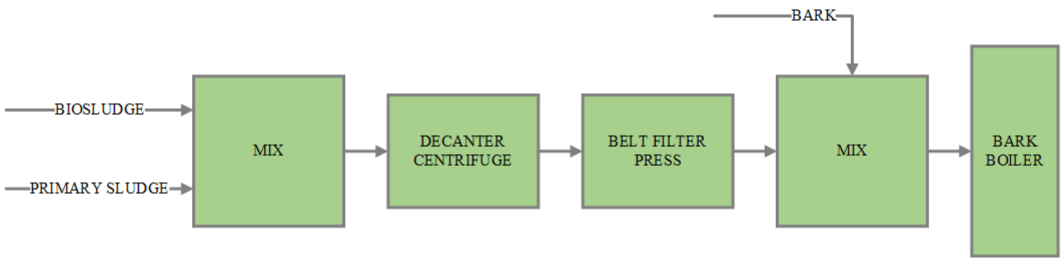

Figure 19. Sludge treatment process in Oulu Mill before the transition.

7.7.2. Sludge utilization

At the moment, in Oulu Mill sludge is utilized in energy production as sludge is burned in bark boiler along with bark. As mentioned before, after the transition, the amount of biosludge will increase significantly. Burning the biosludge is not desired due to the low dry content. However, Oulu Mill is highly interested in new biofuel products. If biosludge could be utilized into biofuel, Oulu Mill could eventually dispose the use of peat in energy production.

Oulu Mill has also preliminary studied, if sludge could be utilized in soil improvement applications. However, the final outcome will be clarified as soon as the board production starts and there is sufficient amount of data from the sludge characteristics. Since Oulu Mill shares their wastewater treatment plant with other smaller production units located nearby, there might be some characteristic issues for soil improvement applications.

7.8. Heinola Mill

Heinola Fluting Mill belongs in Stora Enso's Packaging Materials division. Mill has facilities for pulp production, but their main product is high-quality semi-chemical fluting. Fluting is used in the corrugated board industry. Annual fluting production rate is 300 000 tonnes. (Stora Enso, 2020) From Heinola Fluting Mill, environmental specialist Kaisa Vuori was interviewed.

7.8.1. Sludge treatment process

In Heinola Fluting Mill biosludge and primary sludge are produced. Approximately 39 wet tonnes of sludge is annually produced from which roughly 55 % is primary sludge and 45 % is biosludge. Biosludge and primary sludge are processed separately, since they are utilized separately. Biosludge is dewatered with decanter centrifuge, with which approximately 13 % dry content is achieved. Primary sludge is dewatered with belt filter press. After dewatering, biosludge continues to utilization. Primary sludge is mixed together with bark before utilization. The flowsheet of the sludge treatment process in Heinola Mill is presented in Figure 20.

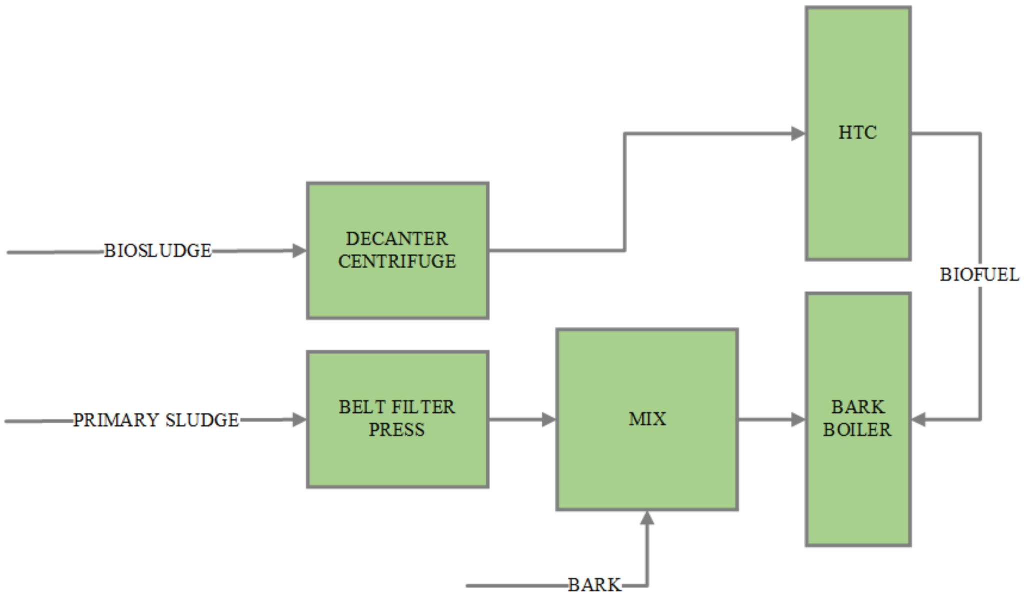

Figure 20. Sludge treatment process in Heinola Mill.

7.8.2. Sludge utilization

In Heinola Mill, sludge is utilized in energy production. Due to low heating value in biosludge, primary sludge and biosludge are processed in two different processes.

Recently Heinola Mill has invested in HTC experimental plant. HTC plant function is to improve heating value by generating biofuel out of biosludge. HTC plant is expected to be fully operating as in the near future. It has been estimated that burning the biofuel is better option than burning biosludge in energy recovery.

Primary sludge has rather good heating value, which is why primary sludge is utilized in energy production at Heinola Mill. Primary sludge is burned in bark boiler along with bark, in which also biofuel will be utilized once HTC plant starts operating.

7.9. Conclusion based on interviews

Since sludge dry content is crucial characteristic in utilization applications, sludge dewatering equipment is in high interest. In technical point on view, each Stora Enso mill in Finland uses similar technical implementations in their sludge treatment processes. Most commonly used dewatering equipment are belt filter press and screw press. These two are the most common within mills, which dewaters primary sludge and biosludge as one or primary sludge as its own. According to literature, belt filter press and screw press are exceptionally good for dewatering primary sludge, but since mixing primary sludge with biosludge improves biosludge's dewaterability, equipment choice seems reasonable. Along with belt filter press and screw press, decanter centrifuge was also commonly used, especially in dewatering biosludge as its own.

The most common sludge utilization application is energy recovery. Each mill uses their sludge either totally or mostly in energy recovery, in which they burn sludge along with bark or other wood waste in a boiler. Couple of mills, such as Imatra Mills and Anjalankoski Mills, utilize some of their sludge as soil improvement. However, most of the other mills do actively study other sludge utilization possibilities in addition to energy recovery. Conclusion for each mill main products along with annual sludge production, sludge fraction percentages, utilization applications and highlights are presented in Table 7.

Based on the interviews and study on each mill, differences between mills can be seen. Each mill has slightly different main products and annual production rates. There is some differences in sludge treatment processes, annual sludge production rates and individual differences in sludge fractions and characteristics. In addition, each mill has their own highlight either in their sludge treatment process or in sludge utilization uses. Therefore, it is safe to say that in order to execute valid evaluation in terms of sludge treatment process and sludge utilization, each mill has to be evaluated more closely case by case.

Table 7. Conclusion based on interviews. For each mill main products along with annual sludge production, sludge fraction percentages, utilization application and highlights are presented.

Mill and main products	Sludge production annually	Sludge fraction percentages	Utilization application	Highlights
Imatra (consumer board, pulp, plastic coating)	100-150 thousand wet tonnes	66 % primary 33 % bio	90-95 % in energy recovery 5-10 % in soil improvement	Natural gas required as support fuel.
Sunila (softwood pulp, lignin)	14 thousand wet tonnes	53 % primary 47 % bio	Energy recovery	Cadmium content limits utilization as soil improvement.
Varkaus (containerboard, pulp)	25 thousand wet tonnes	60-70 % primary 5 % bio 20 % tertiary 1-1.5 % sludge from fishery	Energy recovery Other applications under study	Multiple different sludge fractions.
Anjalankoski (paper, boxboard)	43 thousand wet tonnes	50 % primary 25 % bio 25 % bark	90 % in energy recovery 10 % in soil improvement	Exceptionally good qualities for soil improvement applications, but not enough demand.
Uimaharju (softwood pulp, dissolving pulp, sawmill)	7300 wet tonnes	45 % primary 55 % bio	Energy recovery	Primary sludge and biosludge dewatered separately.
Veitsiluoto (paper, pulp, sawmill)	96 wet tonnes	60 % primary 40 % bio	Energy recovery	Landscaping utilization forbidden by the end of year 2023.
Oulu (-)	Not relevant	Not relevant	Energy recovery Other applications under study	Paper production transferred into board production, ready in late autumn 2020.
Heinola (semi chemical fluting, pulp)	39 wet tonnes	55 % primary 45 % bio	Energy recovery HTC	Biosludge converted into biofuel at HTC plant.

8. Introduction to case study of three different mills

For more detailed case study, three of the Stora Enso's mills are taken into evaluation. In this chapter, introduction to case study is presented along with used methods and analyses that have been made.

Selected case mills are located in Imatra, Sunila and Varkaus. In case study, typical sludge characteristics are taken into more detailed examination along with each mill's sludge treatment processes and utilization applications. According to outcome, a SWOT analysis is performed for each mill.

In order to present different factors in case study clearly, results for sludge characteristics are presented in separate chapters for each mill. However, sludge characteristics are taken into account in the SWOT analysis.

8.1. Study on sludge characteristics case mills

In order to perform reliable case study, sludge characteristics are taken into study. Therefore, for valid evaluation on sludge characteristics, sludge samples are gathered from each case mill. From these samples, most important sludge characteristics in terms of sludge utilization possibilities are being analysed. Collection of samples along with methods and analysed characteristics are presented as it follows. In following, each analyse method used is presented briefly.

8.1.1. Collection of samples and analytical methods used

Sludge samples were collected from each mill within one week for four days. In order to minimize weekly deviations in sludge characteristics, samples were collected every other day: at Monday, Wednesday, Friday and Sunday. In order to minimize daily deviations in sludge characteristics, for each day three subsamples were collected approximately eight hours apart from each other. Each subsample was at one litre volume.

In sample pretreatment, one representative sample for each day was combined from subsamples and mixed homogenous. In other words, each mill had four different samples to represent their typical sludge. For analyses, approximately one litre of sample was prepared. In preparation, sample was dried in oven at 105 °C temperature overnight after which each sample was grind. Flowchart presentation of sample collection and pretreatment of samples is presented in Figure 21.

The collection of samples were located in process at each mill differently. Samples were collected at the very end of sludge treatment process before utilization. However, if bark or any other waste was mixed with sludge before utilization, sludge sample was collected before mixing.

Scheduling the collection of samples was executed in cooperation with mills. Under given instructions, each mill collected their sludge samples in steady and as normal process conditions as possible. Therefore, possible abnormalities in wastewater treatment or sludge treatment processes would not influence the results. Eventually, Imatra Mills collected their samples within week 27, Sunila Mill within week 26 and Varkaus Mill within week 34.

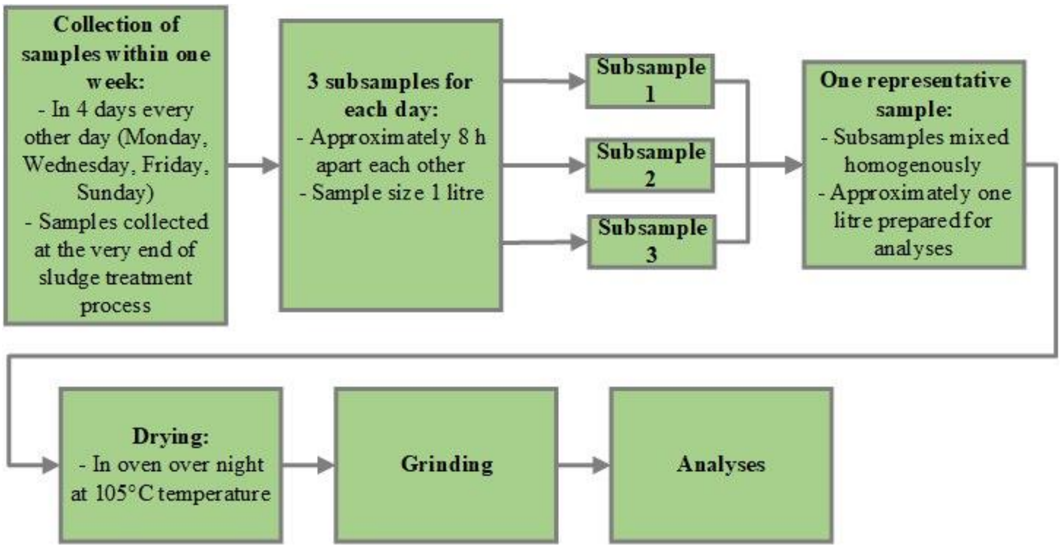

Figure 21. Flowchart presentation of sample collection and pretreatment before analyses.

Conclusion of used analyse methods and standards along with use are presented in Table 8. All analyses were done at Stora Enso R&D Center in Imatra. One of the analysed sludge characteristics was the dry content, which was defined for each representative sludge sample. Samples were dried in oven at 105 °C temperature overnight. By measuring sludge’s weight before and after drying, dry waste content was defined. Weigh of dry sludge were defined immediately after taking the sample out of the oven in order to minimize humidity in the sample. In calculation, following equation was used

$$dry\ content = \frac{weight\ of\ dry\ sludge}{weight\ of\ wet\ sludge} \cdot 100\ \%. \tag{1}$$

For other sludge characteristic, different analytical methods were performed. Ash content in sludge was analysed with TGA, also known as *thermogravimetric analyser*. Ash content was analysed in two different temperatures: in 525 °C and 925 °C. By doing so, calcium carbonate content can be defined, since calcium carbonate breaks only in higher temperature. In other words, ash content is higher in lower temperature due to calcium carbonate presence.

In order to analyse different chemical element contents in sludge, OEA and EDXA analyses were used. Organic content in sludge was analysed with OEA, also known as *organic elemental analysis*. In OEA carbon, hydrogen and nitrogen contents of sludge were analysed. Different inorganic elements were analysed with EDXA, also known as *energy dispersive X-ray analysis*. Since some of the element are more selective for EDXA than others, some of the inorganic elements, such as heavy metals in interest, were analysed with ICP, also known as *inductively coupled plasma spectrometry*. Based on defined dry content, ash content and analysed chemical element content in sludge, oxygen content is defined computationally as remaining substance in difference.

Calorific value for higher heating value were defined according to international standard ISO 1928. In this standard, calorimetric measurements are considered in the calculations of efficient heating value for wet sludge along with dry content and ash content, for instance. In calorimetric measurements bomb calorimeter is used.

Table 8. Conclusion of used analyse methods and standards along with use.

Analyse method / Standard	**Characteristic analysed**
Dry content determination	dry content
Thermogravimetric analyser (TGA)	ash content
Organic elemental analysis (OEA)	carbon, hydrogen and nitrogen content
Energy dispersive X-ray analysis (EDXA)	inorganic element content
Inductively coupled plasma spectrometry (ICP)	inorganic element and heavy metal content
ISO 1928 standard	higher heating value

8.2. Case study and SWOT analysis

In case study, each mill's sludge treatment processes along with their sludge streams and utilization applications are reread briefly according to previous chapters. In case study, analysed characteristics are evaluated in terms of sludge treatment processes, sludge utilization and based on the available literature, studies and legislation on this matter. Based on outcome, a SWOT analysis is performed in terms of sludge utilization.

As strategic planning and management tool, theoretical SWOT analysis can be used. Organization is presence in two environments: in itself and at outside in its' environment. Therefore, in strategic planning and management, internal factors along with external factors are taken into account. As tool, SWOT analysis is termed according to these factors. Internal factors are strengths and weaknesses, external factors are opportunities and threats. (Gurel & Tat 2017)

9. Case study on three different mills

9.1. Imatra Mills

As mentioned before, wastewater treatment plant at Imatra Mills produces approximately from 100 to 150 thousand wet tonnes of sludge annually. Approximately 33 % is biosludge and 66% is primary sludge. In sludge treatment process, there is two pathways for biosludge handling: conventional sludge treatment process along with primary sludge and chemical recovery. In this master's thesis, focus is on the conventional sludge treatment process, in which approximately 30 % dry content is achieved. Sludge is mostly utilized in energy recovery, in which natural gas is used as support fuel, if needed. Approximately 5 to 10 % of the sludge from Imatra Mills is utilized in soil improvement applications.

9.1.1. Results for sludge characteristics in Imatra Mills

For analysing sludge characteristics, Imatra Mills collected their sludge samples within week 27. From total amount, approximately 65 % was primary sludge, 30 % biosludge and 5 % other sludges. Average dry content of samples was approximately 27.4 %, which is significantly lower than alleged 30 % dry content achieved in sludge treatment process.

Ash content was analysed with TGA in two different temperatures, 525 °C and 925 °C, in which calcium carbonate is no longer present in the higher temperature. In Imatra Mills, difference between these two values is not very significant. Average ash content of samples in lower temperature was approximately 5.22 % and in higher temperature approximately 5.00 %.

For each sludge sample, calorific value for higher heating value was determined in the terms of international standard ISO 1928. According to standard, efficient heating value was determined computationally for wet sludge in its' specific dry content achieved in sludge treatment process. Average efficient heating value for wet sludge samples was approximately 3.39 MJ/kg. According to literature, efficient heating value of fuel must be at least 5 MJ/kg in order to support burning process.

With organic elemental analysis, OEA, organic content in sludge was analysed. Organic chemical content along with sulphur content analysed with EDXA and computationally defined oxygen content is presented in Table 9.

According to results, sludge from Imatra Mills is high in carbon and oxygen, which suggests fibrous composition. According to literature, sludges high in fibre and low in ash are the easiest to dewater. However, biosludge increases resistance towards dewatering, which might explain poor dry content.

Table 9. Organic chemical content in Imatra Mills as an average of four samples. Content is informed in percentage per one kilogram of dry sludge. Elements marked with '*' were analysed with EDXA, others with OEA, expect oxygen content, which is computational.

Chemical element	**Average content in samples, %**
C	49.1
H	5.62
N	1.24
S*	0.35
O	40.9

In order to determine inorganic content in sludge, EXDA and ICP analysers were used. These two methods were used, since some of the elements are more selective to EXDA than ICP, and vice versa. Since EXDA gives results as percentage per dry sludge, EXDA results were converted to match ICP's unit of mg per one kilogram of dry sludge. Inorganic chemical content is presented in Table 10. According to laboratory's own quality standards, EXDA results below 0.5 % must be treated with caution. If the result is below 0.5 %, validity of results is questionable.

According to results, sludge from Imatra Mills is high in aluminium. High aluminium content was expected, since coagulant used in wastewater treatment process contains aluminium. Calcium content is also high, but this is typical for sludges from cardboard and pulp mills due to fillers used in production. Sludge samples from Imatra Mills were also high in natrium, phosphorus, silicon and chlorine.

Table 10. Inorganic chemical content in Imatra Mills as an average of four samples. Content is informed in mg per one kilogram of dry sludge. Elements marked with '*' were analysed with EDXA, others with ICP. Element contents marked with red have been below 0,5% in EDXA. Therefore, these results must be treated with caution. Cr-content has been below EDXA's detection limit

Chemical element	**Average content in samples, mg/kg**
Al*	9821
B	19
Ba	39
Ca	4575
Co	0.37
Fe*	626
K*	397
Mg*	543
Mn*	191
Mo	0.72
Na	2950
P*	1398
Sb	0.33
Se	0
Si*	5881
V	1.8
Cl	1175
Ti*	123
Cr*	-

For agricultural and soil improvement uses, maximum heavy metal content of sludge is defined by legislation. Heavy metal content in Imatra Mills along with maximum limits are presented in Table 11. Mercury content of sludge was not analysed. According to results, neither of the heavy metals analysed exceeded defined maximum limits.

Table 11. Heavy metal content in Imatra Mills as an average of four samples. Content is informed in mg per one kilogram of dry sludge. As baseline, maximum heavy metal content for sludge utilized in agricultural uses according to legislation (MMM, decree 24/11 2011). Elements marked with '*' were analysed with EDXA, others with ICP. Mercury content in sludge was not analysed and zinc content was below EDXA's detection limit.

Heavy metal	Average content in samples, mg/kg	Maximum content according to legislation, mg/kg
As	< 0.75	25
Hg	-	1.0
Cd	0.5	1.5
Cr	3.9	300
Cu	5.1	600
Pb	0.7	100
Ni	1.1	100
Zn*	-	1500

9.1.2. SWOT analysis for Imatra Mills

In terms of sludge characteristics, treatment process and sludge utilization, Imatra Mills has multiple strengths. First of all, primary sludge fraction is relatively high in Imatra Mills. According to literature, dewatering of biosludge alone with typical mechanical devices is challenging due to in-cell water and slimy texture of the sludge. Therefore, biosludge is often mixed with primary sludge in order to increase dewaterability. In addition, Imatra Mills has two possible pathways for biosludge handling: conventional sludge treatment and chemical recovery, which eases troublesome biosludge handling. In addition, as sludge is mostly utilized in energy recovery at Imatra Mills, low ash content is favourable in terms of efficient heating value. According to literature, two main characteristics, that suggest higher efficient heating value, are low ash content and high dry content.

However, strengths of sludge from Imatra Mills do not reflect directly to their weaknesses. Despite low ash content, efficient heating value is low, approximately 3.39 MJ/kg, most likely due to low dry content achieved in sludge treatment process. According to literature, efficient heating value of fuel must be at least 5 MJ/kg in order to support burning process. Therefore, with their current sludge treatment process, sludge utilization in energy recovery is not efficient and Imatra Mills has to use natural gas as a support fuel. However, heavy metal content is low, which is a good feature in terms on soil improvement and agricultural uses.

In addition to weaknesses, sludge from the Imatra Mills seems to be high in fibre. This suggests poor production design, since valuable raw material is lost in waste stream. Therefore, fibrous sludge is considered as a weakness, but it also could be considered as an opportunity. According to studies, fibrous sludges used in agricultural uses could bind carbon into soil and therefore improve its' health. However, sludge from Imatra Mills has relatively low nitrogen content, which is important nutrient for vegetation.

Fibrous sludge can be seen as an opportunity, but also as a threat. According to literature, sludges, which are high in fibre and low in ash are the easiest to dewater. If fibre content is decreased in sludge by technically improving production process, this might have great impact in sludge dewaterability along with other characteristics. Therefore, achieved benefits from improving overall production process needs further studies in terms of sludge treatment.

On the other hand, technical improvements in sludge treatment process, especially in sludge dewatering, can be great opportunity for Imatra Mills in terms of energy recovery. Since sludge from Imatra Mills is already low in ash, by improving dry content, major improvements in efficient heating value could be achieved. Eventually, natural gas would not be necessary as support fuel.

Sludge from Imatra Mills have a great potential in agricultural and soil improvement applications. Despite the relatively low nitrogen content, sludge from Imatra Mills is also low in heavy metals, especially in cadmium, which is a good thing in the eyes of law. According to literature, cadmium content can easily achieve its' limits in sludges from pulp and paperboard industry.

However, each opportunity has its' own threats. Due to global warming and emission commitments set by the National Emission Ceilings Directives, fight against emissions is in high importance, which will eventually lead to more strict legislation. Therefore, current burning processes in energy recovery might not be valid in the future. On the other hand, improving sludge treatment process in order to improve the burning process might not be efficient. If more energy is invested in improving heating value than energy achieved from improvements, process is no longer efficient in energy balance's point of view. Also, even though burning process of sludge could be improved with investments, costs can be too high.

Nevertheless, Imatra Mills is located in area, which has many other pulp and paper mills. In terms of demand and supply, there is over supply within Imatra Mills area. Therefore, utilizing sludge in agricultural and soil improvement uses might not be economically reasonable.

In total SWOT analysis for Imatra Mills is presented in Table 12.

Table 12. SWOT analysis for Imatra Mills in terms of sludge characteristics, treatment process and sludge utilization.

Internal origin	**STRENGTHS**	**WEAKNESSES**
	- High primary sludge percentage (66 %) - Primary sludge and biosludge are mixed → improves biosludge's dewaterability - Two possible pathways for biosludge handling - Simplified sludge treatment process design - Low ash content (5 %) - Low heavy metal content (Cd 0.5 mg/kg)	- Low dry content achieved (27.4 %) - Low heating value (3.39 MJ/kg) - Relatively low nitrogen content (1.24 %) - Fibrous sludge
External origin	**OPPORTUNITIES**	**THREATS**
	- Legislation: low heavy metal content (maximum Cd 1.5 mg/kg) - Technical improvements in sludge dewatering - Technical improvements for decreasing fibre content in sludge	- Emissions from burning process - Achieved benefits from technical improvements uncertain - Investment costs - Over supply of sludge within area

9.2. Sunila Mill

As mentioned before, at Sunila Mill, approximately 2000 dry tonnes of biosludge and 2300 dry tonnes of primary sludge are produced annually. Sludge treatment process at Sunila Mill is straightforward: primary and biosludge are mixed together and dewatered up to approximately 30 % dry content. Sludge is utilized in energy recovery along with bark. If needed, natural gas is used as support fuel.

9.2.1. Results for sludge characteristics in Sunila Mill

For analysing sludge characteristics, Sunila Mill collected their sludge samples within week 26. From total amount, approximately 53 % was primary sludge and 47 % biosludge. Average dry content of samples was approximately 30.3 %, which is according to alleged 30 % dry content achieved in sludge treatment process.

Ash content was analysed with TGA in two different temperatures, 525 °C and 925 °C, in which calcium carbonate is no longer present in the higher temperature. In Sunila Mill, there is some difference between these two. Average ash content of samples in lower temperature was approximately 16.97 % and in higher temperature approximately 15.33 %. According to literature, higher ash content is expected due to higher biosludge percentage at Sunila Mill than at Imatra Mills.

For each sludge sample, calorific value for higher heating value was determined in terms of international standard ISO 1928. According to standard, efficient heating value was determined computationally for wet sludge in its’ specific dry content achieved in sludge treatment process. Average efficient heating value for wet sludge samples was approximately 3.17 MJ/kg. According to literature, efficient heating value of fuel must be at least 5 MJ/kg in order to support burning process. Despite higher dry content in Sunila Mill, efficient heating value is lower than in comparison with Imatra Mills due to higher ash content.

With organic elemental analysis, OEA, organic content in sludge was analysed. Organic chemical content along with sulphur content analysed with EDXA and computationally defined oxygen content is presented in Table 13.

According to results, sludge from Sunila Mill is high in carbon and oxygen, which suggests fibrous composition. On the other hand, carbon and oxygen content is significantly lower than in Imatra Mills. However, sludge from Sunila Mill has higher nitrogen content most likely due to high biosludge percentage. In agricultural and soil improvement uses point of view this is desired feature.

Table 13. Organic chemical content in Sunila Mill as an average of four samples. Content is informed in percentage per one kilogram of dry sludge. Elements marked with '*' were analysed with EDXA, others with OEA, expect oxygen content, which is computational.

Chemical element	**Average content in samples, %**
C	43.7
H	4.88
N	2.00
S*	0.60
O	39.3

Inorganic chemical content analysed with EDXA and ICP is presented in Table 14. According to laboratory's own quality standards, EXDA results below 0.5 % must be treated with caution. If the result is below 0.5 %, validity of results is questionable.

According to results, sludge from Sunila Mill is also high in aluminium due to coagulant used wastewater treatment process. Calcium content is also high, but this is typical for sludges from pulp mills due to fillers used in production. Sludge samples from Sunila Mill were also high in iron, potassium, magnesium, manganese, natrium, phosphorus, silicon and chlorine.

Table 14. Inorganic chemical content in Sunila Mill as an average of four samples. Content is informed in mg per one kilogram of dry sludge. Elements marked with '*' were analysed with EDXA, others with ICP. Element contents marked with red have been below 0,5% in EDXA. Therefore, these results must be treated with caution. Cr-content has been below EDXA's detection limit

Chemical element	Average content in samples, mg/kg
Al*	3756
B	40
Ba	225
Ca	35500
Co	5.53
Fe*	29143
K*	1020
Mg*	2122
Mn*	1771
Mo	0.73
Na	3650
P*	5012
Sb	1.70
Se	0
Si*	9634
V	7.5
Cl	1175
Ti*	303
Cr*	-

For agricultural and soil improvement uses, maximum heavy metal content of sludge is defined by legislation. Heavy metal content in Sunila Mill along with maximum limits are presented in Table 15. Mercury content of sludge was not analysed. According to results, neither of the heavy metals analysed exceeded defined maximum limits expect cadmium content, which exceeded the limit clearly. Maximum level for cadmium according to legislation is 1.5 mg/kg, whereas cadmium content in sludge from Sunila Mill is approximately 5.6 mg/kg. Exceeding cadmium levels is typical for pulp mills in which hardwood is used as raw material. However, only softwood is used as raw material in Sunila Mill.

Table 15. Heavy metal content in Sunila Mill as an average of four samples. Content is informed in mg per one kilogram of dry sludge. As baseline, maximum heavy metal content for sludge utilized in agricultural uses according to legislation (MMM, decree 24/11 2011). Elements marked with '*' were analysed with EDXA, others with ICP. Mercury content in sludge was not analysed and zinc content was below EDXA's detection limit.

Heavy metal	Average content in samples, mg/kg	Maximum content according to legislation, mg/kg
As	0.84	25
Hg	-	1.0
Cd	5.6	1.5
Cr	15.0	300
Cu	13.3	600
Pb	6.0	100
Ni	12.3	100
Zn*	-	1500

9.2.2. SWOT analysis for Sunila Mill

In terms of sludge characteristics, treatment process and sludge utilization, Sunila Mill has few strengths. First of all, Sunila Mill has extremely simplified sludge treatment process design, which is good in terms of process maintenance and further process developments. Second of all, since biosludge is mixed with primary sludge, dewaterability of biosludge is increased. As mentioned before, dewatering of biosludge alone with typical mechanical devices is challenging due to in-cell water and slimy texture of the sludge.

However, Sunila Mill has some troublesome weaknesses, which are most likely due to their relatively high biosludge percentage. According to literature, two main characteristics, that suggest higher efficient heating value, are low ash content and high dry content. Sludge from Sunila Mill has relatively high ash content as well as low dry content. According to literature, biosludge increases ash content as well as it increases dewatering resistance. Therefore, efficient heating value is low, approximately 3.17 MJ/kg. According to literature, efficient heating value of fuel must be at least 5 MJ/kg in order to support burning process. Therefore, with their current sludge treatment process along with sludge characteristics, sludge utilization in energy recovery is not efficient. In addition, sludge from Sunila Mill is high in cadmium, which is why it can not be used as soil improvement according to legislation.

However, Sunila Mill still has an opportunity to improve their situation in energy recovery. By investing in sludge dewatering improvements, heating value of sludge could be increased. Without major changes in overall process design, ash content of sludge cannot be improved. Therefore, heating value is the easiest to improve by increasing dry content.

On the other hand, improving sludge treatment process in order to improve the burning process might not be efficient. If more energy is invested in improving heating value than energy achieved from improvements, process is no longer efficient in energy balance’s point of view. Also, even though burning process of sludge could be improved with investments, costs can be too high, which is a major threat. In addition, due to global warming and emission commitments set by the National Emission Ceilings Directives, eventually more strict legislation is set. Therefore, current burning processes in energy recovery might not be valid in the future.

Most of the weaknesses in sludge treatment process at Sunila Mill are due to relatively high biosludge percentage. If the amount of biosludge could be decreased in current sludge treatment process, it might improve situation in Sunila Mill. However, this requires great investments in sludge treatment process, such as separate treatment process for surplus biosludge, along with new utilization use. Therefore, in terms of treatment process and sludge utilization, biosludge from Sunila Mill requires further studying.

In total SWOT analysis for Sunila Mill is presented in Table 16.

Table 16. SWOT analysis for Sunila Mill in terms of sludge characteristics, treatment process and sludge utilization.

	STRENGTHS	WEAKNESSES
Internal origin	- Simplified sludge treatment process design - Primary sludge and biosludge are mixed → improves biosludge's dewaterability	- High biosludge percentage (47 %) - Relatively high ash content (15.33 %) - Relatively low dry content (30.3 %) - Low heating value (3.17 MJ/kg) - High cadmium content (5.6 mg/kg)
	OPPORTUNITIES	**THREATS**
External	- Technical improvements in sludge dewatering	- Emissions from burning process - Achieved benefits from improvements uncertain

9.3. Varkaus Mill

As mentioned before, Varkaus Mill together with local fishery share same wastewater treatment plant, in which 25 thousand wet tonnes of sludge is being produced annually. From annual sludge quantity, approximately from 60 to 70 % is primary sludge, 5 % is biosludge and 20 % is tertiary sludge. Fishery produces approximately 1 to 1.5 % of total sludge amount. At Varkaus mill, in sludge treatment process all sludge fractions are mixed before treatment, in which approximately from 30 to 40 % dry content is achieved. Sludge is mostly utilized in energy recovery, in which coal is used as support fuel, if needed. Other sludge utilization possibilities are also actively studied.

9.3.1. Results for sludge characteristics in Varkaus Mill

For analysing sludge characteristics, Varkaus Mill collected their sludge samples within week 34. From total amount, approximately 60 % was primary sludge, 5 % biosludge and rest is other sludges. Average dry content of samples was approximately 36.4 %, which is according to alleged from 30 to 40 % dry content achieved in sludge treatment process.

Ash content was analysed with TGA in two different temperatures, 525 °C and 925 °C, in which calcium carbonate is no longer present in the higher temperature. In Varkaus Mill, there is some difference between these two. Average ash content of samples in lower temperature was approximately 16.80 % and in higher temperature approximately 15.18 %. According to literature, higher ash content is expected due to different sludge fractions, such as tertiary sludge.

For each sludge sample, calorific value for higher heating value was determined in terms of international standard ISO 1928. According to standard, efficient heating value was determined computationally for wet sludge in its' specific dry content achieved in sludge treatment process. Average efficient heating value for wet sludge samples was approximately 4.94 MJ/kg. According to literature, efficient heating value of fuel must be at least 5 MJ/kg in order to support burning process. In comparison with Imatra Mills and Sunila Mill, efficient heating value is significantly higher in Varkaus Mill.

With organic elemental analysis, OEA, organic content in sludge was analysed. Organic chemical content along with sulphur content analysed with EDXA and computationally defined oxygen content is presented in Table 17.

According to results, sludge from Varkaus Mill is high in carbon and oxygen, which suggests fibrous composition. On the other hand, carbon and oxygen content is significantly lower than in Imatra Mills. However, Varkaus Mill has higher nitrogen content like at Sunila Mill. In agricultural and soil improvement uses point of view this is desired feature.

Table 17. Organic chemical content in Varkaus Mill as an average of four samples. Content is informed in percentage per one kilogram of dry sludge. Elements marked with '*' were analysed with EDXA, others with OEA, expect oxygen content, which is computational.

Chemical element	**Average content in samples, %**
C	45.6
H	5.08
N	2.37
S*	2.01
O	36.3

Inorganic chemical content analysed with EDXA and ICP is presented in Table 18. According to laboratory's own quality standards, EXDA results below 0.5 % must be treated with caution. If the result is below 0.5 %, validity of results is questionable.

According to results, sludge from Varkaus Mill is also high in aluminium. High aluminium content was expected, since coagulant used in wastewater treatment process contains aluminium. Calcium content is also high, but this is typical for sludges from pulp mills due to fillers used in production. Sludge samples from Varkaus Mill were also high in iron, potassium, magnesium, phosphorus, silicon and titanium.

Table 18. Inorganic chemical content in Varkaus Mill as an average of four samples. Content is informed in mg per one kilogram of dry sludge. Elements marked with ‘*’ were analysed with EDXA, others with ICP. Cr- and Mn-content have been below EDXA’s detection limit

Chemical element	**Average content in samples, mg/kg**
Al*	17465
B	7.7
Ba	79
Ca	11600
Co	7.6
Fe*	24205
K*	1015
Mg*	3563
Mn*	-
Mo	4.6
Na	395
P*	3177
Sb	1.8
Se	0
Si*	20066
V	19
Cl	348
Ti*	1021
Cr*	-

For agricultural and soil improvement uses, maximum heavy metal content of sludge is defined by legislation. Heavy metal content in Varkaus Mill along with maximum limits are presented in Table 19. Mercury content of sludge was not analysed. According to results, neither of the heavy metals analysed exceeded defined maximum limits. However, cadmium level is very close to the limit. Maximum level for cadmium according to legislation is 1.5 mg/kg, whereas cadmium content in sludge from Varkaus Mill is approximately 1.3 mg/kg. Exceeding cadmium levels is typical for pulp mills in which hardwood is used as raw material. However, most of the raw material, approximately 95 %, used in Varkaus Mill is softwood.

Table 19. Heavy metal content in Varkaus Mill as an average of four samples. Content is informed in mg per one kilogram of dry sludge. As baseline, maximum heavy metal content for sludge utilized in agricultural uses according to legislation (MMM, decree 24/11 2011). Elements marked with '*' were analysed with EDXA, others with ICP. Mercury content in sludge was not analysed and zinc content was below EDXA's detection limit.

Heavy metal	**Average content in samples, mg/kg**	**Maximum content according to legislation, mg/kg**
As	1.1	25
Hg	-	1.0
Cd	1.3	1.5
Cr	18	300
Cu	57	600
Pb	19	100
Ni	18	100
Zn*	-	1500

9.3.2. SWOT analysis for Varkaus Mill

In terms of sludge characteristics, treatment process and sludge utilization, Varkaus Mill has multiple strengths. First of all, in a case of malfunction in sludge treatment process, Varkaus Mill has alternative pathway for sludge dewatering, which makes the process reliable. In terms of sludge dewatering, sludge treatment process at Varkaus Mill seems to be efficient since relatively high dry content is achieved. On the other hand, percentage of troublesome biosludge is relatively low, which improves dewaterability of sludge significantly.

Despite relatively high ash content, sludge from Varkaus Mill has relatively high efficient heating value, approximately 4.49 MJ/kg. Efficient heating value is almost high enough for sludge to support the burning process as a fuel, which is good in terms of energy recovery. In addition, sludge from Varkaus Mill has also relatively high nitrogen content, which is a wanted quality for sludges used in soil improvement uses.

However, due to tertiary sludge fraction at Varkaus Mill, for instance, ash content is relatively high. Therefore, in order to improve heating value for energy recovery uses, dry content needs to be improved. However, this might be difficult, since dry content is already in good level. On the other hand, since Varkaus Mill has multiple sludge fractions and sources, cause for radical changes might be difficult to locate, which makes their sludge treatment process vulnerable.

Varkaus Mill has an opportunity to utilize their sludge in agricultural and soil improvement uses. However, as presented before, cadmium levels of sludge from Varkaus Mill are very close to maximum levels. Therefore, cadmium levels require close monitoring. In energy recovery's point of view, slight improvements in sludge dewatering would increase heating value of sludge and therefore increase efficiency of burning process., However, if more energy is invested in improving heating value than energy achieved from improvements, process is no longer efficient in energy balance's point of view. Also, even though burning process of sludge could be improved with investments, costs can be too high, which is major threat. In addition, due to global warming and emission commitments set by the National Emission Ceilings Directives, eventually more strict legislation is set. Therefore, current burning processes in energy recovery might not be valid in the future.

In total SWOT analysis for Varkaus Mill is presented in Table 20.

Table 20. SWOT analysis for Varkaus Mill in terms of sludge characteristics, treatment process and sludge utilization.

	STRENGTHS	**WEAKNESSES**
Internal origin	- Alternative possibility in treatment process in a case of malfunction - Low biosludge percentage (5 %) - Relatively high dry content (36,4 %) - Relatively high efficient heating value (4.94 MJ/kg) - Relatively high nitrogen content (2.37 mg/kg)	- High ash content (15.18 %) - Multiple sludge fractions and sources: cause for radical changes difficult to locate
	OPPORTUNITIES	**THREATS**
External origin	- Legislation: low heavy metal content (maximum Cd 1.5 mg/kg) - Technical improvements in sludge dewatering	- Legislation: cadmium levels require close monitoring (current 1.3 mg/kg) - Emissions from burning process - Investment costs - Achieved benefits from improvements uncertain

10. Conclusions

This thesis was done to present sludge treatment processes along with typical utilization applications at Stora Enso mills in Finland. Case by case information from the mills was gathered by interviews. The main objective was to take three of these mills, Imatra Mills, Sunila Mill and Varkaus Mill, into more detailed case study, in which their sludge treatment processes and utilization uses were evaluated. Evaluation was executed based on their typical sludge characteristic and theoretical study on this matter.

For case study, sludge samples were gathered and analysed from each case mill. Different sludge characteristics were analysed. Dry content of sludge was determined along with ash content of sludge, which was analysed with TGA, also known as *thermogravimetric analyser*. Carbon, hydrogen and nitrogen contents of sludge were analysed with OEA, also known as *organic elemental analysis*. Different inorganic elements were analysed with EDXA, *energy dispersive X-ray analysis*, and ICP, *inductively coupled plasma spectrometry*. Calorific value for higher heating value were defined according to ISO 1928 standard. The SWOT analysis was performed for sludge utilization uses in each case mill in terms of current sludge treatment process and sludge characteristics.

Over all, it is safe to say that each Stora Enso mill in Finland have slightly different sludge treatment processes and utilization uses. This is because each mill is its' own individual production unit. Since each mill have slightly different annual sludge production rates along with sludge fractions, sludge treatment process and utilization use are tailored. Despite differences, similarities can be pointed out. Each mill utilizes sludge either totally or mostly in energy recovery, and based on the interviews, most of the issues in sludge treatment and/or sludge utilization uses are caused by biosludge. For instance, due to biosludge's dewaterability resistance, support fuel is often required in burning process. Unfortunately, most of the mills have to resort in fossil fuels on this matter. Therefore, more or less each mill is willing to decrease their sludge rate in energy recovery and find more potential sludge utilization uses.

Based on close case study and the SWOT analysis performed for each case mill, common advantages and disadvantages can be pointed out. Sludges from Imatra Mills and Varkaus Mill are potential raw material for soil improvement and in energy recovery whereas sludge from Sunila Mill is potential only in energy recovery due to high cadmium content. However, each case mill could improve their sludge energy recovery efficiency by investing in new technology and improve their sludge treatment process in terms of dewatering. If the quality of sludge as fuel can be improved, need for support fuel might be no more. In other words, unnecessary use for fossil fuels can be reduced.

In legislation point of view, investing in energy recovery can be beneficial. Due to air pollution commitments given by the National Emission Ceiling Directive, current burning processes might not be valid in the future. Therefore, it is crucial to take emissions from burning sludge and how these emissions could be decreased in close study. On the other hand, same commitments encourage to invest in different sludge utilization uses, such as soil improvement uses. However, the legislation point of view cannot be ignored in either case especially when legislation in Finland is very strict on this matter. Maximum heavy metal content limits for soil improvement uses can be even ten or twenty times higher in other European countries than in Finland. These limitations in Finland should be taken under close study and be critically re-evaluated.

Conclusions of common disadvantages in Stora Enso mills in Finland in terms of sludge utilization are presented in Table 21. For each disadvantage suggested solution for improvements along with potential benefits are also presented.

Table 21. Conclusion of common disadvantages in Stora Enso mills in Finland in terms of sludge utilization. For each disadvantage suggested solution for improvements along with potential benefits are presented.

Disadvantages	Suggested improvement	Potential benefits
Poor dry content achieved in sludge treatment process	Investments in more specific dewatering technology in terms of sludge characteristics	- Efficiency in utilization uses such as energy recovery is increased → need of support fuel in burning process is significantly decreased - Improvements in sludge transportation
Emissions from sludge burning	Investments in improving burning process	- More energy efficient burning process is achieved → need of support fuel can be decreased - Emission reduction
	Investments in different sludge utilization uses instead burning	- Need of support fuel in burning process is significantly decreased - Potential economic benefits from other utilization uses
Fossil fuels are used as support fuel in the energy recovery of sludge	Investments in improving sludge as fuel such as HTC or increasing dry content	- Need for fossil fuels can be diminished

Either way, in terms of circular economy, sludge from pulp and paperboard industry has shown its' potential as 'a raw material' rather than as 'a waste'. It can be agreed, that effluent treatment sludge can be troublesome raw material. However, most of the difficulties are due to unsuitable technology used in sludge treatment. Each Stora Enso mill in Finland should take their sludge in close study and learn their sludge characteristics in detail. Once done, each mill could critically evaluate their sludge treatment process in order to improve the process with most suitable technology available in terms of their sludge characteristics.

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APPENDIX

Extended table of results for sludge characteristics analysed with ISO 1928, TGA, EXDA and OEA along with dry content

Analysed characteristic	Method	Unit	Imatra 1	Imatra 2	Imatra 3	Imatra 4
Moisture content for wet sludge	Oven 105 °C	%	70.6	72.6	75.1	72.4
Dry content for wet sludge	Oven 105 °C	%	29.5	27.4	24.9	27.6
Ash	TGA (525 °C)	% in dry sludge	6.26	5.94	4.15	4.53
Ash	TGA (925 °C)	% in dry sludge	5.90	5.62	3.93	4.33
C	OEA	% in dry sludge	48.5	48.6	49.9	49.6
H	OEA	% in dry sludge	5.52	5.71	5.73	5.51
N	OEA	% in dry sludge	1.16	1.32	1.27	1.21
S	Ash (925 °C) EDXA	% in dry sludge	0.37	0.38	0.33	0.33
O	Computational	% in dry sludge	41.3	40.9	40.6	41.0
Higher heating value(HHV)	ISO 1928	MJ/kg for dry sludge	19.87	20.12	20.17	20.31
Efficient heating value (LHV)	ISO 1928	MJ/kg for dry sludge	18.67	18.88	18.92	19.11
Efficient heating value for wet sludge	ISO 1928	MJ/kg for wet sludge	3.77	3.40	2.87	3.51
Na	Ash (925 °C) EDXA	% in dry sludge	0.23	0.29	0.29	0.34
Mg	Ash (925 °C) EDXA	% in dry sludge	0.06	0.06	0.05	0.05
Al	Ash (925 °C) EDXA	% in dry sludge	1.4	1.3	0.59	0.71
Si	Ash (925 °C) EDXA	% in dry sludge	0.77	0.67	0.43	0.49
P	Ash (925 °C) EDXA	% in dry sludge	0.13	0.14	0.14	0.15
S	Ash (925 °C) EDXA	% in dry sludge	0.05	0.07	0.13	0.13
Cl	Ash (925 °C) EDXA	% in dry sludge	0.00	0.00	0.00	0.00
K	Ash (925 °C) EDXA	% in dry sludge	0.05	0.04	0.04	0.04
Ca	Ash (925 °C) EDXA	% in dry sludge	0.44	0.44	0.44	0.41
Ti	Ash (925 °C) EDXA	% in dry sludge	0.02	0.01	0.01	0.01
Ba	Ash (925 °C) EDXA	% in dry sludge	0.0000	0.0000	0.0000	0.0000
Cr	Ash (925 °C) EDXA	% in dry sludge	0.0000	0.0000	0.0000	0.0000
Mn	Ash (925 °C) EDXA	% in dry sludge	0.03	0.02	0.02	0.01
Fe	Ash (925 °C) EDXA	% in dry sludge	0.09	0.05	0.06	0.05
Ni	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Cu	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Zn	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0

* below detection limit
** EDX value below 0,5 %

Analysed characteristic	Method	Unit	Sunila 1	Sunila 2	Sunila 3	Sunila 4
Moisture content for wet sludge	Oven 105 °C	%	70.0	71.0	69.8	68.0
Dry content for wet sludge	Oven 105 °C	%	30.0	29.0	30.2	32.0
Ash	TGA (525 °C)	% in dry sludge	16.9	16.6	16.9	17.5
Ash	TGA (925 °C)	% in dry sludge	15.5	15.0	15.2	15.6
C	OEA	% in dry sludge	43.5	44.0	43.7	43.5
H	OEA	% in dry sludge	4.73	5.15	4.94	4.69
N	OEA	% in dry sludge	2.13	1.71	2.06	2.10
S	Ash (925 °C) EDXA	% in dry sludge	0.74	0.54	0.56	0.55
O	Computational	% in dry sludge	39.3	39.3	39.3	39.5
Higher heating value(HHV)	ISO 1928	MJ/kg for dry sludge	17.25	17.03	17.28	17.06
Efficient heating value (LHV)	ISO 1928	MJ/kg for dry sludge	16.22	15.91	16.20	16.04
Efficient heating value for wet sludge	ISO 1928	MJ/kg for wet sludge	3.16	2.88	3.18	3.46
Na	Ash (925 °C) EDXA	% in dry sludge	0.41	0.29	0.41	0.43
Mg	Ash (925 °C) EDXA	% in dry sludge	0.20	0.21	0.20	0.25
Al	Ash (925 °C) EDXA	% in dry sludge	0.38	0.35	0.37	0.40
Si	Ash (925 °C) EDXA	% in dry sludge	0.98	0.93	0.96	0.98
P	Ash (925 °C) EDXA	% in dry sludge	0.49	0.50	0.50	0.52
S	Ash (925 °C) EDXA	% in dry sludge	0.57	0.56	0.54	0.53
Cl	Ash (925 °C) EDXA	% in dry sludge	0.03	0.04	0.02	0.00
K	Ash (925 °C) EDXA	% in dry sludge	0.10	0.10	0.11	0.10
Ca	Ash (925 °C) EDXA	% in dry sludge	3.1	3.2	3.3	3.5
Ti	Ash (925 °C) EDXA	% in dry sludge	0.02	0.04	0.03	0.04
Ba	Ash (925 °C) EDXA	% in dry sludge	0.0000	0.0000	0.0000	0.0000
Cr	Ash (925 °C) EDXA	% in dry sludge	0.0000	0.0000	0.0000	0.0000
Mn	Ash (925 °C) EDXA	% in dry sludge	0.16	0.19	0.17	0.19
Fe	Ash (925 °C) EDXA	% in dry sludge	3.1	2.9	2.9	2.8
Ni	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Cu	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Zn	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0

* below detection limit

** EDX value below 0,5 %

Analysed characteristic	Method	Unit	Varkaus 1	Varkaus 2	Varkaus 3	Varkaus 4
Moisture content for wet sludge	Oven 105 °C	%	63.38	63.59	64.05	63.54
Dry content for wet sludge	Oven 105 °C	%	36.62	36.41	35.95	36.46
Ash	TGA (525 °C)	% in dry sludge	16.30	17.38	15.42	18.08
Ash	TGA (925 °C)	% in dry sludge	14.74	15.58	13.72	16.43
C	OEA	% in dry sludge	45.97	45.33	45.50	45.66
H	OEA	% in dry sludge	5.29	5.04	5.02	4.96
N	OEA	% in dry sludge	2.35	2.37	2.37	2.39
S	Ash (925 °C) EDXA	% in dry sludge	2.07	2.12	1.88	1.98
O	Computational	% in dry sludge	35.8	36.3	37.4	35.8
Higher heating value(HHV)	ISO 1928	MJ/kg for dry sludge	19.03	18.99	18.54	19.25
Efficient heating value (LHV)	ISO 1928	MJ/kg for dry sludge	17.88	17.90	17.45	18.17
Efficient heating value for wet sludge	ISO 1928	MJ/kg for wet sludge	5.00	4.96	4.71	5.07
Na	Ash (925 °C) EDXA	% in dry sludge	0.11	0.09	0.09	0.16
Mg	Ash (925 °C) EDXA	% in dry sludge	0.33	0.35	0.33	0.41
Al	Ash (925 °C) EDXA	% in dry sludge	1.6	1.9	1.6	1.9
Si	Ash (925 °C) EDXA	% in dry sludge	1.9	2.0	1.8	2.3
P	Ash (925 °C) EDXA	% in dry sludge	0.30	0.33	0.30	0.34
S	Ash (925 °C) EDXA	% in dry sludge	0.16	0.21	0.26	0.36
Cl	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
K	Ash (925 °C) EDXA	% in dry sludge	0.11	0.10	0.09	0.11
Ca	Ash (925 °C) EDXA	% in dry sludge	1.0	1.1	1.2	1.4
Ti	Ash (925 °C) EDXA	% in dry sludge	0.1	0.1	0.1	0.1
Ba	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Cr	Ash (925 °C) EDXA	% in dry sludge	0.000	0.000	0.000	0.000
Mn	Ash (925 °C) EDXA	% in dry sludge	0.00	0.00	0.00	0.00
Fe	Ash (925 °C) EDXA	% in dry sludge	2.8	2.6	2.1	2.2
Ni	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Cu	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0
Zn	Ash (925 °C) EDXA	% in dry sludge	0.0	0.0	0.0	0.0

* below detection limit

** EDX value below 0,5 %

Extended table of results for sludge characteristics analysed with ICP

Analysed characteristics	Unit*	Imatra 1	Imatra 2	Imatra 3	Imatra 4	Sunila 1	Sunila 2	Sunila 3	Sunila 4	Varkaus 1	Varkaus 2	Varkaus 3	Varkaus 4
Al	mg/kg	12000	11000	4900	6100	1900	1600	2000	1900	9100	10000	8500	8500
As	mg/kg	<0.75	<0.75	<0.75	<0.75	<0.75	0.75	<0.75	0.93	1.1	1.1	0.93	1.2
B	mg/kg	18	19	20	20	39	40	38	43	7.3	7.8	7.8	7.7
Ba	mg/kg	41	39	38	36	200	220	220	260	71	72	78	95
Ca	mg/kg	5000	4700	4400	4200	33000	34000	36000	39000	9400	11000	13000	13000
Cd	mg/kg	0.41	0.49	0.56	0.59	5.6	5.5	5.6	5.8	1.2	1.1	1.1	1.6
Co	mg/kg	0.18	<0.1	0.56	<0.1	5.1	5.7	5.5	5.8	7.6	7.8	7.4	7.4
Cr	mg/kg	4.7	3.7	3.9	3.2	15	15	14	16	18	19	18	18
Cu	mg/kg	5.4	5.3	4.6	5	13	13	13	14	51	58	59	60
Fe	mg/kg	670	410	510	400	27000	25000	26000	27000	25000	24000	22000	21000
K	mg/kg	380	370	360	350	1100	1100	1200	1100	610	710	810	730
Mg	mg/kg	490	420	380	390	1500	1500	1500	1600	2100	2300	2400	2500
Mn	mg/kg	130	88	130	95	1600	2000	1900	1900	140	130	130	130
Mo	mg/kg	0.73	0.68	0.75	0.72	0.72	0.84	0.71	0.65	4.7	4.8	4.4	4.4
Na	mg/kg	2500	3100	2900	3300	3500	3900	3700	3500	330	340	390	520
Ni	mg/kg	1.5	0.97	1.3	0.77	12	12	12	13	18	18	17	17
P	mg/kg	1400	1500	1400	1500	4400	4200	4400	4800	2700	2900	2800	2800
Pb	mg/kg	0.41	0.63	0.84	0.9	5.7	5.7	6.2	6.2	17	19	19	19
Sb	mg/kg	0.27	0.39	0.33	0.32	1.6	1.6	1.7	1.9	1.8	1.7	1.6	2.2
Se	mg/kg	0	0	0	0	0	0	0	0	0	0	0	0
Si	mg/kg	550	570	540	530	1700	610	3100	980	410	350	400	390
V	mg/kg	2.4	2	1.3	1.3	7.8	7.2	7.4	7.7	19	19	18	18
Zn	mg/kg	42	36	40	44	300	310	320	310	260	260	250	280
Cl	mg/kg	1100	1200	1200	1200	1200	1100	1200	1200	310	350	370	360

*unit presented mg per one kilogram of dry sludge