Biomass pre-treatment for bioenergy

Case study 5: Leaching as a biomass pre-treatment method for herbaceous biomass. Sugar cane trash and palm oil mill residues.

Pressed, dried and milled EFB

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Abstract

Herbaceous biomass originates from plants that typically have a non-woody stem and that dieback at the end of the growing season, in contrast to trees which build up woody biomass over years. Herbaceous biomass comprises a 50% of the EU biomass potential, worldwide this should be a similar percentage. For most applications the high inorganic / ash content causes problems. Particularly Cl and K are problematic. Chlorine (together with K) contributes to corrosion problems in thermal conversion and K and Na are correlated with low ash melting temperatures causing ash slagging and agglomeration. In most cases Cl and K content of herbaceous biomass needs to be reduced by 10 to 20 times to fall within acceptable levels set by current thermal conversion standards. Fortunately K and Cl (and Na) can easily be removed by leaching with water, which has been proven for many types of biomass. Practical methods for doing so have not yet been presented. Tests were executed on oil palm empty fruit bunch (EFB) and sugar cane field trash. Both are typically underutilized residues which currently have little uses.

Extraction experiments with EFB and sugar and cane trash have shown that potassium and chloride concentrations can be reduced by 80% respectively 90% after four consecutive extractions with fresh water, bringing Cl and K down or close to acceptable levels. Experiments showed that one kilo of dry matter biomass absorbed approximately 2 litres of water. After 30 minutes (EFB) and 15 minutes (trash) equilibrium was reached and the water was removed. The loss of biomass after 4 washing cycles was 6% DM for EFB and 15% for trash.

Under practical conditions repeated leaching with water will require too much water and generate large quantities of polluted water which is hard to recycle.

Using a counter-current extraction system would make it possible to use 3.3 litre water per kg of (DM) biomass to remove 94% of K and Cl in 10 extraction stages. Or 5.4 litre of water in 4 counter-current stages.

The cost of extraction on a scale of 40.000 tons DM (equivalent to a large oil palm mill) was estimated to be approximately 8 US$/ton (6.5 €/ton). Which is 5 to 10% of the delivery cost of biomass pellets to European harbours.

Table of contents

1   Introduction

Currently almost all biomass used for thermal conversion consists of wood; wood chips, wood pellets and logs. Wood has good thermal conversion characteristics which include low ash content, high ash melting point, low corrosion potential.

Herbaceous biomass is biomass from plants that typically have a non-woody stem and that die back at the end of the growing season (Obernberger and Thek, 2012), in contrast to trees that build up woody biomass over years. This herbaceous biomass includes most agricultural residues and grasses, including bamboo and wheat straw and also residues from oil palm and sugar cane production.

Both woody and herbaceous biomass are included in biomass potential studies. In practice herbaceous biomass is however hardly used for energy production, because the composition is variable and generally of low quality for thermal conversion (Panoutsou et al. 2016).

This is illustrated by the recent assessment of lignocellulosic biomass potential in wider Europe, which shows, that most of the forest (wood) potential for energy production is used while the potentially available crop residue is not used (Table 1).

Table 1. Lignocellulosic biomass potential of the EU27 plus neighbouring countries of the western Balkans, Ukraine, Moldova and Turkey (ref. Panoutsou et al. 2016). Showing that the agricultural (herbaceous) residues are mostly not used now.

	Current potential	Used potential
	------------- Million tons dry matter per year ---------------	
Wood from forests	325	350
Other forest biomass (forest industries)	185	140
Agricultural residues (field and agri-industries)	**342**	**15**
Waste	89	60
Cropped biomass	152	2

Table 2 shows the amount of residues produced by the 10 most important crops producing lignocellulosic field and local mill residues. It shows that some 800 million hectares of these crops produce 3.8 billion tons of mostly dry lignocellulosic crop residues. Most of this material is currently not used.

Table 2. List of the most important crops producing lignocellulosic crop residues on the field of at the local processing plant. Based on FAOSTAT database for 2014 and typical product to residue ratios.

		Total field	Total mill
	Million hectares	Million ton DM crop residue per year	
Maize	185	1,038	
Rice, paddy	163	816	
Wheat	220	729	
Sugar cane	27	264	264
Oil Palm	19	192	52
Barley	49	173	
Sorghum	45	103	
Sunflower seed	25	66	8
Millet	31	43	
Seed cotton	35	35	
Sum:	**800**	**3,459**	**316**
All crops worldwide:	1,414		

Though a whole range of factors determine the quality for thermal conversion of biomass, the most fundamental desirable characteristics are low chlorine content, low ash melting temperature, and low nitrogen content (Elbersen et al. 2017). Chlorine (together with potassium) contributes to corrosion problems in thermal conversion and K and Na are correlated with low ash melting temperatures causing ash slagging and agglomeration. In thermal conversion nitrogen is less of a problem than chlorine or potassium, but it may increase the risk of NOx emissions, requiring costly emission controls. Emission reduction measures are costly especially at low scale. Total ash content is also relevant, it consists mainly of silica and other oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, P_2O_5, and SO_3. Ash does not contribute to energy production, it may increase wear of machinery, it has to be discard and many conversion systems cannot deal with high ash content biomass. The ash melting temperature is negatively correlated with high alkali (K) contents.

In Table 3 the typical content and the desirable contents of the most important inorganic compounds of herbaceous biomass are shown.

Table 3. Typical contents of critical inorganic components in (living) herbaceous biomass, and the desirable levels needed for thermal conversion. Based on Elbersen et al (2017) and Lewandowski and Kicherer (1997) and existing pellets norms (Obernberger and Thek, 2010).

Inorganic compound	Explanation and effects	Typical content	Norms or desirable contents
Chlorine (Cl)	Variable in living tissue, depends mainly on soil Cl content. Causes corrosion, HCl and dioxin emission.	0.3 to 2% of dry matter	< 0.02% or <0.3%
Potassium (K)	Essential in living tissue. Causes corrosion and lowering of ash melting point	0.6 to 2 % of dry matter	Difficult to quantify but < 0.03 % K+Na is sometimes mentioned
Sodium (Na)	Variable in living tissue, depends mainly on soil Na content.	0 to 1% of dry matter	See above
Nitrogen (N)	Essential in living tissue. Contributes to NOx emissions. Measures can be taken to limit effects	0.5 to 2%	0.03% to 1%
Ash	Ash content of herbaceous biomass depends on soil and tissues type. Ash will lower efficiency and increase operating costs.	1 to 15%	0.5 to 3.5 %.

As Table 3 shows, herbaceous biomass will not be able to comply with the current norms for pellets used for thermal conversion. Cl and K (and Na) contents will almost always be too high and also ash and N will generally be problematic unless adaptations to the combustion system can be made. The Cl and K content needs to be reduced by a factor of 10 to 20.

For other biomass applications such as pyrolysis, potassium is known to decrease pyrolysis oil yield and increase char yield (Jensen and Dam-Johansen, 1998). To increase pyrolysis oil yields washing of biomass is therefore a pre-requisite when using herbaceous biomass.

Fortunately K and Cl (and Na) can easily be removed by leaching. This has been shown under field conditions for switchgrass, *Miscanthus,* reed and wheat and rice straw.

Since the early 1990's research has been conducted into leaching of herbaceous biomass in order to increase quality for thermal conversion. The research was conducted on herbaceous biomass types such as rice straw (Jenkins et al, 1996 and others) and banagrass or *Pennisetum Purpureum* (Turn et al, 1997).

As far as we know these leaching concepts have not been put into practice, though more recently new research into leaching of biomass has been reported again for oil palm residues (Lam et al, 2014) and grasses and crop residues (Yu et al., 2014; Cui et al, 2015; 2017).

Counter current extraction is a technology that can efficiently remove Cl and K using minimal amounts of water, making leaching as an upgrading technology for herbaceous biomass a viable option. Here we describe the case of counter current extraction of sugar cane and oil palm residues.

2 Removal of potassium and chloride from agro-residues and herbaceous biomass

Agro-residues and herbaceous biomass have a huge potential as biofuel, but are currently underutilized because of high potassium and chloride concentrations (see chapter 2). Potassium and chloride are both highly soluble in water and may be extracted from the biomass quite easily. Problem is that high volumes of water (10:1 ratio) are needed (Turn *et al.* (1997), Hong *et al.* (2017), Yu *et al.* (2014), Deng *et al.*, (2013). Through counter current extraction, the water usage could be reduced. At the same time, the extracted minerals will be more concentrated, reducing the costs to concentrate the minerals and transport them back to the fields for use as fertilizer. Experiments and modelling with two examples of agro-residues and herbaceous biomass have shown that over 90% of potassium and chloride can be removed with a water to dry matter ratio of approximately 3 or 4 to 1 using counter current extraction.

Figure 1, Pressed, dried and milled EFB

2.1 EXTRACTION OF AGRO-RESIDUES AND HERBACEOUS BIOMASS WITH REPEATED FRESH WATER EXTRACTIONS

First the water absorption of biomass is established. Three kilos of dry matter absorb approximately 6 litres of water. Nine litres of water was then used in 4 extraction cycles (Table 4). After 30 minutes (EFB, Figure 3) and 15 minutes (trash, Figure not shown) of recycling, the conductivity of the liquid was stable (equilibrium presumably achieved). Each subsequent extraction, the final conductivity, and Chemical Oxygen Demand (COD), and concentration of potassium and chloride was reduced by a factor of two compared to the previous extract.

Extraction experiments with EFB and trash have shown that conductivity of the extracted fluid is reduced by 90% in four consecutive extractions with fresh water (Figure 2). The potassium and chloride concentrations are then reduced by approximately 80% respectively 90%.
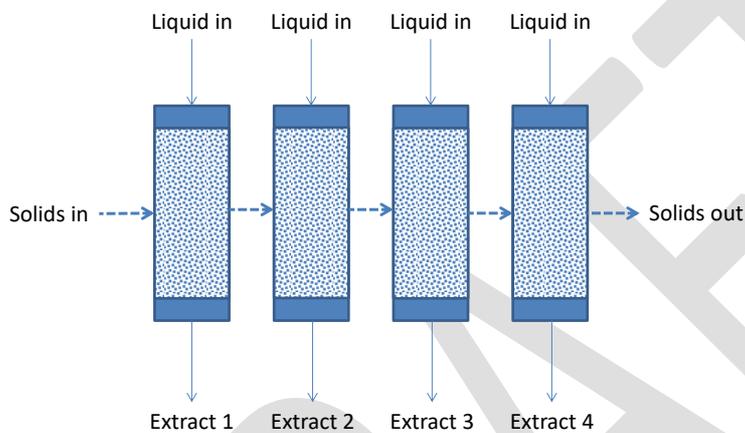

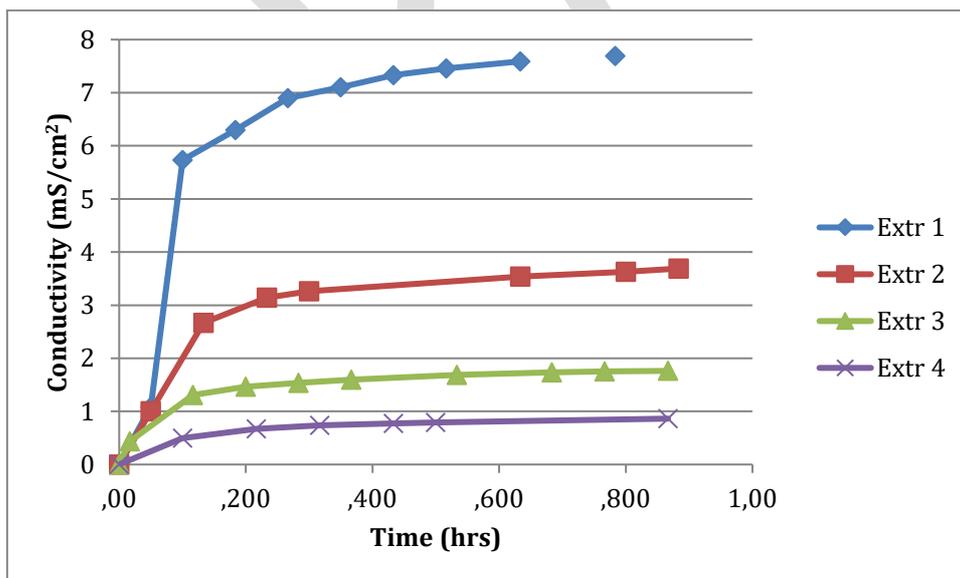*Figure 2, Repeated extraction of biomass*

Figure 3, Conductivity of extraction liquid pool (EFB) (ref. Pascal van der Hoogt 2017)
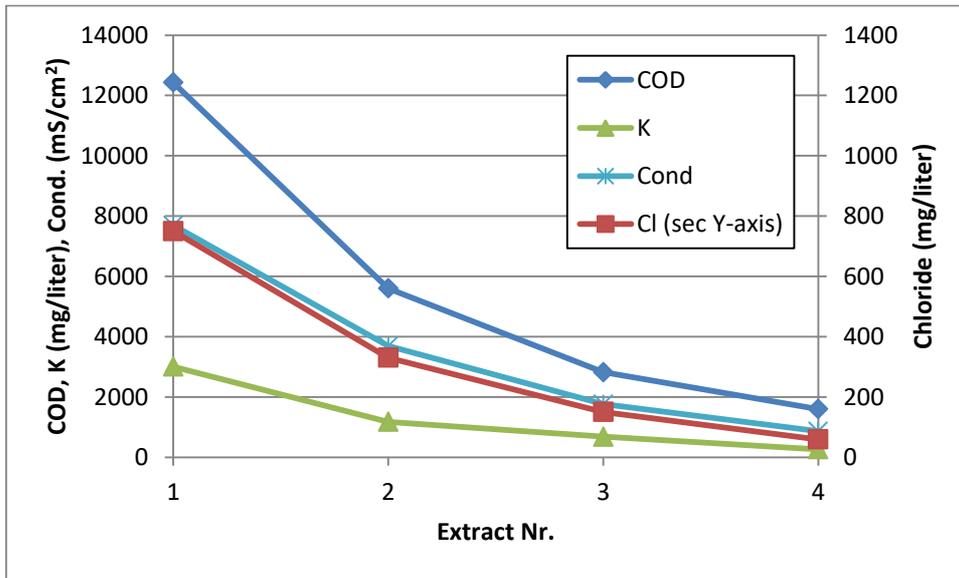
Figure 4, Final COD, potassium, chloride concentration and conductivity in EFB extracts (ref. Pascal van der Hoogt 2017).

The composition of the pressed EFB before and after extraction steps is presented in Table 4. It shows that over 80 percent of potassium present in the starting material ends in the extracts.

Table 4, Potassium balance of repeated extraction of EFB (TM = total matter, DM = dry matter)

In		TM	DM	K	K	K
		kg	kg/kg	kg/kg	gram	gram
	Starting material	3	94.80%	2.05%	58.30	58.30
	Total in					**58.30**

Out		TM	DM	K	K	K
		kg	kg/kg	kg/kg	gram	gram
	Column	8.77	29.50%	0.40%	10.35	10.35
		litre	mg/litre			gram
	Extract 1	8.19	3005			24.60
	Extract 2	9.64	1175			11.32
	Extract 3	10.03	680			6.82
	Extract 4	7.07	263.5			1.86
	Drainage	4.09	307.5			1.26
	Total out					**56.21**
	K removed					82%

Table 5, Potassium and chlorine content before and after 4 extractions (% of DM)

	EFB	Trash
K before	2.05%	0.68%
K after	0.4%	0.07%
Cl before	0.38%	0.13%
Cl after	0.02%	0.033%*

*Chlorine content was calculated from chlorine balance over the experiment (measured was lower than 0.05%)

The recovery of DM after extraction was 94% for EFB and 85% for trash.

2.2 COUNTER CURRENT EXTRACTION

The above described results strongly indicate that potassium and chloride are distributed more or less equally over the water absorbed to the solid phase and the free flowing extraction liquid. Four consecutive extractions with a volume as high as used in the experiments leads to a large consumption of water and, at the same time, will yield a large amount of extract (ratio of liquid to dry matter 12:1). In a counter current set up (Figure 5), this water consumption may be strongly reduced.
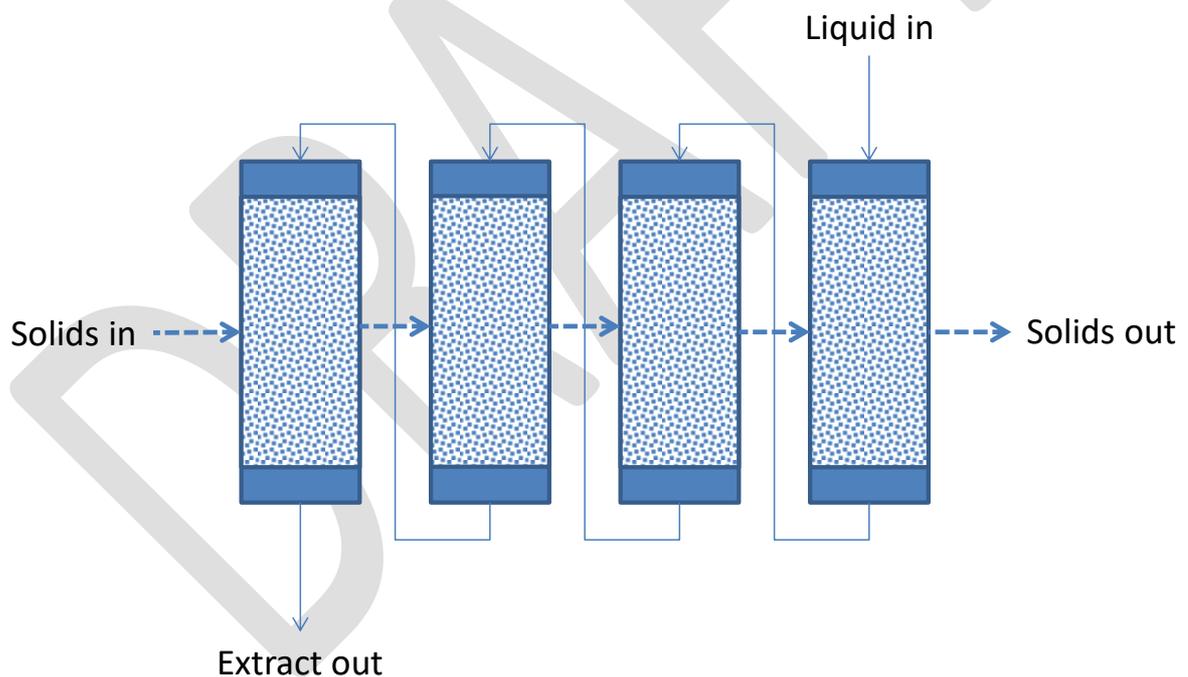
Figure 5, Counter current extraction of biomass

It is difficult to realise a counter current flow of solids against a liquid flow. Therefore, it was decided to apply a simulated moving bed. In a simulated moving bed, the solids are not really moving; instead, a series of valves take care that the liquid runs through the cleanest bed of solids first, and through the bed with the highest K and Cl concentration last. This is depicted in Figure 6 for a 4 column system. Three columns are washed, the fourth column is reserved to unload and load the solids.

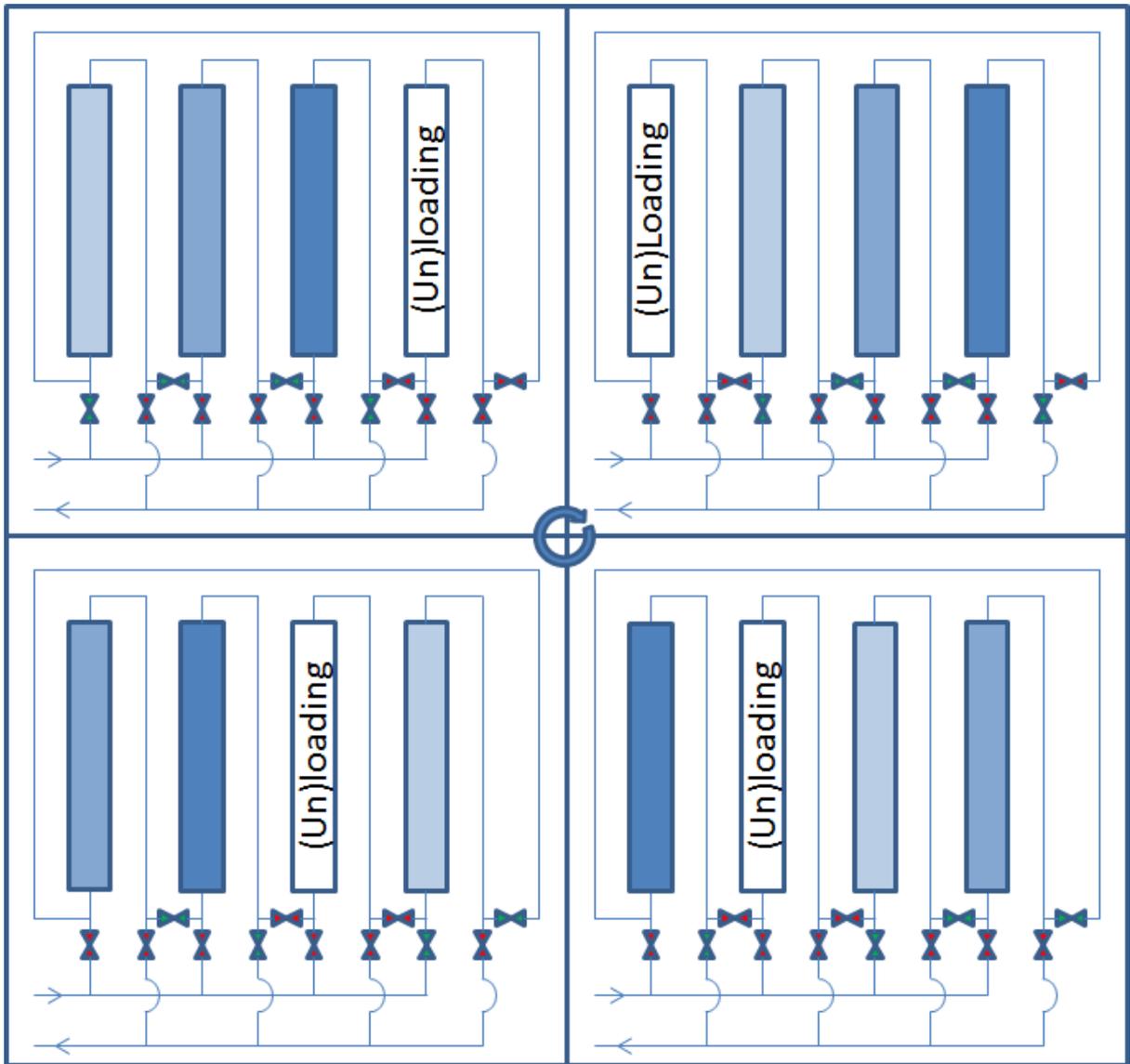*Figure 6, 4 stages of a 4 column simulated moving bed cycle (green valves are open, red valves are closed, darker blue indicates higher salt concentrations)*

Figure 7, Counter current L/S pilot system at WFBR

The pilot system was filled with shredded EFB (Figure 7) and washed with water in a 20:1 ratio. A counter current extraction with 3 columns was executed. The high water to solids ratio was needed because shredded EFB is very fluffy and therefore a very large volume of water is needed to fill the column. Figure 8 shows that the effluents have high ion concentrations and conductivity, and that the water that was drained from the column had very low ion concentrations. The uneven concentrations are a result of the start up and closing procedure of the process (causing concentrations in E1, E2, E3, (E4), E7 and E8 to be lower). Therefore, it is best to have a look at E5 and E6 only. Here we see an almost 10 fold lower concentration in the drainage compared to the extract. So a 90% removal is possible.
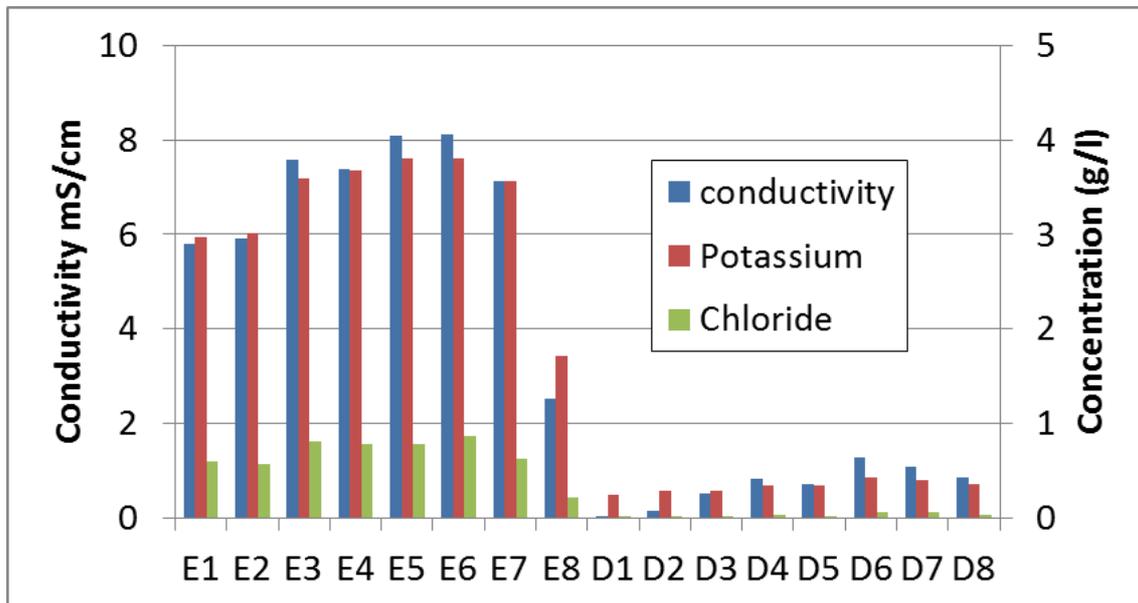
Figure 8 Counter current SMB extraction of EFB with water to biomass ratio of 20 to 1 (E is effluent, D is drained water). (ref. Pascal van der Hoogt 2017)

The high water usage could be reduced if the water is applied from the top instead of the bottom. This way, there is no need to completely fill the column with water, the column will act like a trickling filter. Simulations were executed to estimate the achievements of a counter current simulated moving bed extraction with trickling filtration. First of all, the ratio of extraction liquid compared to solids needs to be chosen. For a counter current liquid-liquid extraction, Kremser *et al. (1984)* have shown that high extraction efficiencies can be reached as long as the extraction factor (E) is chosen above 1 (see box 1).

Counter current extraction in depth

It is assumed that counter current extraction is described by a series of equilibrium stages (Figure 9), where the component of interest is extracted from the heavy phase to the light phase.
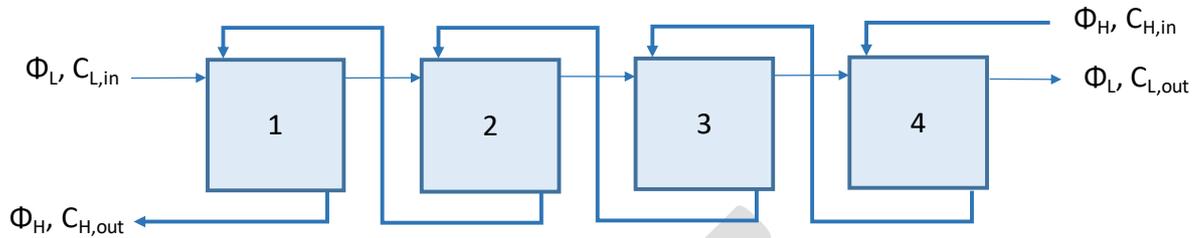
Figure 9 Schematic representation of L/L counter current system with 4 equilibrium stages

Each equilibrium stage consists of a mixer and a settler (Figure 1).
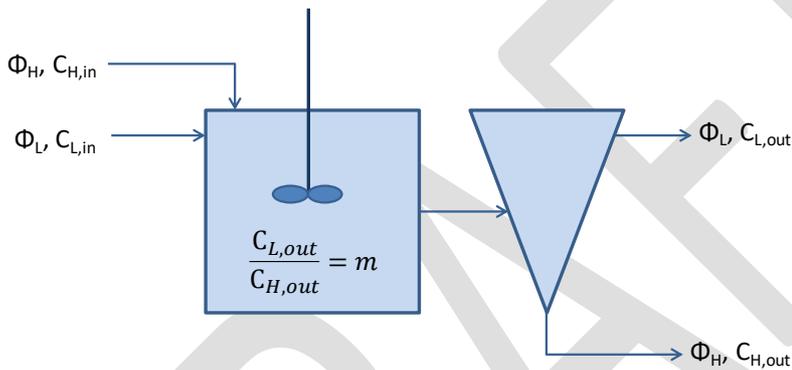
Figure 10, Schematic representation of one equilibrium stage of L/L extraction

For each equilibrium stage, the mass balance is described by equation 2 and the phase equilibrium is described by equation 3.

Equation 1

$$\Phi_L C_{L,in} + \Phi_H C_{H,in} = \Phi_L C_{L,out} + \Phi_H C_{H,out}$$

Equation 2

$$\frac{C_{L,out}}{C_{H,out}} = m$$

Kremser *et al.* (1984) have solved this system of equations. An extraction factor E was defined and it was shown that a high recovery is possible if E>1.

Equation 3

$$E = \frac{\Phi_L m}{\Phi_H}$$

2.3 TRANSLATION OF EXPERIMENTAL DATA TO FULL SCALE APPLICATION

In counter current extraction, several factors will influence the separation efficiency:

- Extraction factor (see equation 3 in box 1)
- Mass transfer limitation
- Number of columns

From Kremser et al (1984) we know that if the extraction factor is chosen higher than 1, a high recovery is easily reached within a limited number of equilibrium stages (see also Table 6). From the experiments it appeared that the partition coefficient of chloride and potassium is close to 1. This is to be expected as free water and water immobilized in the biomass will show comparable affinity towards chloride and potassium. Hence, in order for the extraction factor to be larger than 1, the extraction liquid flow should be larger than the immobilized water 'flow' in order to reach high potassium and chloride recovery (a factor of 1.1 was assumed).

From the experiments it appeared that equilibrium is reached after approximately half an hour for EFB and 15 minutes for sugar cane trash.

In a 10 equilibrium stage system with 1.1 times more extraction liquid than water absorbed in the biomass, it should be possible to reduce potassium and chlorine concentration by 94% (Table 6, third column, last row: C_{S_eq} = 0.06). Each stage is at equilibrium (equation 2 and 3 fulfilled). Solids move downwards (C_{S_eq} of stage n is equal to $C_{S start}$ of stage n+1) and liquids move upwards (C_{L_eq} of stage n is equal to C_{L_start} of stage n-1).

Table 6, Concentration of solute in solid and liquid phase at start and after equilibrium is reached (normalized to starting concentration of 1 in the solids)

Stage	C_{S_start}	C_{S_eq}	C_{L_start}	C_{L_eq}
1	1.00	0.87	0.75	0.87
2	0.87	0.75	0.64	0.75
3	0.75	0.64	0.54	0.64
4	0.64	0.53	0.44	0.53
5	0.54	0.45	0.36	0.45
6	0.44	0.35	0.27	0.35
7	0.36	0.27	0.20	0.27
8	0.27	0.19	0.13	0.19
9	0.20	0.13	0.06	0.13
10	0.13	0.06	0.00	0.06

At higher extraction factors (E), more extraction liquid and less equilibrium stages will be needed to reach the same removal (after 10 equilibrium stages, 6% of the solute is left in the solid phase and thus 94% is removed). An overview is given in Table .

15

Table 7, Nr. of stages needed to reach 94% removal as a function of the Extraction factor chosen

Extraction factor (E)	20	4	2.3	1.8	1.5	1.35	1.30	1.23	1.18	1.10
Nr. of stages or columns needed	1	2	3	4	5	6	7	8	9	10

Clearly the number of stages is strongly reduced when using more liquid. The optimum amount of equilibrium stages will depend on the actual costs and benefits of adding additional equilibrium stages. In our case study we have chosen to use 10 equilibrium stages. Even if full equilibrium is not reached, we can still assume that the needed liquid flow will not be larger than 150% of the water immobilized in the biomass.

If we want to reduce the K and Cl content by 94% through counter current extraction in 10 or in 4 stages we can calculate the need amount of water as follows:

We assume that fully wetted biomass has a dry matter content of 35%. For 1 kg of DM biomass we need 65/35 = 1.8 litre of water for wetting and 1.8 x 1.1 = 2 litre of water for extraction in 10 stages (see table 7). Overall 1.8 + 2 = 3.8 litre of water is needed.

If 4 extraction steps are used we need 1.8 * 1.8 = 3.24 litre for extraction, so overall we need 1.8 + 3.24 = 5.04 litre of water.

If we need dry biomass for thermal conversion we would then press the material to approximately 50% moisture content (assumption). Thereby generating 2.8 litre if 10 stages are used and 4.04 litre if 4 stages are used.

3 Estimated cost of counter current extraction for reduction of chloride and potassium content

The economic feasibility of counter current extraction for reduction of chloride and potassium content will be highly case specific. Two cases will be discussed here in more depth (EFB and sugar cane trash). The issues that are seen in these cases will apply to other cases as well, but should be evaluated with case specific information.

3.1 CASE 1: COUNTER CURRENT EXTRACTION OF EMPTY FRUIT BUNCH

3.1.1 Process flow scheme

The following process is envisaged for CC extraction of EFB. First the EFB is pressed. Then it is shredded to increase the area to mass ratio. After that the shredded EFB is extracted and then pressed. After pressing, two options may be foreseen: 1. Drying and pelletizing of EFB or 2. Burning of EFB in the palm oil mill CHP unit so that shells and fibre will be available as biofuel.
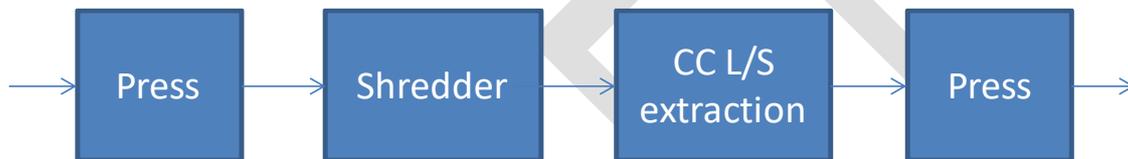

Figure 21, Process flow scheme of EFB extraction

3.1.2 Counter current extraction

It is assumed that the EFB will be processed at the site of the palm oil mill. Therefore, conveyer belts can be used to transport the EFB to the counter current extraction unit. The extraction unit will consist of ten equilibrium stages. Instead of columns, a series of ten heaps on a concrete floor will be used. A conveyer belt will be used to feed the biomass to the heaps. A shovel will be used to push the heaps off the floor after extraction onto a second conveyer belt that brings the washed biomass to the press. Sprayers will be used to spray water over the biomass heaps at a rate of 2 $m^3/(m^2 \cdot hour)$. A series of valves will be used to organize counter current flow without actually moving the biomass (simulated moving bed). Each heap will have a gutter where the sprayed water is collected and a pump to spray the water onto the heap.

As a starting point, a palm oil mill of 60 ton FFB (full fruit bunch) per hour was assumed. Such a plant will produce a flow of 12.9 ton per hour of pressed EFB @35% DM. The extraction liquid flow will be 9.2 m^3/hr (=Q_{EFB} x (1-0.35)). It was assumed that 1 hour is needed to reach full equilibrium. It was further assumed that the heaps will be 10m x 4.6m x 2.4m (L x W x H). If the heaps are positioned at two sides of a transport belt, then five times the width of a heap (23m) of belt is needed to feed the heaps and to carry away the cleaned biomass. The liquid will be recirculated over the heaps at a rate of 110 m^3/hr (=L x W x 2 $m^3/(m^2 \cdot hour)$).

3.1.3 Economic feasibility (EFB)

The uninstalled equipment costs were estimated based on the costs of an EFB shredder, a concrete floor, two 25 m conveyer belts and 10 pumps. The installed equipment cost was estimated to be 4 times the uninstalled equipment cost.

Table 8. Installed equipment costs of counter current EFB extraction

Item	Unit cost	Amount	Cost (1000 Euro)
Concrete floor	64 €/m^2	552 m^2	35
Conveyer belt	525 €/m	50 m	26
Pumps	7,300 €/piece	10 pieces	73
EFB press	50,000 €/piece	1 piece	50
EFB shredder	50,000 €/piece	1 piece	50
Uninstalled equipment cost			**234**
Installed equipment cost**			**938**

**A Lang factor of 4 was used to estimate installed equipment costs based on uninstalled equipment costs

The operating costs were estimated based on labour costs, water costs and electricity costs. The labour costs are estimated to be 10 €/hour. This will include a frontwheel loader and fuel for the front wheel loader.

Table 9. Running costs of counter current EFB extraction (OPEX)

Item	Cost	Per	Amount	Unit	Cost	Unit
Worker (incl. shovel)	2920	hr/yr	10	€/hr	29	k€/yr
Water	80000	m^3/yr	0.2	€/m^3	16	k€/yr
Electricity (incl. press)	400	(MW.hr)/yr	0.07	k€/(MW.hr)	28	k€/yr
Costs					**73**	**k€/yr**

The cost of capital per year was assumed to be 0.2 €/(€·yr) (10% depreciation, 5% maintenance and 5% interest). The total costs of the installation are then 73 + 938 * 0.2 =261 k€/yr. Divided over 40.000 ton (DM) of EFB dry matter this results in 6.5 €/ton, which equals 8 US$/ton.

3.1.4 Treatment of washing water (EFB)

Independent of the scenario, a washing water stream will result. This stream will be rich in potassium, but will also hold other extractives from the EFB. It may contain organic acids, sugars, protein, sugar oligomers, etc.

The cheapest way to get rid of the washing water would be to use it for irrigation of nearby (palm) plantations, where the minerals (K) should also have a value. Local conditions determine the possibilities to use the washing water and the costs or value.

This will very much depend on irrigation options (how many plantations are situated downstream from the mill and how many can easily be reached via pipes or channels.

The potassium concentration of the washing water will not be sufficient for direct marketing of this liquid. Concentrating the K via membrane filtration (Reverse Osmosis) would be an option. Fouling of membranes may be a serious issue as the liquid also contains a considerable amount of organic substances that will also be concentrated. The permeate could be used as boiler feed water (reducing water treatment costs).

Another option would be to spread the water over an active compost heap. The water will

evaporate and help to rewet and cool the compost. The potassium may be sold together with the compost as potassium enriched compost fertilizer.

Here it is assumed that the washing water may be disposed off at zero costs. If effluent treatment would cost 0.5 €/m^3, then the costs of cleaning the biomass would increase by approximately 2 € per ton DM.

3.1.5 Drying of extracted EFB

The first step of drying would be a press. This would yield EFB with approximately 35% to 50% water content. The remaining water may be removed by evaporation in a tunnel dryer. The tunnel dryer may be heated with hot off gasses from the CHP unit. Sufficient heat is present in these off gasses.

Another option would be to burn the wet biomass in the CHP unit and have the water evaporated while burning. Drying with off gasses from the CHP unit is the most efficient method as in this way the low quality heat from the off gasses is used for evaporation. In both other cases, high quality heat is lost. Of course, direct burning of wet biomass in the CHP unit will save on capital costs, as no tunnel dryer will be needed.

Table 10. Mass flows for typical palm oil mill of 30 ton FFB per hour

	Shells to CHP unit	Fibre to CHP unit	EFB to CHP unit	Shells avail. for sale	Fibre avail. for sale	EFB avail. for sale
DW	86%	65%	65%	86%	65%	90%
	ton/hr	ton/hr	ton/hr	ton/hr	ton/hr	ton/hr
Drying of EFB using off gasses from CHP unit	1.38	2.67				2.1
Direct firing of EFB in CHP		1.89	2.91	1.38	0.78	

3.1.6 Discussion

In the calculation above, it was assumed that the partition coefficient (concentration in liquid/concentration in solid) is equal to 1. Potassium is not removed as easily as chlorine. This could be caused by the fact that the partition coefficient of potassium is lower than 1. Negative charged side groups in the lignocellulose (such as galacturonic acid) could selectively attract the potassium. Other positive charged groups or acids could force potassium to leave the negative groups.

3.2 CASE 2: COUNTER CURRENT EXTRACTION OF SUGAR CANE TRASH

The case of sugar cane trash is different from the case of EFB in several aspects. The sugar cane trash is not available at the sugar mill, but is usually left in the field. So, costs for sugar cane trash collection should be taken into account. With the sugar cane trash, also nutrients will be removed from the field. Therefore, the farmer will need to apply more fertilizer after removal of sugar cane trash.

Table 11. Nutrients in sugar cane trash (Hristov, 2016)

	N	P	K
Nutrients content of sugar cane trash (% DM)	1%	0.13%	1.1%

The costs of fertilizer application (to replace the nutrients that are removed from the field with the trash) are estimated to be 13,- €/ton sugar cane trash dry weight. The costs of harvest and transport are estimated to be 13,- €/ton sugar cane trash dry weight (Hristov, 2016). The loss of nutrients may be reduced if the green part of the trash is left in the field, but this will increase the cost of collection. It is estimated that the cost of nutrients removed plus collection could be reduced to 20 €/ton sugar cane trash dry weight

The costs of extraction are expected to be comparable to extraction of EFB (6.5 €/ton DM). All in all, the costs will be approximately 26.5 €/ton sugar cane trash dry weight delivered and leached at the processing plant.

Most probably the sugar cane trash will be burnt in the CHP unit of the sugar cane mill. The bagasse that is burnt today can then be sold for other purposes.

The washing water from the sugar cane trash extraction may be sent to the ethanol fermentation unit of the sugar cane mill. The nutrients will then end up in the vinasse and may be sent to the land at zero extra costs (as vinasse needs to be distributed anyway)

4 Ash composition and melting point

Ash melting point is an important property of solid biofuels. A high ash melting point will enable thermal applications such as co-firing in coal fired power plants. A low ash melting point may cause severe fouling of heat exchanger surfaces. As mentioned presence of potassium is known to reduce the ash melting point of biofuels. Many agro-residues have a high potassium content and cannot be used in a coal fired power plant. Counter current extraction can be used to reduce the potassium content of agro-residues, making them suitable for co-firing in a power plant. Ash melting point was measured on pressed EFB and extracted EFB (Table 12 and Table 13).

Table 3Composition of Empty Fruit Bunch before and after extraction with water.

EFB		Before	After
Ash (550 °C)	(% of DW)	4.64	1.85
Ash (815 °C)	(% of DW)	3.77	1.73
S	(% of DW)	0.063	0.023
Cl	(% of DW)	0.38	0.024
SiO_2	(% of ash 815 °C)	30.8	33.5
Al_2O_3	(% of ash 815 °C)	0.53	0.92
TiO_2	(% of ash 815 °C)	< 0,1	< 0,1
P_2O_5	(% of ash 815 °C)	4.87	10.1
SO_3	(% of ash 815 °C)	1.89	9.54
Fe_2O_3	(% of ash 815 °C)	0.99	1.11
CaO	(% of ash 815 °C)	4.35	17.9
MgO	(% of ash 815 °C)	9.51	12.7
Na_2O	(% of ash 815 °C)	2.93	0.78
K_2O	(% of ash 815 °C)	37.8	12.7
Mn_3O_4	(% of ash 815 °C)	0.12	0.26

Table 13. Ash melting behaviour of EFB before and after extraction

EFB			Before	After
SST	**°C**		990	1080
DT	**°C**		1210	1120
HT	**°C**		1250	1160
FT	**°C**		1270	1170

Table 13 shows that even though the potassium content is reduced significantly, the ash melting temperature is hardly affected. This effect was also described in literature (Forsberg, 2002). Upon lowering the potassium to Si ratio, the ash melting point goes up and down between 800 and 1050 °C. Only at very low potassium to Si ratios, the ash melting temperature increases to values higher than 1200 °C. During this research the point just before this high rise was reached.

As Vassilev *et al.* (2014) and others have shown there is a negative correlation between ash initial deformation (DT) temperatures and hemispherical (HT) ash fusion temperature ( ) and K2O content of ash. For P2O5 there is also a negative correlation while for CaO there is a positive correlation with ash melting points.

Yu *et al.* (2014) have shown that ash melting temperatures of different species of biomass improved after leaching. The EFB in our work is high in potassium and therefore comparable to wheat straw that was reported in their work. An interesting observation is that the leaching of EFB reduces the potassium content and total ash content, at the same time the relative calcium and phosphate content of the ashes is increased. Ash melting is very complex and hard to predict.

It seems worthwhile to reduce K content further and to also try reducing Ca and P content. It is expected that a reduced pH (value below 4.5) will lead to better extraction of Ca and P which is expected to be complexed by organic acids in the pectins.

5 Discussion and Conclusions

A very large part of the biomass potential on earth consist of herbaceous biomass. This biomass is difficult to use for thermal conversion, and for many other biobased applications, due to the high content of ash and minerals, particularly Cl and K.

Potassium and chlorine content can be reduced by a factor of 10- to 20 via water extraction to levels that are acceptable for thermal conversion. The reduction in chlorine should be such that corrosion problems are avoided.

This should avoid corrosion problems caused by Cl (and K). Counter current water extraction of biomass also reduced ash content of the biomass and offers the possibility to reuse the extracted minerals (mainly K). The loss of biomass in the leaching process varied, depending on biomass type. For EFB and sugar cane trash it was 6% and 15% respectively.

The water extraction may also increase ash melting temperatures, though the results are less predictable. As shown in our experiments (and literature reports) leaching and reducing K by a factor of 5 to 10 times will not in all cases also reduce ash melting temperatures sufficiently for reaching current biomass norms.

We speculate that a reduction in P and maybe Ca content in biomass should also be pursued. Further research into further removing K and also removing P (and Ca) by lowering the pH of the leaching water should be worth pursuing. The ash melting temperature could also be improved by addition of kaolin, dolomite or coal ash. Since the ash content after counter current extraction is much lower, it is easier to improve ash melting behaviour.

Counter current extraction may require as little as 3 to 4 litres of water per kg of biomass to remove 95% of K and Cl. Without counter current extraction more than 20 litres of water will be required.

Counter current saves water but also may allow easier reuse of the removed minerals as fertilizer.

The cost counter current extraction of oil palm empty fruit bunch was estimated to be approximately 8 US$/ton DM (6.5 €/ton DM) for a 40.000 ton per year system.

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