DESIGN OF A PRETREATMENT INSTALLATION FOR THE WASHING OF EMPTY FRUIT BUNCHES AT A PALM OIL MILL

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SUMMARY

Empty fruit bunch (EFB) is a residual product of the palm oil mill industry. When bio-oil is generated during the pyrolysis of EFB, the yield is relatively low. In general, biomass types with high ash content result in low oil yields during pyrolysis. EFB has a quite high ash content ranging from 3 to 7 %. Of the ashes, the alkalis are the main catalyst to reduce the oil yield. Potassium is the most common of the alkalis in biomass and can take up to half the amount of ashes in EFB. Reducing the amount of ashes, with in particular potassium, in EFB can increase the oil yield from below 40% to yields higher than 60%.

Water washing of EFB can reduce the amount of potassium with about 90%. A basic design for a washing installation for a 5 t/h is created. It is tried to to minimize water usage and waste, energy usage and complexity while ash reduction is maximized. Three washing tanks are placed in series were the washing water is going in counter flow to the EFB to increase ash washout. After each washing tank a screw press will mechanically press out water to minimize ash and potassium content in the EFB.

LIST OF ABBREVIATIONS

EFB	*Empty Fruit Bunch*
FFB	*Fresh Fruit Bunch*
POME	*Palm Oil Mill Effluent*
mf	*Moisture Free*
wt%	*Weight percentage*
BOD	*Biological Oxygen Demand*
COD	*Chemical Oxygen Demand*
K	*Potassium*
t/h	*Ton per hour*

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1 INTRODUCTION

The purpose of this study is to design a washing installation in order to reduce the ash content of Empty Fruit Bunches (EFB), a residual product of the pail oil industry. Ash inside a biomasses has an influence on the oil yield and quality during fast pyrolysis. Biomass with lower ash contents will generally results in more and better oil. The ash content of EFB is quite high and thus has a quite low oil yield during pyrolysis. Reducing the ash content in EFB is potentially a method to increase oil production significantly.

The industrial process of EFB production from the fresh fruit bunches is charted to understand what pretreatments the EFB has undertaken. Also the process steps in the production of sugar from sugarcane were studied. This because bagasse, the residual product in the sugar cane industry, showed promising results in high oil yield during pyrolysis contradicted the relative high ash content.

Scientific literature is studied about the ash content and composition in EFB and other types of biomass. The components of the ash that are the probable cause of the reduction in oil yield are studied and identified. Also results in ash content and composition when washing EFB and other feedstock are studied and used to set up a list of design parameters for an industrial scale washing installation.

A basic design has been made where is tried to minimize water usage and waste, energy usage and complexity while ash reduction is maximized.

This study is done at BTG-BTL as an internship for the master mechanical engineering at the University of Twente. The author wants to thank his UT supervisor Gerrit Brem and his BTG-BTL mentor Ardy Toussaint for their guidance and this assignment.

2 INFLUENCE OF ASH ON THE YIELD OF PYROLYSIS OIL

2.1 ASH CONTENT

It is known that ash content of each type of biomass has a strong influence on the yield of bio-oil that can be obtained by fast-pyrolysis. Biomass that has low values of ash content, ordinarily slow growing crops such as trees, have a high yield of bio-oil. Fast growing crops, such as switchgrass or straw, have usually a relative high percentage of ash that results in a significant lower bio-oil yield. In Figure 1 it can be seen that roughly a linear slope can be drawn for the relation between ash content of the biomass and the yield of bio-oil.

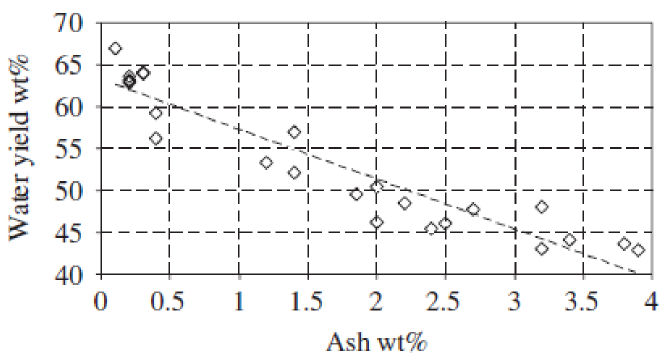

Figure 1: Yield of bio-oil set against the ash content of the biomass [1]

In Table 1 the ash content and the yield after pyrolysis can be seen for a number of different types of feedstock. Relevant for this study are the values for EFB. As can be seen, empty fruit bunches have a very high ash content that results in a low yield. Results of the same order of magnitude for EFB are also found in other literature [2] [3].

Kind of Feedstock	Ash content, mf wt.%	Maximum yield of organics, mf wt%	Temp,°*C*	Source
IEA poplar	0.46	72	485	Aston
Pine wood	0.5	68	477	Aston
White spruce	0.5	66.5	500	Waterloo
Pine wood	0.5	65.9	602	Aston [ablative]
IAE poplar	046	65.8	500	Waterloo
Washed EFB	1.03	61.3	500	This work
Pine wood	0.5	60	504	Aston
Sweet soghum bagass	Nd	58	515	Waterloo
Sugar cane bagasse	2.44	58	498	Waterloo
Miscanthus	5.7	55	458	Aston
Beech wood	0.6	54.2	555	Aston [ablative]
Rape straw	5.2	48	457	Aston
Rape meal	7.7	47	429	Aston
Wheat straw	4.6	43	582	Waterloo
Poplar bark	Nd	43	500	Waterloo
Pine bark	1.79	38	505	Aston
Unwasched EFB	5.29	36.9	453	This work

Table 1: Ash contents and yields of different types of biomass, table from [4]

From Table 1 can also be seen that sugar cane bagasse has a quite high ash content while the bio-oil yield is significant higher. In [5] 4.1 wt% ash was measured and after some temperature and feedstock size optimization a liquid yield of 56% was achieved. Also in [6] such results are found. Lab test from BTG also show this behavior. In Appendix C sugar cane bagasse is further studied.

2.2 ASH CONTENT AND COMPOSITION OF EFB

To show in more detail the ash content and composition of EFB, Table 2 is acquired from [2]. It shows an ash content of EFB ranging from 3 to 7 mf wt%. Potassium is a main component of the ash and ranges between 2 to 2.4 mf wt%.

Properties of EFB (mf wt%), cited literature [8,10,19–26]

Component/property	Literature values	Measured	Method
Cellulose	59.7, 38.1–42.0	–	–
Hemicellulose	22.1, 16.8–18.9	–	–
Lignin	18.1, 10.5–11.7	–	–
Elemental analysis			
Carbon	48.9, 48.8, 49.2–50.6	49.07	Combustion analysis
Hydrogen	7.33, 6.3	6.48	
Nitrogen	0.0, 0.7, 0.78–1.19, 0.2, 0.8, 0.44	0.7	
Sulphur	0.68, 0.2	<0.10	
Oxygen	40.2, 36.7	38.29	By difference
K	2.41, 2.24	2.00	Spectrometry
K_2O	3.08–3.65	–	
Proximate analysis			
Moisture	–	7.95	ASTM E871
Volatiles	87.3, 75.7	83.86	ASTM E872
Ash	3.02, 7.3, 4.3	5.36	NREL LAP005
Fixed carbon	9.6, 17	10.78	By difference
HHV (MJ/kg)	19.0, 17.86, 15.5, <10	19.35	Bomb calorimeter
LHV (MJ/kg)	17.2	–	–

Table 2: Properties of EFB (mf wt%), from [2]

2.3 ALKALIS AND POTASSIUM

It is found in studies [7] [8] [9] [10] that alkalis act as a catalyst during pyrolysis of biomass. In the presence of alkalis, the fragmentation of monomers that make up the natural polymer chains of lignocellulosic materials is enhanced over the depolymerization that otherwise occurs. This catalytic effect results in higher yields of water, gas and char.

Potassium is the most common of the alkalis found in most types of fast growing biomass and therefore the likely suspect of this catalytic effect by alkalis. For EFB, it can take up to 50% of the total amount of ash in biomass. One of the properties of potassium is that it is water soluble and thus can be easily washed out.

A possible explanation of the higher yields during pyrolysis of bagasse (see also Appendix C) is that this catalytic effect is reduced due to the absence of most of the alkalis. In chapter 3 it can be seen that washing of the feedstock can lower the ash content of the biomass.

3 *EMPTY FRUIT BUNCHES*

Empty Fruit Bunches, or short EFB, is a residual product in the palm oil industry. In this chapter the process of palm oil production is sketched and can be seen where the EFB originate. Furthermore the EFB itself is described. Also the existing waste water of a palm oil mill plant are examined in order to see where washing water must comply to.

3.1 PALM OIL PRODUCTION

In Figure 2, a flow diagram for the production of palm oil can be seen. The empty fruit bunches are taken out quite in the beginning of the process after sterilization. Sterilization is a batch process in which the fresh fruit bunches are heated with steam for a period of 60-90 minutes. The process stops enzymes and softens the fruit bunches for processing. In a stripper the fruits are separated from the fruit bunches with as remainder the empty fruit bunches (EFB). No further attention is given to the palm fruits since only the EFB is of interest in this study.

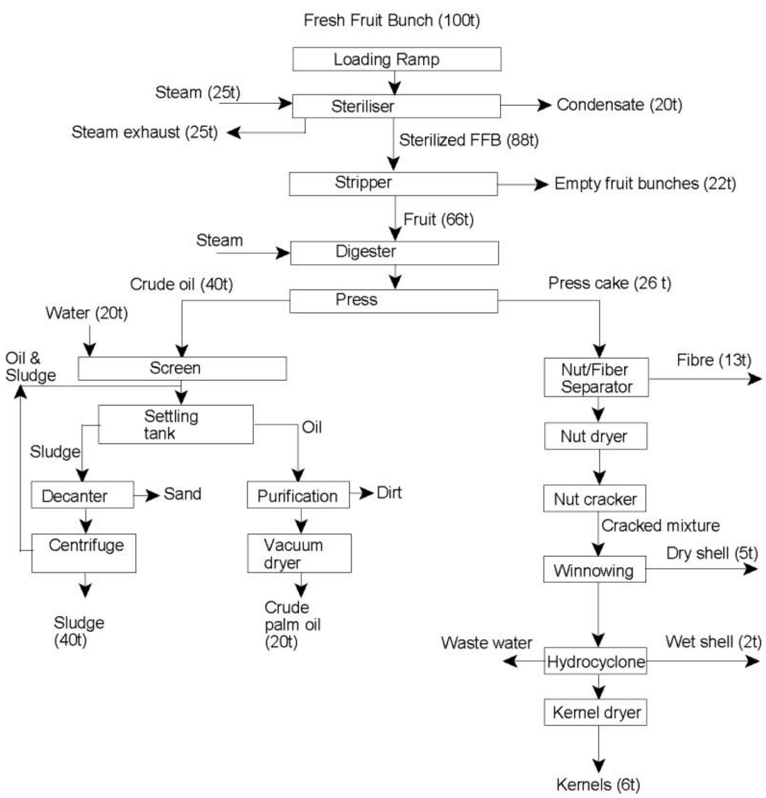

Figure 2: A typical flow diagram of a palm oil refinery, from internal communications

3.2 EFB

EFB is a very fibrous material of fibers of about 20 – 30 *cm* in length. Due to the sterilizing pretreatment it is soaked with water and has a moisture content of about 65%. However, due to this pretreatment it is also very clean biomass and contains almost no sand or other contaminants. In Figure 3 an example of a whole empty fruit bunch is shown. Its size can vary from 17 – 30 *cm* long and 25 – 35 *cm* wide. In Figure 4 can the fibrous structure be seen of shredded EFB.


Figure 3: A whole EFB, from [11]


Figure 4: Shredded EFB, from internal communications

In the past, most EFB was used as a fuel in palm oil plants in order to generate the heat required in the palm oil production. Another commonly used practice is to shred the EFB and return it to the palm tree plantations in order to use it use it as a natural fertilizer. This last practice is nowadays more promoted by the Malaysian government since combustion of EFB results in a large amount of air pollution and it reduces the need for buying (artificial) fertilizers [12].

3.3 Palm oil mill effluent

Palm oil mill effluent (POME) is a collection of all waste water streams from a palm oil mill. For each ton of FFB (or 0.22 *ton* of EFB), 1.5 *ton* of POME is generated. These effluent streams originate from for example the sterilizer or the press. From a typical EFB mill the waste water stream is about 60% of the total waste produced [13]. This source also gives an amount of potassium oxide of 6.5 mf wt% in the effluent.

Table 3 is taken from [14] and it can be seen that the BOD and COD values for the effluent is about a factor 1000 to high for Dutch or Malaysian legislation (see Appendix A). Therefore, POME needs treatment before the water can be discharged. Further legislation and washing techniques can also be seen in Appendix A .

Parameters	Sterilizer condensate	Oil clarification wastewater	Hydrocyclone wastewater
pH	5.0	4.5	-
Oil & Grease	4,000.0	7,000.0	300
BOD; 3-day, 30°C	23,000.0	29,000.0	5,000
COD	47,000.0	64,000.0	15,000
Suspended solid	5,000.0	23,000.0	7,000
Dissolve solid	34,000.0	22,000.0	100
Ammonical Nitrogen	20.0	40.0	-
Total Nitrogen	500.0	1,200.0	100

* All the units are in mg/L except for pH

Table 3: Characteristics of individual waste water streams, from [14]

4 *WASHING OF BIOMASS*

The washing of biomass can have a positive influence on the yield of bio-oil. This is because of the removal of ashes with in particular the alkalis during washing. In this chapter scientific literature is discussed that is found on the topic of biomass washing and its influence on ash content or the bio-oil yield after pyrolysis of the biomass. Especially the different washing techniques and parameters with their result in ash reduction are studied.

4.1 EMPTY FRUIT BUNCHES

The washing of EFB was extensively studied in the thesis of Abdullah [4]. In this theses multiple parameters were studied in order to determine what parameters have the most influence in the amount of ash that is washed out of the EFB. The following parameters were studied with their corresponding conclusion.

- Soaking or stirring: stirring is more effective.
- Type of water: distilled water is more effective than tap water.
- Water temperature: higher temperature (up to 90 $°C$) is more effective. However, at higher temperature the feedstock losses are also higher.
- EFB particle size: smaller particles are more effective.
- Residence time of EFB in water: for small particles two distinct phases can be seen. The first 10 minutes a very fast reduction in ash, then between 10 min. and 2 hours a linear reduction followed by no reduction. See Figure 5.
- Amount of water: more water is more effective. For 100 g feedstock, until 1.5 L of water ash removal is increasing fast. With more than 1.5 L the ash removal still increases but not very strong. See Figure 6.
- Fresh EFB vs. old EFB that is contaminated with soil: ash from old EFB is more easily removed.

In paragraph 4.4 the washing parameters are studied more in debt using literature about EFB and other types of biomass.

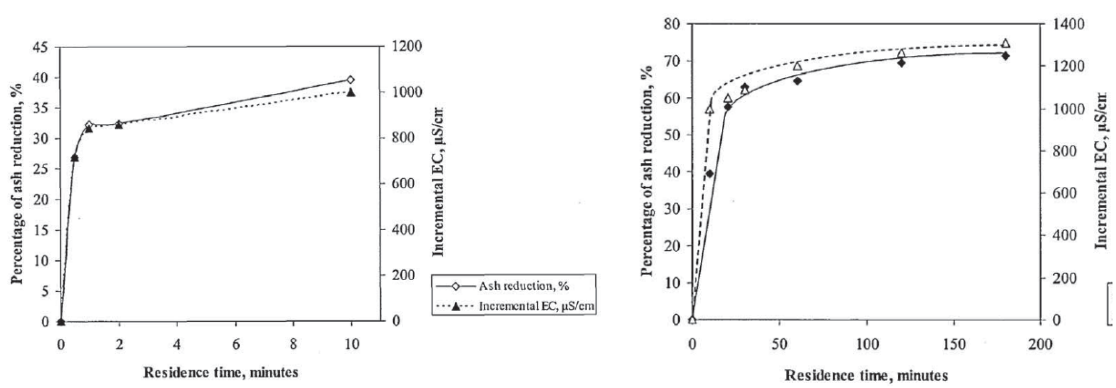

Figure 5. The ash reduction percentage of feedstock and incremental electrical conductivity of leachate by (a) quick washing and (b) soaking the feedstock of size 2-3cm, from [4]

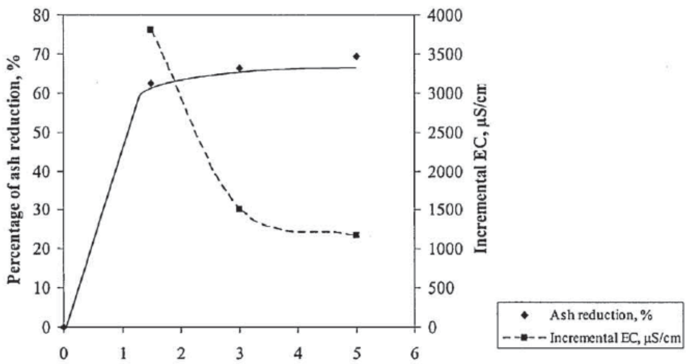

Figure 6. The percentage of ash reduction as the function of water amount by soaking the feedstock of size 2-3 cm, from [4]

The ash content of the unwashed EFB was around 5.2-5.5 moisture free (mf) wt%. The maximum yield that can be achieved by washing EFB is 72 mf wt% with an ash content of 1 mf wt%. From [2] can be read that a homogeneous pyrolysis oil can be obtained when the ash content of EFB is washed to below 3 mf wt%. Washing increased the bio-oil yield from around 50% for unwashed EFB to 72% for washed EFB. Organic feedstock losses during washing are not mentioned.

4.2 OTHER TYPES OF BIOMASS

Other types of biomass are also studied on the relation between ash content reduction by washing and the bio-oil yield.

In [15] sugar cane bagasse is studied that is washed in water and two different acids. It shows that 1 hour of water leaching reduces the amount of potassium with more than 90% which is even better than washing with a 5M HCl acid solution. A hydrogen fluoride (HF) solution resulted in an almost complete removal of all ashes but HF is a very dangerous acid so it is not practical applicable in the intended washing plant.

In [16] banagrass and sugar cane is studied. Two different kinds of shredding methods for the banagrass were used: a forage chopper and a cutter grinder where the latter produced smaller biomass chops (3.9 vs 1 mm). It was also studied that, after washing, the effects were of dewatering the biomass with a press and the effects of a second washing and pressing step. The optimal results were achieved from the cutter grinder cut material with two washing steps: 90% of the potassium was removed. The chops from the forage chopper was about 15-20% less effective. It can be seen in Figure 7 that, in the case of potassium (K) the first press step results in the largest reduction and the second pressing results in about the same reduction as is leached during washing. Both leaching as pressing the biomass are thus important steps in order to decrease the amount of ashes.

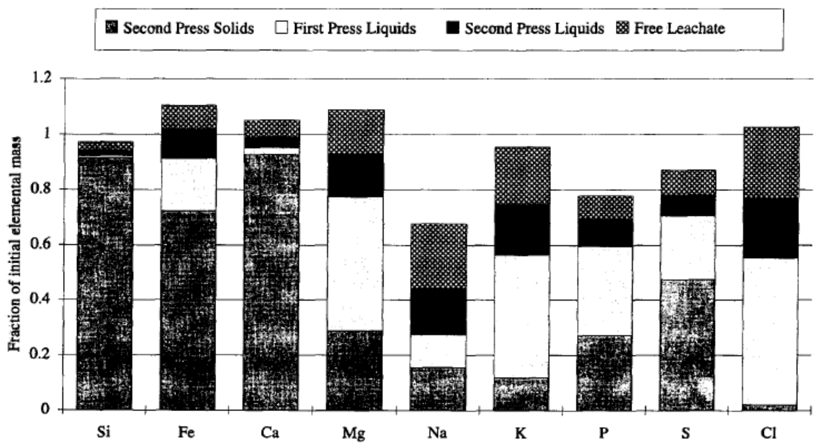

Figure 7: Distribution of initial elemental mass in output streams, cutter grinder cut - press rinse press, from [16]

Also in [17] a similar research with two pressing steps has been done where less than 10% of the initial potassium remained in the sugar cane bagasse.

The washing of straw is studied in [18]. A number of different washing strategies are studied and compared to rain washing of straw lying on a field. The washing strategies are: hand spraying for 1 minute, pouring water (7 and 20 liter) through the biomass on a fine mesh and submerging the biomass in water(7 liter, 24 hour). The amount of potassium in the ash was reduced in all the washing methods. Hand spraying already reduced the amount of potassium by a third while soaking and rain washing removed both around 80%.

From [19] can be seen that the washing of straw has a positive influence on the liquid yield. Washing the straw, in this case done by soaking the straw in water (100 ml for 1 gram straw) at $90°C$ for 2 hours, resulted in a 5-10% higher bio-oil yield. In Figure 8 it can be seen that varying the pyrolysis temperature results in various yields but the washed straw always produces more liquids and less chars.

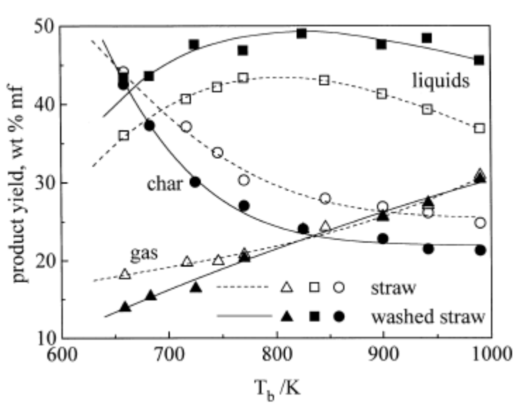

Figure 8: Product yields (expressed as percent of the initial moisture free (mf) mass) for straw (dashed lines) and washed straw (solid lines) as function of the temperature. From [19]

In [20] and [21] the washing of straw by natural rainfall and simulated natural rainfall is studied. Rainfall can reduce the amount of ash in the straw provided that the straw is already dried.

Following Figure 9, rain washing of fresh straw does not have significant changes in the ash content. The amount of potassium is not significant lowered (or increased).

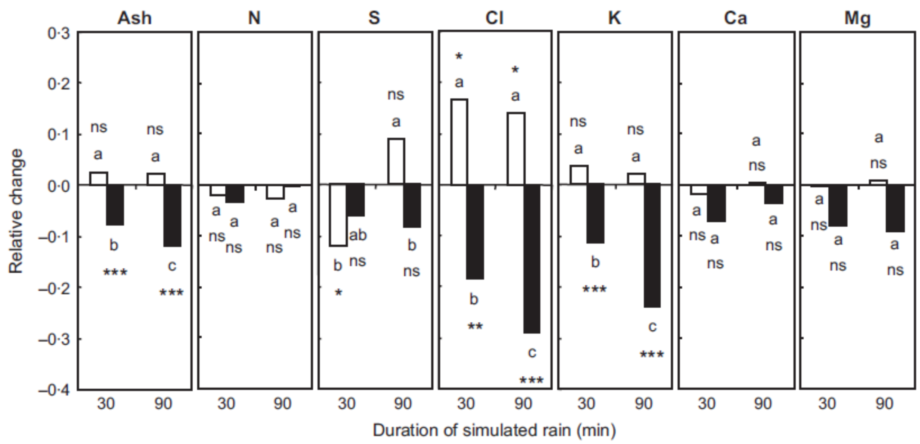

Figure 9 Relative change in concentrations of ash and combustion-relevant elements in 'fresh' (unfilled) and 'dry' (filled) grassland herbage after 30 and 90 min of simulated rain, compared with an unleached control. Significant differences from the control are marked by asterisks (ns, non-significant at α= 0.05; *significant at α = 0.05; **significant at α = 0.01; ***significant at α = 0.001). Treatments not sharing the same letter differ significantly at $\alpha \leq 0.05$ in their relative concentration changes. From [20]

In [22] washing of switchgrass and pine wood is studied. As can be expected, the fast growing crop switchgrass contains more ashes including more potassium. Ash removal experiments were conducted with distilled water and varying leaching times and amount of leaching water with a maximum of 60% ash removal. However, the particle size was not remained constant so no conclusions could be drawn on the influence of the parameters. Pine wood washing was not very effective since it contains not much water soluble metals like potassium, natrium or magnesium.

The washing of dry sugar beet pulp and fermented grape pomace (fresh and dry) is studied in [23]. Both biomass was subjected to washing of 30 and 120 minutes and 1/20 and 1/50 ratio between biomass and distilled leaching water. For sugar beet pulp the most effective washing method to reduce the percentage of ash was more water and shorter time. This was probably caused by a higher percentage of organic material leaching compared with ash leaching. Washing of the dry pomace resulted in more ash reduction 62-75% versus 41-45% of the fresh pomace, but this was likely caused by the lack of size reduction of the fresh pomace. Smaller particles have a smaller diffusion length and thus increase ash extraction.

In [24] natural washing of corn stover is studied with in particular the properties of the biomass directly after harvest over the seasons. Potassium is the most present in summer and in spring the lowest. The paper suggest that the yield of corn stover as fuel decreased with delayed harvest but the quality increased due to leached ashes. Similar results were found for rice straw in [25].

4.3 WASHING OF BIOMASS IN OTHER FIELDS

A few other industrial appliances of washing are reviewed in order to widen the perspective on industrial washing techniques.

4.3.1 *Fiberboard*

For the production of fiberboard the feedstock, usually wood chips, shavings and saw dust, is first cleaned of all impurities. Ferro metals can be removed by a magnet while soil, sand and most other impurities are washed out by submerging in water. When the feedstock is clean, it is put in a steaming bin in order to heat and soften the material.

A budgetary quotation for a wood chip washing machine was requested from Metso, Fiberboard, Central Europe North. As biomass feedstock scenario, wood chips originating from a forest were used. The type of the woodchips is G50, has a moisture content of 50% and a maximal contamination of 4% sand, stones, metals etc. The quantity of wood chips to be washed is 10 t/h (on wet biomass basis).

4.3.2 *Coal*

In a coal preparation plant, coal is washed in order to remove soil and rocks. In this way the combustion of coal is cleaner and the transport costs lower. Washing of coal usually is done with a dense medium separation process. In this a liquid medium is adjusted to a specific density in which the pieces of up to 50mm float, while denser contaminants sink. A dense medium cyclone is usually used to speed up the process.

4.4 Influence of washing parameters

In this paragraph the information found in the sources from paragraphs 4.1 to 4.3 are discussed. A large distinction can be made on the type of washing: natural washing in the fields by rainfall and mechanized washing. The first is not feasible for the intended purpose of EFB washing since in the EFB is already on the palm oil production site and not on the fields.

In the literature, for washing are numerous varying parameters found for different types of feedstock. In general, these types of parameters are most studied.

4.4.1 *Size of the feedstock*

The size of the feedstock is an important parameter on how much (and how fast) ashes are washed out of a biomass. A smaller average size of a feedstock results in a shorter diffusion length of the ash and thus a smaller diffusion time and thus more ash is washed out in the same time compared to larger sized feedstock.
Tested EFB sizes in literature were 250-355 μm , 1 cm and 2-3 cm in length [2] [3]. For long soaking times (24h) the size does not matter. However, for washing for shorter periods of time size does matter. Other types of feedstock sizes range from $\leq 250\ \mu m$ [15] to 3.9 mm [16]. For a test from BTG a kind of loosely compacted pellet of size 10 mm was used [internal communications].

4.4.2 *Fresh or dry*

From [16] it can be read that reducing the feedstock size is much harder for fresh than for dry biomass. Also does [21] report that ash was not washed away when fresh straw was used. Also [4] reports that ash from fresh feedstock is harder to purge but adds the comment that the cellular structure of the old EFB might be weakened.

4.4.3 *TEMPERATURE*
An increased temperature of the washing water results in more ash washed out of the biomass. [4] reports that, using water with a temperature range of 27-90 °C that the ash reduction was enhanced between 74% to 77% (tap water, stirring, 2-3 cm). It must be noted that on higher temperatures the amount of feedstock that is washed away also increases from 8% to 14%. All other literature performed washing experiments at room temperature except [19] at 90 °C but here was not varied in temperature. Temperature dependence can be explained by higher diffusion rates at higher temperatures.

4.4.4 *AMOUNT OF WATER*
The amount of water used for washing varies between a ratio between biomass and water of 1:8.3 [16] (by weight, dry matter to water) to 1:100 [19]. In [23] the difference in ash reduction between 1:20 and 1:50 is studied. For sugar beet pulp, the difference in ash reduction is 48% and 51% (30min) and for grape pomace the difference was 56% and 61%. From [16] can be seen that during the washing about 40% of the total potassium is washed out with a water ratio of 1:11.5. In [4] the amount of water is also varied; ratios of 1:15, 1:30 and 1:50 (for 10% moisture in the feedstock) resulted in an ash reduction of respectively 62%, 66% an 69%.

4.4.5 *RESIDENCE TIME*
In [16] the shortest residence time of 3 minutes was used and about 20% of the potassium was washed out. In [23] the difference between 30 and 120 minutes was studied: for sugar beet pulp(1:50 water ratio) it increased from 57% to 54% ash reduction but for grape pomace ash reduced from 61% to 69%. As stated, this phenomena can be explained by the unwanted leaching of biomass. [4] states that the diffusion is very fast in the first 10 minutes(250-355 μm) and after that just slowly more ash is washed out. For the 2-3 cm size feedstock ash is very quickly reduced in the first minutes (32% reduction) while after 20 minutes the fast diffusion becomes slow when about 60% ash is washed out.

Washing clearly has a minimal time in which the ash removal is fast and a maximum time were organic parts significant leach out. The residence time of the EFB in a washing tank should thus not be too long or too short. In Appendix B a very rough estimation of the diffusion time is calculated.

4.4.6 *TYPE OF WASHING*
Numerous types of washing are found in the literature. Most used is soaking where the biomass is put under water for a specified time. Better results are obtained when the biomass is also stirred but the extra ash removed is only 2-3% [4]. In [16] and [17]the biomass is pressed, washed and pressed again. Pressing is useful in two ways before washing: first it decreases the amount of water with soluble ashes and second it weakens the cellular structure so washing is more effective. In chapter Appendix C sugar cane processing is discussed that has many similarities with this method. A second washing step can also be envisioned but in none of the found literature this is studied.

4.4.7 *Type of water*

As washing water, tap water and distilled water are studied. In [4] both were compared and distilled water gave a better ash reduction 76% in contrast to 73% with tap water (2-3 cm feedstock) or 80% versus 73% for feedstock size 250-355 μm. A third possibility to reuse washing water that is already polluted with ashes was not found in literature.

4.5 Conclusions

- Tap water or other clean water available at the palm oil mill will be used for washing. The costs of distilled water is much too high to use in an industrial process when only a slight increase in ash reduction is gained. Also no additives like acids will be added to the water.
- The desired size will be the size that is required for the pyrolysis process. The EFB is shredded to loose fibers of length 0.5 – 1 inch or 1.25 – 2.5 mm. Larger feedstock requires longer residence times while smaller feedstock has the side effect that organics start to dissolve in water.
- The EFB are directly used after the separation of the fruits and are thus considered fresh. However, the fruit bunches have undertaken a steam treatment so the cellular structure is already damaged.
- The temperature of the water will not be increased since the effects are not very large while large amounts of energy are required to heat up the water. When additional 'free' steam is available at the palm oil mill it can be used.
- The amount of water is very decisive; more water will increase the ash release. The ration between dry biomass and water is best between 1:10 and 1:20. This because of the relative large amount of ash washed out compared to the increase in water usage.
- Based on the very fast ash reduction during the initial washing time, the residence time for shredded feedstock is estimated to be optimal at 10-15 minutes.

5 FOULING AND SLAGGING

In a large scale pyrolysis plant, char is combusted to produce the heat required for the pyrolysis process. Char is about 20% of the products after the pyrolysis of a biomass. When char is combusted, inorganic components of the char can be sticking on the surfaces of the combustion unit and this is called fouling. When these deposits start melting it becomes sticky and after cooling form a glassy layer it is called slagging.

In literature it is found that burning a fuel containing ash, has a negative effect on a boilers efficiency. Some components in the ash like $NaCl$, KCl, Na_2SO_4 and K_2SO_4 will lowers the melting temperature of the ash and thus enhance the adhesion of fly ash particles. This can cause fouling in the heat transfer regions of the boiler and thus reduce efficiency and increases the frequency of maintenance [26] [27]. According to [28], sugar cane bagasse does not exhibit fouling since both chorine as potassium are leached during the process of extracting sugar. [29] concludes that washing biomass feedstock results in the reduction of alkali release during combustion.

The temperature of when the ash starts melting/evaporating is dependent on the composition of the ash. [30] shows in his research that the amount of potassium remaining in the ash is very temperature dependent. The higher the temperature, the more potassium is evaporated and thus more fouling occurs, see Figure 11.

In Figure 10 it can be seen how alkali components in gaseous form react and cause the slagging on heating surfaces in boilers.

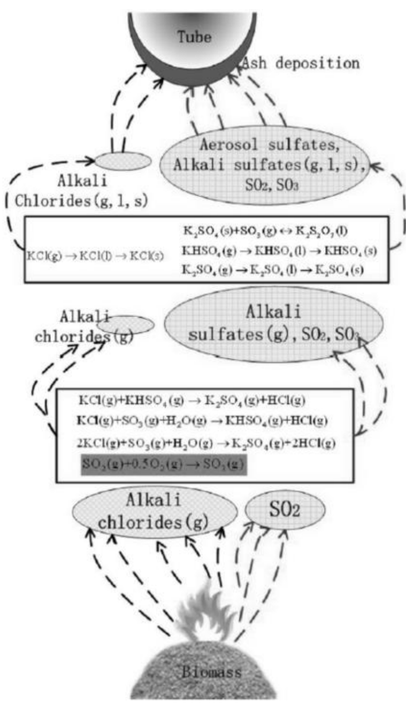

Figure 10 Schematic pathways of sulfate–alkali deposition on a heating surface, from [31]

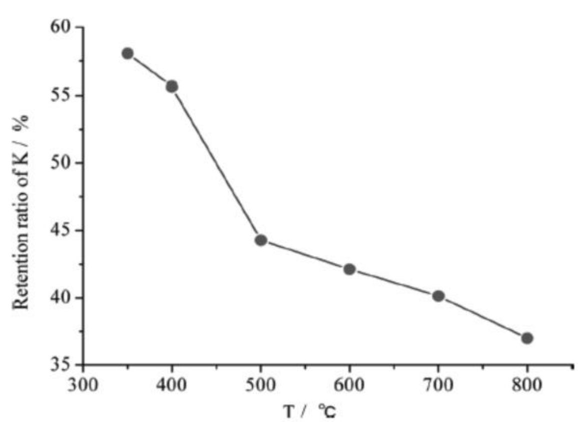

Figure 11 Emission of potassium versus temperature (720 s), from [30]

As a design parameter, [32] states that one must strive to fuel with alkali level smaller than 0.17 kg/GJ in order to prevent fouling. Alkali levels greater than 0.34 kg/GJ will cause definitely fouling and possibly slagging.

Char produced by the pyrolysis of EFB has an HHV of about 20 MJ/kg or 50 kg/GJ. It is assumed that all Potassium from the biomass after pyrolysis is incorporated in the char as a worst case scenario. EFB contain about 2.4% potassium while char is about 20% of the mass of the initial EFB. This results in an potassium content of almost 10% of the char. This results in 5 kg/GJ of potassium which will definitely cause fouling and slagging.

During the washing of the EFB it is assumed that 90% of the potassium is washed out. This results in a potassium amount of 0.5 kg/GJ and thus still a factor 3 too high to prevent fouling. However, small part of the potassium will also end up in the pyrolysis oil. Experiments must show how much potassium will end up in the char.

6 *DESIGN*

In this chapter a cost effective EFB washing installation is designed that can be implemented at an palm oil mill. It is tried to minimize water usage and waste, energy usage and complexity while maximizing the washout of potassium. The washing installation will be placed after the size reduction pretreatment and before the drying of the feedstock. In this way, possible existing plants can easily be modified for washing of EFB

6.1 DESIGN PARAMETERS

The following design parameters were used for the design for the washing of EFB. All are based on results found in chapter 4, minimizing complexity and their application in the pyrolysis unit.

- 5 tons per hour EFB (dry), moisture content about 65% moisture (wet basis) so 14.3 t/h
- Fiber length of the feedstock is 0.5 – 1 inch (or 1.25 – 2.5 cm)
- Water biomass ratio 1:10
- Average residence time 12 minutes
- Tap water without additives is used
- No heating of the water
- Amount of potassium washed out 90%

6.2 SIZING PRETREATMENT

In order to convert the EFB in a pyrolysis plant, it first has to be reduced in size for good conversion. The effectiveness of washing EFB is also increased when the EFB is reduced in size. It is thus a logically step to reduce the EFB in size to the required size for pyrolysis before washing.

The size reduction will be done in two separate steps. The first step will consist of a shredding step in which the whole EFB will be shredded to chumps of about size of length 2 to 4 inch (5 to 10 cm). In the next step the EFB will be run through a hammer mill in order to reduce the size even more to 0.5 to 1 inch (1.25 to 2.5 cm) and loosening the fibers.

6.3 WASHING

For washing two different setups are studied. In the first setup, the EFB is, after the size reduction pretreatment, washed in a single water tank. The second setup consists of multiple washing tanks in series with in between dewatering equipment. In this chapter mostly the taking out of potassium is discussed since this is the mineral that is most required to be washed out.

In theory, a single tank installation requires more water to obtain an equivalent removal of potassium compared to the water usage in multiple tanks. The concentration of potassium in the washing water has to be remained relative low in order to wash most potassium out. In a single tank setup this can only be done by using large amounts of water. In a multiple tank setup the low concentration has only to be maintained in the last tank to remove the remainder of the potassium. In the tanks upstream, higher concentrations of potassium in the washing water can be used since not all potassium has to be removed in that tank. A multiple tank setup has also as advantage that not only diffusion acts as mechanism to remove the potassium from the EFB, also the mechanical dewatering removes water dissolved potassium.

In Figure 14 a basic design is sketched how large all equipment is an how they can be placed relative to each other. The screw presses are placed above the water washing tanks so both the water as the dry EFB fall down into the correct tank.

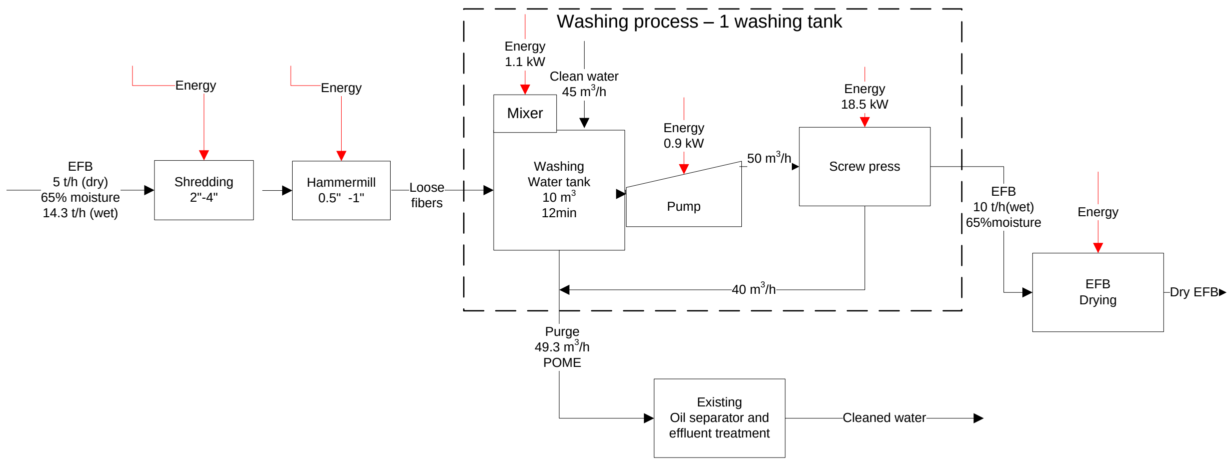

Figure 12, flowchart of the washing installation with one washing tank

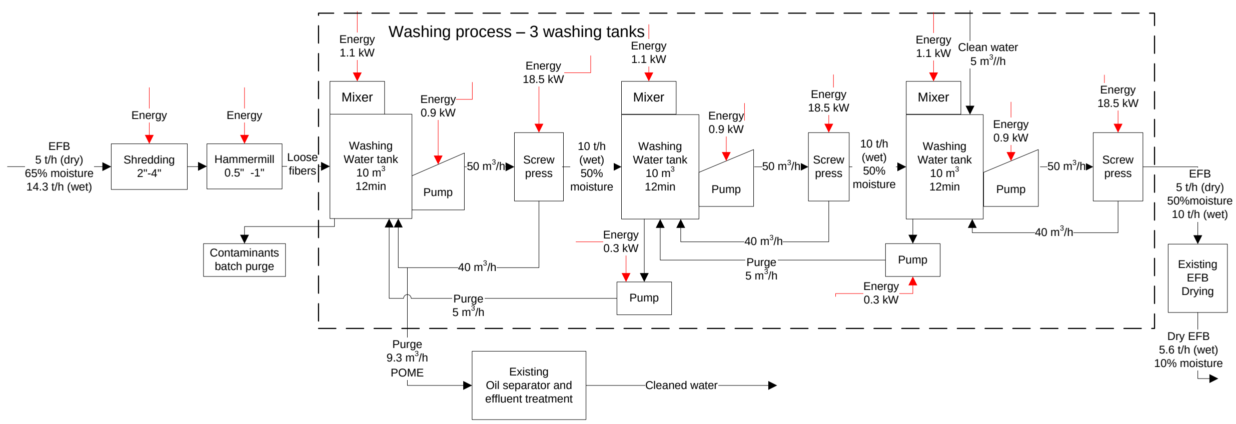

Figure 13, flowchart of the washing installation with three washing tanks in series

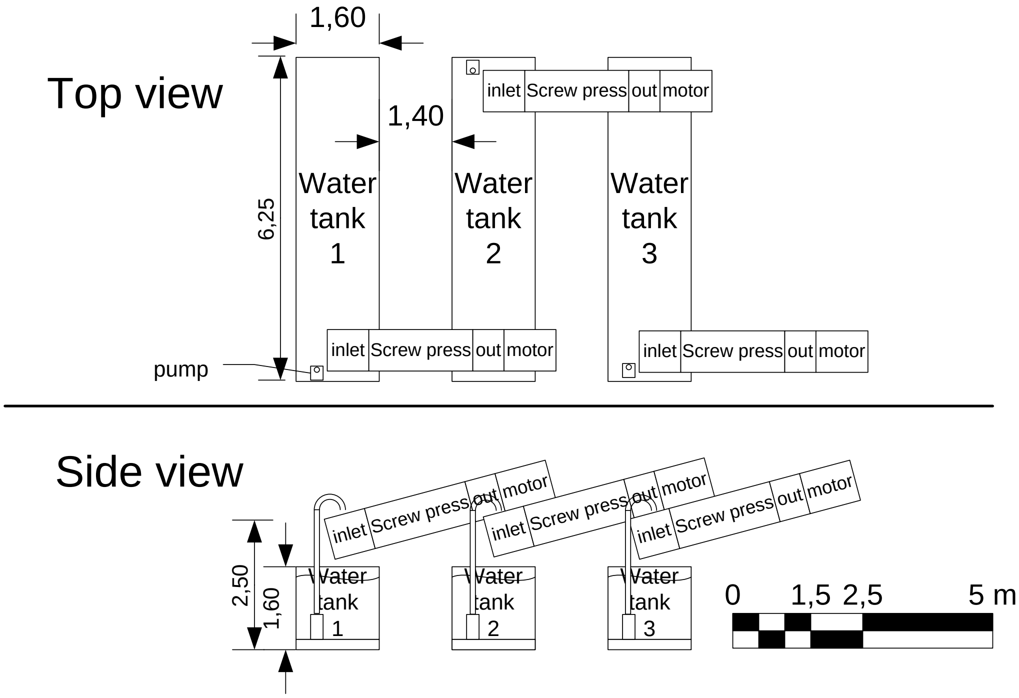

Figure 14: Basic design top and side view of a water washing setup with three tanks

6.3.1 *MINIMAL WATER PURGE*

In the one tank scenario, almost all potassium must dissolve in the water of the only washing tank. When all potassium dissolves this results in a potassium flow of 120 kg/h based on an EFB flow of $5t/h$ with an potassium content of 2.4%. The maximum amount of potassium that is soluble in water (based on KOH at $25°C$) is $1.21kg/kg$ thus a mass fraction of 0.55. This results in a minimal theoretical purge of 100L/h in order to remove all potassium when the solution is saturated with infinite washing times. It must be noted that the influence of all kinds of other organic and nonorganic components dissolving are not taking into account in this simple calculation. Therefore experimental data from literature is used to make better purge calculations.

6.3.2 *WATER PURGE*

Purging water is required to maintain a predetermined concentration of species in the washing tanks. The maximum potassium mass fraction is determined from experiments in literature [4]. Assumed was that 90% of all potassium in EFB (2,4%) is washed out when using 1 kg of EFB in 10 to 15 liters of water. This results in a mass fraction of $w = 0.0014\ to\ 0.0024$.

In order to remove 90% of all potassium in a single water tank with a potassium mass fraction of $w = 0.0024$ a water purge of 45 m^3/h is necessary.

When three washing tanks are used, it is estimated that in the first one 50% of the potassium is removed, the second one 30% and the third one 10% and thus a total removal of 90% of the potassium. When in the third tank a mass fraction of $w_3 = 0.0024$ of potassium in water is used, a purge of 5 m^3/h is required. This same purge is required in both other tanks in order to prevent a buildup of water. This purge together with the estimation of the amount of potassium washed out results in a potassium mass fraction in the first and second tank of respectively $w_1 = 0.022$ and $w_2 = 0.0096$.

In both scenarios an additional amount of 4.3 m^3/h of POME is generated due to water that is pressed out of the biomass. Three washing tanks is chosen in favor over one washing tank based on the amount of washing water required in the latter case.

6.3.3 POTASSIUM CONTENT IN THE POME

From [33] can be read that normally POME contains about 2 kg of potassium per cubic meter so the mass fraction is about $w = 0.002$. For each ton of FFB (or 0.22 ton of EFB), 1.5 ton of POME is generated. Based on the 5 t/h EFB washing this correspondents with an POME production of 34 ton/h and a potassium amount of 68 kg/h. When 90% of the potassium in EFB is washed out this results in a potassium flow of 108 kg/h. Therefore it is unavoidable that the potassium content is raised in the POME unless the amount of water added is almost doubled. The potassium mass fraction will become $w = 0.003$.

6.3.4 WATER WASHING TANKS

In the water tanks the actual washing of the biomass takes place. The tanks will be sized at 10 liters of water for each kilogram of EFB is inside it. An average residence time of 12 minutes per tank will be maintained so that at any given time one ton of EFB is in each tank. For the washing of 5 ton/h are thus tanks of size 10 m^3 necessary.

The water tanks are envisioned that EFB enters from above on one side and the washed EFB is taken out on the other side at the bottom. In Figure 15 a basic 3D design of a water washing tank is show. As can be seen the EFB enters at the right side from above through an opening in the tank. The EFB is positioned above this opening by a conveyor belt for the first tank. The EFB inlet of the other two tanks have the outlet of the screw press directly above then so the EFB can fall through a chute directly in the tanks.

On the left side a vortex pump will pump the EFB-water mixture up. The soaked EFB is taken out together with large amounts of washing water and transported to the inlet of a screw press that is positioned roughly above the pump.

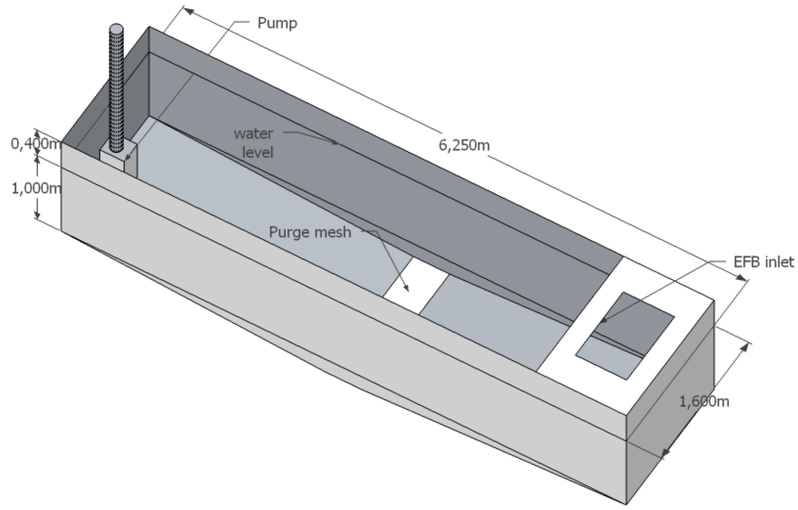

Figure 15: Basic design of a water washing tank

A mixer is used in order to create a turbulent flow inside the tank to improve diffusion of ashes coming out of the biomass and have a uniform distribution of the EFB. As a 150N axial trust mixer a MX-ii 18.07.4 (Figure 16) from Bedu can be used that uses 1.1 kW of electricity. It must be noted that no mixers are displayed in Figure 15. A uniform residence time of the EFB cannot be guaranteed since all is mixed. The EFB will be in the tank according a gaussian distribution with an average of 12 minutes. The variance will be small when three tanks are used.

A purge of washing water is once in a while required to remove impurities like sand. Therefore, the bottom of the tank is not flat but has its lowest point in the center of the tank. This way heavy contaminants like sand will collect at this lowest point and will be taken out in the purge mesh also at this point. The mesh size must be smaller than the EFB size in order to prevent biomass to be removed from the washing process, but large enough to let contaminants pass.

Figure 16: Bedu MX ii mixer, image taken from brochure

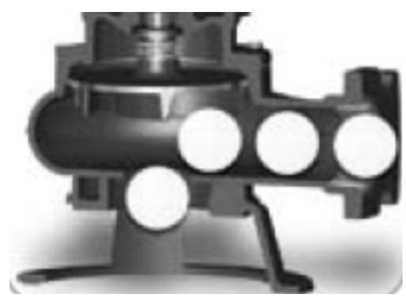

Figure 17: Bedu DGO vortex pump, image taken from brochure

6.3.5 PUMPS

The pump that pumps the water-EFB mixture from one tank to the next needs a capacity that can handle the 5 t/h EFB that is soaked 1:10 in water. This results in a capacity of the pump of 50 m^3/h minimal. A pump that is capable to pump solids soaked in a liquid must be used in order to prevent jamming or additional wear. A vortex compeller is chosen based on the large free passage, high throughput and low head.

A vortex pump from the Bedu DGO series is chosen (DGO 150/4/80 A0CM/50). This pump can deliver at a flow of 50 m^3/h a head of 2.3 m and thus is capable of taking the water with EFB to the screw press installation above the tank. The power used by this pump is 0.9 kW.

A pump for transporting the water purge from one tank to the previous tank needs a capacity of 5 m^3/h. A Bedu U3KS meets this requirement with a head of 3 m and a power usage of 0.3 kW.

6.3.6 *Screw press*

A screw press is used for dewatering and pressing the biomass after washing. It is assumed that the screw press can reduce the moisture content to about 50% in the EFB after pressing. Pressing is done since from [16] can be learned that a significant amount of ashes is removed from the biomass. This can be explained by a local very high concentration of potassium dissolved in the water inside the EFB that has not diffused out yet. In the three water tanks case the screw press is positioned that the leachate water will flow down back into the water tank where the water-EFB mixture was just pumped out of. The pressed EFB exits at the other side and falls though a chute into the next water tank.

A KSP-450 screw press from Klinkenberg is chosen. This screw press can handle the large amounts of water coming from the water tank and is specified for a throughput of $5 - 7\ t/h$. The KSP-450 has a power consumption of 18.5 kW [personal correspondence].

7 *Energy usage*

Washing EFB results in a higher oil yield. However, the energy required during the washing of the EFB must be lower the amount of electricity that can be produced from the increase in oil yield. Otherwise washing is just a waste of electrical energy.

For a 5 t/h washing installation with one washing tank, the electrical power demand is 20.5 kW. For the case with three washing tanks this demand is 62.1 kW. This results respectively in 14.8 kJ/kg_{EFB} and 44.7 kJ/kg_{EFB}.

In Table 1 can be read that unwashed EFB has an oil yield of 36.9% while washed EFB results in a yield of 61.3%. From [4] can also be read that the higher heating value of EFB is about 20 MJ/kg. As efficiency for the electricity production $\eta = 35\%$ is assumed. Per kilogram of EFB this results in 2.6 MJ for unwashed EFB and 4.3 MJ for washed EFB and thus an increase of 1.7 MJ/kg_{EFB}.

Washing is energy efficient since only 0.9% (one tank) or 2.6% (three tanks) of the additional produced electrical energy is used in the washing process.

8 *DISCUSSION & RECOMMENDATIONS*

The design of a washing installation for EFB is based on the determined design parameters. These parameters are determined after a literature study on the subject of washing all kinds of biomass. However, it is not certain how well the results from batch experiments in a lab can be translated to a continuous industrial process. Variation of the EFB in freshness, ash and alkali content, moisture content, structure, size, etc. can all occur so predicting the exact properties of washed EFB is very difficult.

In literature, the batch test were done using fresh water. It is recommended that test are done to verify the amount of ash washed out in a washing tanks when using purge water from the next washing tank while using the specified purge concentrations. Also it can be studied if the concentration of ashes in the washing water can be higher to reduce POME production while maintaining the same quantity of ash washed out.

The moisture and ash reduction by pressing out water is based on practices and literature about the sugarcane process. EFB has a different structure so it must be tested how effective pressing is in reducing moisture and ash with in particular potassium. Also the need for mechanical dewatering in between the water washing tanks can also be discussed. A screw press or other similar dewatering equipment uses quite a lot of electrical energy while the dewatering is directly undone when the EFB is ditched in the next water tank. Lab test must verify that a significant amount of ash and potassium is removed from the EFB when pressing.

An uniform residence time cannot be guaranteed. A mixer is placed in every washing tank to enhance EFB distribution. Death spots where some EFB holds up too long or EFB that is almost instantaneous pumped out after entry cannot be avoided. However, using three water tanks in series, the total residence time of a EFB particle is averaged with small deviations. In a detailed design it can be considered using a screw of perforated drum to have a plug flow like throughput so the residence time for all EFB is the same.

Reduction in organic components of the biomass in purge water is mentioned in literature and is mainly affected by particle size. However, no quantitative value could be determined for this reduction during washing in the designed installation. Test must determine how large the reduction of organics is.

9 CONCLUSION

Ash inside biomass has a negative effect on the yield of oil during pyrolysis. The main cause of this low yield appears to be a catalytic effect that is caused by potassium. Unwashed empty fruit bunches (EFB) may contain up to 7 % of ash of which potassium can be up to half of it. Washing of biomass can reduce the amount of ash inside it. Up to 90% of potassium can be washed out since it is soluble in water.

Scientific literature describes that the washing EFB can greatly improve the oil yield during pyrolysis from below 40% to yields higher than 60%. The energy used in washing is only a small fraction of the potential in electrical energy in the additional generated pyrolysis oil.

From experimental data in scientific literature optimal washing conditions for an industrial process are determined. The used specifications for designing a washing installation are:

- 5 tons per hour EFB (dry)
- Fiber length of the feedstock is 0.5 – 1 inch (or 1.25 – 2.5 cm)
- Water to biomass ratio 1:10
- Average residence time 12 minutes
- Tap water without additives
- No heating of the water

The main part of the designed washing installation for EFB are three washing tanks in which ashes can diffuse out of the biomass. Three water tanks in series are used. Unwashed EFB is entered at the first tank and pumped to the next. Clean water is added in the last tank in the row and from here purged to the previous tank. This way the amount of POME is a factor 5 lower than when only one washing tank is used.

Screw presses are used to dewater the EFB mechanically. Another advantage of this manner is that additional ash, that has not yet diffused out of the biomass, is removed. The EFB-water mixture is pumped out of a tank into the inlet of a screw press situated above the tank. This way, all leaking and pressed out water flows back in to the tank. The next washing tank is situated directly below the outlet of a screw press so the EFB falls directly in the next tank.

It is expected that 90% of the potassium content of EFB will be washed out in the designed installation. Based on a 5 t/h throughput of EFB, the installation uses 5 m^3/h of water and 63 kW of electricity.

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Appendix A Wastewater discharge

The residual water after washing a biomass contains certain pollutants. These pollutants consist of minerals and organic components.

A.1 Organic components

Discharging waste water that contains organic components is not to be considered lightly; too much waste discharged into water can destroy all life in it. The reason for this is that the organic components are broken down by aerobic micro-organisms that use oxygen dissolved in water for it.

Two values are used to determine the amount of oxygen used by the waste water: biological oxygen demand BOD and chemical oxygen demand COD. The BOD value states the amount of oxygen, usually mg/L water at 20°C that is used in 5 days. The COD is slightly different and states the total amount of oxygen needed to break down all organic components in the water.

From [34] it is read that the maximal value for BOD for waste water discharging in surface water in The Netherlands is $BOD_5^{20} = 20\ mg\ O_2/L$.

A.2 Mineral components

In Table 4 and Table 5 are values displayed of design specifications for discharge water of two recent manure processing plants.

Indicatieve lozingseisen:

Zuurgraad (pH):	6,5-8;
Temperatuur:	< 25 °C;
Geleidbaarheid (EGV):	ca. 50;
Fosfaat:	0,12 mg/l (uitgedrukt in P);
Stikstof totaal:	2,2 mg/l; (uitgedrukt in N);
Ammonium:	0,2 mg/l (uitgedrukt in N);
Koper (Cu):	3,8 µg/l totaal;
Koper (Cu)	1,5 µg/l opgelost;
Zink:	7,8 µg/l;
Nikkel	20 µg/l;
Sulfaat:	100 mg/l;
Chloride:	50 mg/l;
Zuurstof:	>5 mg/l;
onopgeloste bestanddelen:	5-10 mgl;
Kalium:	400 mg/l
Natrium	50 mg/l
BZV:	5 mg/l;
CZV:	30 mg/l;
Thermotolerante e-coli's:	<20 (NPM/ml)
Entovirussen, fagen:	afwezig

Table 4: Design specifications for mineral content of waste water from [35], table is in Dutch

Parameter*	Lozingseis per individueel steekmonster	Lozingseis voortschrijdend gemiddelde van 10 steekmonsters	Eenheid
pH	5,5 - 8,0	5,5 - 8,0	n.v.t.
BZV5	15	5	mg/l
CZV	150	50	mg/l
Ntot**	15	5	mgN/l
Ptot	1,5	0,5	mgP/l
Onopgeloste bestanddelen	45	15	mg/l
Chloride	100	100	mg/l
Natrium	150	50	mg/
Kalium	400	400	mg/
Sulfaat	100	100	mg/
Koper	15	5	µg/l
Zink	150	50	µg/l

Table 5 Design specifications for mineral content of waste water from [36], table is in Dutch

A.3 Cleaning

Cleaning of the organic components is done in industrial water treatment plants by the same aerobic mechanism as happens in surface water. However, the process is accelerated in a venting place by bacteria so that in a couple of hours all organic material is consumed. In specific industrial cases where normal aerobic digestion is not applicable, the usage of hydrogen peroxide can be considered.

Reverse osmosis is a process that uses a membrane to remove large molecules and ions from water. It is used as industrial process in creating drinking water, waste water treatment, food industry, car washes etcetera and a cheaper solution than the distillation of water.

A.4 POME treatment Malaysia

POME (Palm Oil Mill Effluent) is the waste stream en an palm oil mill. About 1.5 ton of POME is produced for each ton of FFB(fresh fruit bunch). POME consists of 95–96% water, 0.6–0.7% of oil and grease and 4–5% of total solids. The POME is first collected for about 1-2 days in a sludge pit. In here the residual oil will rise up and will be removed.

Three different treatment methods are commonly used in POME treatment. The first one is: POME pumped into several ponds in series where the BOD value can decrease steadily over time. An aerobic pond is much used since it is a very economical solution but is has a very long hydraulic retention time of 45-80 days, depending on the mill.

Another solution is Tank digestion and mechanical aeration in where air is mechanically forced through the POME in order to speed up digestion. The hydraulic retention time is reduced to about 20 days. A variation on this is a closed anaerobic mixing tank that results in the emission of methane. Additional waste water streams that can originate from cleaning EFB can be treated using existing treatment methods.

POME that is cleaned and meets waste water regulations can be discharged or can be sprayed on the fields. Discharge regulations for Malaysia can be found in Figure 18. The cleaned POME can and is being used as a fertilizer on palm oil farms since it contains high amounts of nutrients as can be seen in Figure 19.

Table 1: Second schedule in the EQA in relation to parameter limits for watercourse discharge for palm oil Millers

Parameters (1)	Limits According to Periods of Discharge 1-7-1978-30-6-1979 (2)	1-7-1979-30-6-1980 (3)	1-7-1980-30-6-1981 (4)	1-7-1981-31-12-1982 (5)	1-7-1982-31-12-1983 (6)	1-1-1984 and thereafter (7)
Biochemical Oxygen Demand (BOD) 3 day, 30°C; mg L^{-1}	5,000	2,000	1,000	500	250	100
Chemical Oxygen Demand (COD); mg L^{-1}	10,000	4,000	2,000	1,000	-	-
Total Solids; mg L^{-1}	4,000	2,500	2,000	1,500	-	-
Suspended Solids; mg L^{-1}	1,200	800	600	400	400	400
Oil and Grease; mg L^{-1}	150	100	75	50	50	50
Ammoniacal Nitrogen; mg L^{-1}	25	15	15	10	150*	150*
Total Nitrogen; mg L^{-1}	200	100	75	50	300*	200*
pH	5.0-9.0	5.0-9.0	5.0-9.0	5.0-9.0	5.0-9.0	5.0-9.0
Temperature °C	45	45	45	45	45	45

Note: *: Value of filtered sample; **Source:** International Law Book Services (2010): 59

Figure 18: Water discharge regulations for palm oil millers in Malaysia, from [12]

Type of Effluent	Ppm BOD	N	P	K	Mg
ANAEROBIC EFFLUENT					
Digested in stirred tank	1,300	900	120	1,800	300
Digested in pond/ditches/lagoon					
-supernatant	450	450	70	1,200	280
-supernatant – 10% slurry	191	320	42	1,495	258
Digested in tank – bottom slurry	1,000-3,000	3,552	1,180	2,387	1,509
AEROBIC EFFLUENT					
Aerobic pond – supernatant	100	52	12	2,300	539
– bottom slurry	1,000-3,000	2,670	461	2,378	1,004
Dried sludge cake	-	45,000	12,000	15,000	12,000

(American Palm Oil Council)

Figure 19 Type of treated POME and their composition, from [37]

Appendix B Estimated diffusion time

To make a rough estimate of the time diffusion will take, Fick's first law of diffusion based on mass fractions is used. A density of $\rho = 400kg/m^3$ for EFB is used and a diffusion coefficient of $1.9 \cdot 10^{-9}m^2s^{-1}$ of Potassium chloride in water is used. It is however doubtful is this number is correct; the number should be larger based on the expected presence of the smaller OH ion (reactant of the reaction between potassium and water). On the other hand the number should be significantly lower because the ions must diffuse through a porous solid in water instead of just water.

$$J = -\rho \cdot D \frac{\partial \mathrm{w_K}}{\partial y}$$

A model of an EFB fiber can be seen in Figure 20. In this model it is assumed that in the pretreatment the EFB is cut and fiberized to a length of 2cm and a radius of 1mm. The water will permeate the EFB completely and instantaneous dissolve the potassium to the maximal soluble amount of $1.21kg/kg$. The water in the tank is stirred and thus has the same concentration everywhere and is maintained relatively low to enhance diffusion.

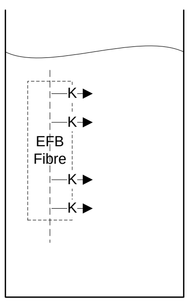

Figure 20: Schematic view of diffusion of potassium from a piece of EFB

For a low concentration of potassium in the water tank the following equation can be used to make an estimate for the diffusion time. In this equation the diffusion length is taken from the center of the EFB particle to the outer surface so $\Delta x = 1mm$.

$$t \approx \frac{\Delta x^2}{2D} \approx 4.4\ minutes$$

This value lies in the same order of magnitude of the determined values of the found literature. The value is rather low but this can be explained by a too large value of the diffusion coefficient. The value of the diffusion coefficient should be lower because diffusion must take place in a porous medium (EFB) instead of just water.

The calculated value is just a very rough estimation and not really useful so experimental literature date is used.

Appendix C Sugar cane bagasse

Sugar cane bagasse is a residual product of the sugar cane industry after the sugar canes are repeatedly pressed and immersed in water in order to remove as much sugar as possible. Sugar cane bagasse is very interesting since the unexpected high yields of bio-oil after pyrolysis based on the relative high ash content. The bagasse is studied on what steps it passes in the sugar production process in order to explain the high yields of bio-oil.

In Table 6 the contents of sugar cane can be seen. In this table, WC-U is the entire sugar cane with leaves still attached to it. It can be seen that the ash content of the whole cane is 6.7 mf wt% and the potassium content is 1.3 mf wt%.

Fuel Treatment	WC-U	WC -M	WC-MLM	SC-MLM	Bagasse*	Coal
Higher Heating Value (MJ/kg, dry basis)	17.46	17.99	18.43	19.24	19.53	34.62
As-fired Moisture (% wet basis)	9	8	8	8	10	7
Proximate Analysis (% dry matter)						
Fixed Carbon	16.87	15.19	13.46	12.75	12.56	44.46
Volatiles	76.42	78.94	81.97	85.23	76.65	41.00
Ash	6.71	5.87	4.57	2.02	10.79	14.54
Ultimate Analysis (% dry matter)						
C	45.13	46.63	47.42	49.84	48.14	68.34
H	5.71	5.83	6.06	4.33	5.13	5.14
O (by difference)**	41.69	40.99	41.54	43.60	35.53	9.93
N	0.48	0.42	0.35	0.16	0.40	1.49
S	0.22	0.14	0.04	0.03	0.07	0.59
Cl	0.65	0.25	0.04	0.04	nd	nd
Ash	6.71	5.87	4.57	2.02	10.79	14.54
Ash Elemental Analysis (% ash, 600°C)						
Si	23.78	33.13	38.23	33.16	22.49	27.70
Al	1.14	0.77	1.01	0.43	10.20	16.17
Ti	0.16	0.13	0.18	0.11	2.06	1.03
Fe	0.95	0.74	1.03	0.94	10.67	2.05
Ca	1.91	1.64	1.74	2.53	3.61	0.91
Mg	2.70	1.82	1.09	1.55	2.53	0.65
Na	0.63	0.62	0.47	0.47	0.81	0.68
K	19.26	10.63	3.92	5.84	1.90	0.54
P	1.09	1.44	0.42	1.24	0.38	0.09
S	2.30	1.32	0.30	0.44	0.29	0.20
Cl	6.51	0.89	0.01	0.13	0.01	0.01
C	0.03	0.01	0.04	0.35	0.15	nd
O (by difference)	39.54	46.86	51.57	52.83	44.90	49.97

*Similar commercial variety, insufficient sample of as-fired material. **Accounts for C, Cl, and S also inclu*

Table 6: content of sugar cane with after different treatments, From [38]

Comparing Sugar cane with Empty Fruit Bunches can be done since both contain a relatively large amount of ashes. Both crops also contain a lot of potassium. In the pressing and washing steps most of potassium present in the sugar cane is washed out.

C.1 Sugar production process

The production of sugar is an process in which multiple times the sugar cane is plunged in water. Therefore it can be considered that the bagasse is already washed at the end of the process. In Figure 21 a schematic overview of the process can be seen. First the fresh sugarcane is washed to remove all dirt and such from the cane. Then in a chopping machine the cane is reduced in size to chops ranging 10-25mm.

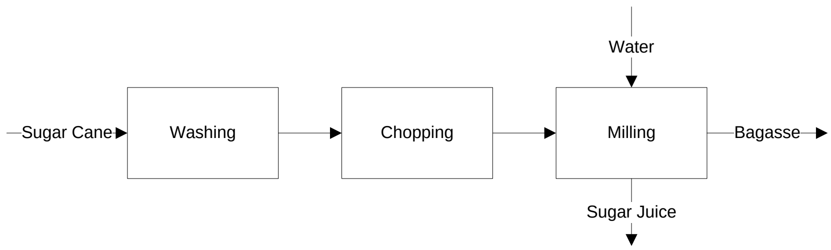

Figure 21: Schematic overview of the sugar cane process

The most interesting step is the milling step. In this step four or five milling machines (usually three rollers per milling machine) are placed in series. An example can be seen in Figure 22 coming from [39]. The bagasse enters the mills on the left en leaves at the right. Imbibition water is used for maximizing sugar yield. Only 40-45% of the moisture can be pressed out of the biomass so water is added to dilute the sugar still in the cane to increase the yield.

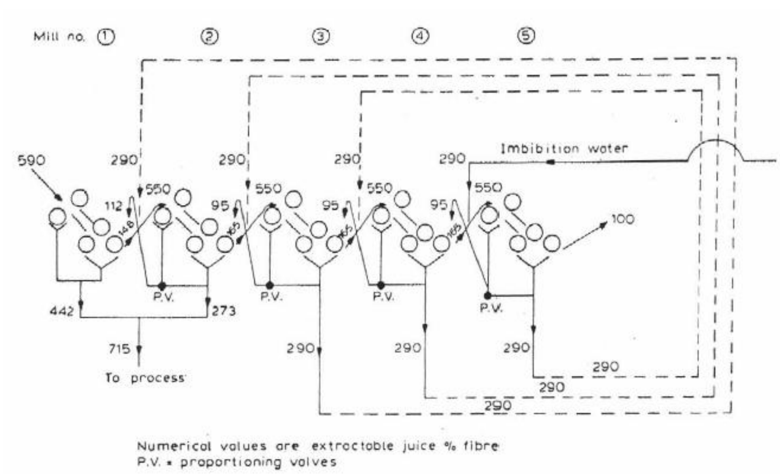

Figure 22. Pressure feeder, imbibition circuit. From [39]

Another, less used, process is sugar cane diffusion. In this method the cane is placed on a transport belt with water flowing perpendicular to the bagasse at the end of the belt. The now sugar containing liquid is forwarded one stage and absorbed more water and so on. This counter flow principle reaches maximum concentration at the beginning of the belt. A schematic drawing can be seen in Figure 23.

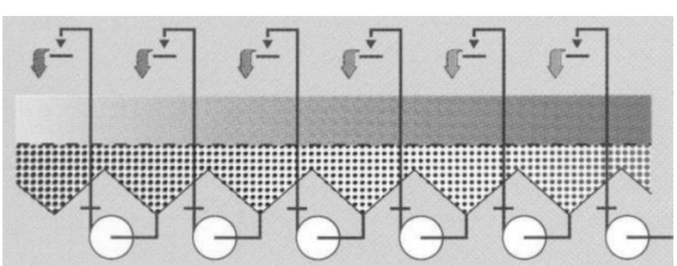

Figure 23 Schematic drawing of sugar cane diffusion. From [40]

C.2 Water usage

In [41] it is mentioned that around 1500 to 2000 liters of water are used for 1 tons of sugarcane to produce sugar. 1000 liter of waste water is produced that has a BOD (biochemical oxygen demand) of 1000 to 1500 mg/liter. It is necessary to clean the waste water, or effluent: discharging it in water will deplete the water of oxygen and makes the environment unfit for aquatic life. Discharging on land will cause clogging of soil pores by oil and grease and decaying organics . However, when condense and cooling water is reused the water usage per ton can be reduced to 100 - 200 L.

In [42] a sugar plant is studied on pollution prevention. It is mentioned that the amount of water used as imbibition water is 35% cane based. The total water usage is about 2100 liter per ton of sugarcane. The waste waters COD (chemical oxygen demand) value is 250 mg/L.In Figure 24, source [43], all streams containing water that enter en leave a sugar plant are displayed. In Table 7 the flows that are dumped are displayed. It can be seen that the imbibition water used in the mills are a significant part.

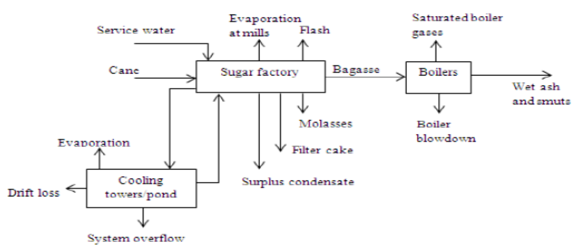

Figure 24: Streams containing water entering and leaving a sugar mill, from [43]

Sinks	Flow (kg/s)	Composition (mg sugar/kg water)
Mills (Imbibition)	6.91	0-80
Boiler	12.53	0-10
Lime make up water	0.14	0-40
Filter wash	1.06	0-80
Centrifuges	0.29	0-80
First heater	1.29	0-40
Total water requirements	22.22	

Table 7: Results from water balances for sinks, from [43]

C.3 Ash content

During the milling process of the sugar cane, ashes are washed out. Untreated sugar cane contains 6.7 mf wt% ash of which 23% potassium(1.54% in total) [17]. Bagasse [15] contains 3.61 mf wt% ash of which 2.59% potassium (potassium content of total biomass is 0.07 mf wt%). [15] give a value for potassium content of 0.014%. Most of the potassium end up in an viscous byproduct called molasses that remains when the sugar is extracted from the sugar juice. On average, molasses contains 8.5 % ash and 3.9 % potassium (79.5° Brix) [44]