Methods to improve biomass quality for thermal conversion[1]

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Colophon

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Abstract

The utilisation of biomass for thermal conversion present limitations in terms of the content of ash and inorganic minerals producing different problems in the combustion systems. Implementing some methods at the growing, harvesting and pre-processing phases upstream in the production chain, increases the fuel value of biomass that will be used for the energy and heat generation. The methods/technologies include: selection of the plant type (species and variety) and plant fraction (leaf, stem, node, panicle), influences growing conditions (soil characteristics, use of fertilizers), harvest (time and method), handling and storage, pre-processing and conversion systems.

This document presents a review of these methods, based on literature review, interviews with experts and case studies. Also in cases where is applicable some of the technologies are analysed considering their strengths, weaknesses, opportunities and threats

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1 Introduction

1.1 Problem statement

The intensive utilization of fossil fuels for power and heat generation is nowadays a topic for discussion. This is the most important source of greenhouse gas concentration in the atmosphere. The world has turned the attention to the utilization of cleaner and renewable sources of energy in order to reduce greenhouse gas emissions as a strategy to mitigate climate change and to strengthen energy security. In this sense biomass plays an important role as a renewable source for conversion to heat, power (electricity), biofuels (ethanol, diesel and biodiesel) and a wide range of chemicals and by-products. In 2008, the use of biomass accounts for 10% (50 EJ/year) of the total energy demand (492 EJ/year). Considering the climate change policy targets, it is expected that biomass will supply 20 – 30% (184 EJ/year) of the total energy demand in 2050 (IPCC, 2011 and IEA Bioenergy, 2007).

There are important feedstocks of biomass. They include residues from wood industry (wood wastes, sawdust), forestry, agriculture (e.g. wheat and rice straw) and perennial grass produced in degraded and marginal lands such as *Miscathus*, switchgrass and reed canary grass. Other sources of biomass are energy crops (starch, sugar cane, and oil crops), manure or dung and organic wastes (IEA Bioenergy, 2007 and Bakker and Elbersen, 2005

The utilisation of biomass for thermal conversion in energy and heat is limited by its quality. Biomass has high content of ash and inorganic minerals such as alkali metals (potassium and sodium, macronutrient in plants), calcium, phosphorous, chloride, silica and sulphur. The presence of these components in biomass, especially potassium and chloride lower the heat value to produce energy and cause ash related problems such as slag formation, fouling deposits and corrosion in boilers and furnaces. These problems reduce the efficiency of the process, increase the operational and maintenance requirements as well as the costs.

However, changes in the production chain (upstream) can be adopted at the crop management and before the conversion systems to improve biomass quality. Some studies with rice straw carried out in California (Bakker and Jenkins, 2003) and Denmark (Sander, 1997) have demonstrated that leaching straw (natural – harvesting after a rain - and mechanical treatment) to remove potassium and chloride can improve substantially the quality of straw and reduce the operational problems mentioned above. The changes can be introduced at the selection of the plant type (species and variety) and plant fraction (leaf, stem, node, panicle), influence growing conditions (soil characteristics, use of fertilizers), harvest (time and method), handling and storage and pre-processing (leaching, dry fractionation, addition of chemicals) (Bakker and Elbersen, 2005 and Sander, 1997).

It is clear that improving biomass quality (reduction of ash content and composition of biomass) has positive impacts on the conversion systems for power generation. However, there are gaps in terms of the state of the art of majority of these methods while others as leaching (natural and mechanical) are well documented.

1.2 General Objective and Research Questions

This research aims to identify and analyse the potential of existing methods/technologies to reduce the effects of ash in biomass used for thermal conversion. This study will focus on answering the following research questions:

RQ1: What methods/technologies are to improve biomass quality for thermal conversion?
- How does the method operate?
- At what extent biomass quality can be change or manipulated?
- What are the costs and the factors affecting these costs?

RQ2: What are the strengths, weaknesses, opportunities and threats (SWOT) of these methods?

- Strengths: What are the Characteristics of the method/technology that give it an advantage over others?
- Weaknesses: What are the characteristics that place the method/technology at a disadvantage relative to others?
- Opportunities: What are the chances to improve the method/technology
- Threats: What are the aspects that could dis-encourage the use of the method/technology?

2 Methodology

RQ1: What methods/technologies are available to improve biomass quality for thermal conversion?

To give answer for this research question, information was gathered from primary and secondary sources. Primary data was collected through interviews and meetings within experts in the teamwork and external experts from ECN (Energy research Centre of the Netherlands) and Jaap Kooppejan from IEA Bioenergy. Secondary data was collected from documents such as scientific papers and other publications with relevant information about the topic.

As a starting point a brainstorm of the methods available was made by the teamwork. Each option was categorized according to the phase in the production chain (growing, harvesting and pre-processing). An inventory of related documents was collected and classified taking in consideration these options. Finally, the literature review will provide a description of the methods and their main characteristics. Also include information about biomass quality changes as a result of experiments and case studies cited by different authors. An overview of these aspects is presented in this report.

RQ2: What are the strengths, weaknesses, opportunities and threats (SWOT) of these methods?

The description of the methods was supported by the analysis of strengths, weaknesses, opportunities and threats (SWOT) for the examined methods. This analysis was only provided for methods well documented. In other cases was included analysis of strengths and weakness or comparisons between methods. Table 2.1 shows some criteria used in the SWOT analysis. Depending on the particular characteristics of the method/technology, some of the criteria may be placed as a strength, weakness, opportunity or threat (e.g. environmental effects or costs)

Table 2.1Examples of criteria used in the SWOT analysis

Strengthens	Weaknesses
Characteristics of the technology that give it an advantage over others. - Implementation, operation and maintenance - Environmental effects - Biomass quality improvement (Ash content)	*Characteristics that place the technology at a disadvantage relative to others* - Economic and financial aspects - Reliability and robustness of methods. - Implementation, operation and maintenance. - Environmental effects
Opportunities	**Threats**
External chance to improve the technology) - Information and research - Market development and competitors - Environmental effects	*External elements that could dis-encourage the use of the technology* - Policy and regulation - Environmental effects - Obstacles faced Investment and operating cost

3 Methods/Technologies to change biomass quality

3.1 Importance of the biomass quality for thermal conversion

The utilization of herbaceous biomass as a fuel for thermal conversion is limited because of its composition. Also, every conversion system has different demand of biomass quality. During combustion processes, the presence of unwanted elements in biomass produces numerous operational problems such as slagging, fouling and corrosion. In addition reduce the efficiency of the systems as well as increase the operational cost. These elements are the ash content in biomass and inorganic minerals (Na, K, Cl, N, Si and S). There are numerous effects and complex reactions due to the presence of these elements during combustion processes (see Table 3.1).

Table 3.1 Related problems for thermal conversion associated with biomass quality.

Parameter	Effect
Ash content	Higher ash content lead higher dust emissions, influences the design of the heat exchanger, and the cleaning system. Also increase the requirements for O&M as well as the associated costs
N	Easily volatile and release in gas phase during combustion at temperatures between 800 – 1100 C - NOx emissions
S	Easily volatile and release in gas during combustion. Produces gaseosus compounds SO3and SO4 - SOx emissions - Corrosive effects
Cl	Easily volatile and release in gas during combustion - HCl formation - Cl influence the formation of polychlorinated dibenzodioxins and furans (PCDD/F) - Corrosive effects when is combined with
Ca	- Increase the melting temperaturte of ash - Relevant plant nutrient, ash can be recycled as a fertiliser
Mg	- Increase the melting temperature of ash
K	Lowering ash melting point: - Slagging and deposit formation in furnaces and boilers Main aerosol forming during combustion - Lowering of the efficiency, higher operating cost KCL formation in the gaseous phase - Raise emission of fine PM and increases fouling in the boiler. - KCL causes corrosion of heating surfaces and it is a catalyst of NOx Can be recycled as fertiliser
Na	Lowering ash melting point: - Slagging and deposit formation in furnaces and boilers Main aerosol forming during combustion - Raise emission of fine particulate matter PM - Increases fouling in the boiler
Silicon	Lowering ash melting point - Formation of potassium silicates

Sources: IEA bioenergy (2009) and Lewandowski (1997); van Loo and Koppejan (2008)

The ash content in biomass varies among plants. Less ash content is preferable for thermal combustion technologies, because it simplify the requirements for operation and maintenance (de-ashing), transport, storage and disposal (van Loo and Koppejan , 2008) . Higher content of alkali earth metals such as K and Na increase risk of ash deposits formation **slagging and fouling**[2] on the heat exchanger surfaces. The alkali specifically K and silica content in biomass are the major ash forming elements. These minerals deposits with low melting point reduce the thermal the efficiency, decreases heat flux, increases temperature on the hot side, decreases temperature on the cold side, induces deposit corrosion and increases use of cooling water. Tortosa et al (1998) In addition, the deposition (fouling) of corrosive Cl and S compounds combined with silica increases the risks of **corrosion** on heat exchanger. Generally, Ca and Mg increase the ash melting temperature, while K and Na decrease it (van Loo and Koppejan , 2008).

3.2 Changes at the production chain

As was mentioned in previous chapters, one of the major limitations in using herbaceous biomass for thermal conversion is the ash and nutrient content affecting functioning of combustion systems. Many factors are influencing biomass quality characteristics such as (Bakker and Elbersen, 2005 and Kopejaan, 2010):

- Type of plant and plant fraction
- Growing conditions such as temperature, type of soil, precipitation, seasonal variation, water, pH, nutrients, age of the plants, .
- Use of fertilisers and pesticides
- Harvesting time and handling methods, transport and storage
- Pre-treatment

Some of these factors upstream in the production chain can be modified or controlled to improve the biomass characteristics for thermal conversion. Table 3.2 provides an inventory of these alternatives grouped into three categories: growing conditions, harvesting and pre-processing. The list was constructed considering the knowledge and experience of the team work. Also includes the inventory of documents containing information related to the methods.

[2] "*Slagging* occurs in the boiler sections that are directly ex posed to flame irradiation. The mechanism of slagging formation: stickiness, ash melting and sintering. Slagging deposits consist of an inner powdery layer followed by silicate and alkali compounds." Tortosa et al (1998)
"*Fouling* deposits occurs in the convective parts of the boiler. The mechanism of fouling: condensation of volatile species that have been vaporised in previous boiler sections and are loosely bonded" Tortosa et al (1998)

Table 3.2 Brainstorm of possible strategies or method to improve ash content and composition in the production chain process

Phase	**Method**	**Comments**	**Type of biomass**	**Experiences**	**# related documents**
Growing	Plant Type	Genetic point of view	Warm (C4) Cool season (C3)		7
	Plant Fraction	Different composition in plant parts	Miscanthus, reed canary grass and switchgrass	Germany, Sweden, UK, Greece	4
	Soil type	Influence in ash content and silica solving.	Miscanthus and switchgrass	Netherlands, Scandinavia, Denmark	2
	Use of fertilizers	Type and amount of fertilizers	Straw and reed canary grass	Denmark, Sweden	2
Harvesting	Delayed harvest	Harvest after maturation (better quality but loss of biomass) Positive nutrient recycling	Miscanthus, reed canary grass and switchgrass and verge grass	Canada, Sweden, Germany, Denmark, Netherlands	15
	Natural leaching	Leaching by natural precipitation before and after harvest for removal of K and Cl	Rice straw	California	11
	Strip harvesting	Let the straw standing in the field after grain harvest	Rice straw	California	1
Pre-processing	Biorefinery- Dry fractionation		Reed canary grass		3
	Adding chemicals	Improving ash melting point		Spain	0
	Hydrolisis				0
	Mixing biomass				0
	On-site leaching	.Leaching biomass at the power plant. Include milling + washing + dewatering and drying processes	Wheat straw, banagrass, rice straw	Denmark, Hawaii and California	8

3.3 Growing phase

3.3.1 Type of plant

Description: Ash content in biomass is also related to the type of plant used as a feedstock for thermal conversion. Herbaceous biomass can be categorized into cool season (C3)[3] and warm season (C4) plants. This classification is related to the different pathways that plants use to capture carbon dioxide from the atmosphere and then the use of different leaf anatomies during photosynthesis. Usually, cool season C3 plants have higher levels of ash than warm season C4 plants (See Table 3.3).

Table 3.3 The ash content of wheat straw and overwintered perennial grasses

Type		Plant	Ash content (%DM)
C4	Perennial	Prairie cordgrass *(spartina pectinata)*	1.6
	Perennial	Switchgrass *(Panicum virgatum)*	1.7
	Perennial	Big bluesterm *(Andropogin gerardii)*	1.8
	Perennial	Prairie sandrees *(Calanovilfa longifolis)*	1.9
	Perennial	Miscanthus *(Miscanthus sinensis)*	2.0
C3	Perennial	Reed Canary Grass *(Phalaris arundinacea)*	6.3
	Perennial	Phragmites *(Phragmites communis)*	7.5
	Annual	Wheat straw	11.1

Source: Samson and Mehdi, 1998

Some characteristic of C3 and C4 plants are included in Table 3.4. C3 plants become less efficient as the temperature increases but have higher protein quantity. C4 plants are more efficient at gathering carbon dioxide and utilizing nitrogen from the atmosphere and recycled N in the soil. Also, warm season grasses (C4) make more efficient use of water then they are more drought tolerant than C3 plants. The decreased water usage reduces the uptake of silica and other inorganic constituents and then decreases the ash content of the plant (Samson and Mehdi, 1998; Bakker and Elbersen, 2005)

Comparing C3 and C4 plants, C4 plants are potentially more attractive biomass energy plants than C3 plants because:

- Higher water use efficiency (typically 50% higher)
- Can utilize solar radiation 40% more efficiently under optimal conditions
- Stand longevity
- More drought tolerant
- Adaptability to marginal soils.

[3] C3 and C4 plants refer to number of carbon molecule involved during photosynthesis process. The first product of carbon fixation in C3 plants involves a 3-carbon molecule, whilst C4 plants initially produce a 4-carbon molecule that then enters the C3 cycle .

Table 3.4 Characteristics of C3 and C4 grasses

Characteristic	Cool season (C3)	Warm season (C4)
Initial molecule formed during photosynthesis	3 carbon	4 carbon
Growth period	Temperate and cold climates or yearlong	Mediterranean and warm climates/seasons
Light requirements	Lower	Higher
Temperature requirements	Lower (18-24 ^{o}C optimum)	Higher (32-35 ^{o}C optimum)
Water requirements	Higher	Lower
Minimum soil temperature to start growing	4 – 7 ^{o}C	16-18 ^{o}C
Frost sensitivity	Lower	Higher
Yield potential	Lower	Higher
Ash content	Higher	Lower
Examples	Wheatgrass, sorghum, reed canary grass, weeping grass and phragmites	Sugar cane, maize, *Miscanthus*, switchgrass Kangaroo grass, red grass and wire grass,

Sources: http://www.dpi.nsw.gov.au/agriculture/field/pastures-and-rangelands/native-pastures/what-are-c3-and-c4-native-grass and http://www.maizegenetics.net/switchgrass-general-info

- Moderate to high productivity, but under the right conditions, C3 can produce similar yield potential.
- High nutrient use efficiency
- Benefit biodiversity and soil fertility. They have more extensive roots systems that store more carbon in the soil.
- Improved biomass quality, decreases Si and ash content
- Overall net conversion efficiency is often much higher for C4 plants
- Responsive to warming climate

3.3.2 Plant fraction

Description: selection of different plant parts could be used to improve the feedstock characteristics of biomass with thermal conversion purposes. The nutrient and ash content in herbaceous biomass varies among different plant parts (leaf, node, stem and panicle). Stems as compared to leaves have lower concentrations of ash and nutrients

Biomass quality:. Bakker and Elbersen (2005) showed that leaves in rice straw may content 18 to19% of total ash whereas stems only content 12%. Also, silica levels are lowest in the stem fraction (Samson and Mehdi, 1998). The results of some studies with switchgrass, *Miscanthus* and reed canary grass have shown that leaves are qualitatively different from stems (see Table 3.5)

Table 3.5 Nutrient and ash concentration (%DM) in leaf and steam of Miscanthus, reed canary grass and switchgrass.

Element	Plant Fraction	Miscanthus (Lewandowsky and Kicherer, 1997) [a]			Reed Canary grass (Landström et al., 1996) [b]						Switchgrass (Elbersen et al., 2001) [c]		
					August			spring					
		Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n
N	Stem	1.61	0.15	10	0.62	0.05	21	0.70	0.04	26	2.65	0.27	31
	Leaf	5.45	0.44	10	2.32	0.07	21	1.86	0.07		6.48	0.49	31
	Ratio L/S	**3.4**			**3.7**			**2.7**			**2.5**		
K	Stem	6.25	0.49	10	0.90	0.07	21	0.24	0.03	26	3.49	0.32	31
	Leaf	3.50	0.52	10	1.59	0.07	21	0.35	0.05	26	2.14	0.21	31
	Ratio L/S	**0.6**			**1.8**			**1.5**			**0.6**		
Ca	Stem	0.73	0.05	10	0.10	0.01	21	0.12	0.01	22	2.41	0.23	31
	Leaf	2.96	0.18	10	0.69	0.03	21	0.35	0.02	22	11.44	0.56	31
	Ratio L/S	**4.1**			**6.9**			**2.9**			**4.8**		
Cl	Stem	0.88	0.10	10	0.52	0.03	21	0.11	0.02	22			
	Leaf	0.56	0.08	10	1.07	0.07	21	0.10	0.02	22			
	Ratio L/S	**0.6**			**2.1**			**0.9**					
Mg	Stem				0.06	0.01	21	0.04	0.00	22	0.68	0.05	31
	Leaf				0.26	0.02	21	0.10	0.01	22	1.65	0.17	31
	Ratio L/S				**4.3**			**2.5**			**2.4**		
P	Stem				0.11	0.01	21	0.08	0.01	26	0.35	0.03	31
	Leaf				0.25	0.01	21	0.20	0.01	26	0.63	0.04	31
	Ratio L/S				**2.3**			**2.5**			**1.8**		
Ash	Stem				4.21	0.23	21	3.42	0.20	26			
	Leaf				8.51	0.31	21	6.60	0.34	26			
	Ratio L/S				**2.0**			**1.9**					

Notes: [a] Experiments with *Miscanthus x Giganteus* carried out in Germany at Durmersheim and at Gutenzell. Soil type: Loamy sand. Harvest date: February 1995, Average of all experiments and SE (standard error) for trials A and B at Durmersheim and trial C at Gutenzell.

[b] Experiments with reed canary grass (*Phalaris arundinacea L.)* in Sweden at Northern and Southern Sweden. Reed canary grass fertilized with 200 kgN/ha and 100 kg K/ha as KCL. Average of all experiments

c Experiments with different switchgrass varieties from Aliartos (Greece) and Rothamsted (UK). Average of all experiments

The N, Ca, Mg and P concentration in leaves were higher than stems in all three types of biomass analysed. The ratio leaf/stem is approximately 2.5, 2.9, 2.4 and 1.8 respectively. However, this behaviour doesn't occur for K and Cl content in both fractions plant. Concentration of K in leaves of Miscanthus and switchgrass were about half of that stems. While reed canary grass presented higher levels of K in stem. Depending on the harvest time (fall harvest or delayed harvest) the Cl concentration in biomass can be changed. Table 3.4 shows the variation in the concentration of Cl in reed canary grass with the harvest time. The harvest time has effect in the concentration of ash and nutrients in stems and leaf. The nutrient content decreases with the mature of the plant and by losses through leaching, especially K and Cl which are very soluble. Bio-refining of biomass plants into leaf and stem fractions may increase quality for thermal conversion

3.3.3 Soil type (texture)

Description: Ash content in herbaceous biomass is influenced by the characteristics of the soil where plants are growing up, specifically the soil texture. There are three main soil texture classifications: sand, silt and clay. Depending on the proportion in which they are presented in soil, combinations between these three components are used to describe the different types of soil e.g. sandy loam, clay loam. Annex 2 presents these relationships. Clay soils have higher levels of silica and better water retention capacity than sandy soils. These two characteristics influence ash content. Considering that silica is one of largest mineral components of ash, it entry to the plant through two ways: the water uptake and soil contamination. Generally, biomass produced in clay soils presents higher ash content (Samson and Mehdi, 1998).

Not only has the type of soil influenced the ash content in biomass, but also the crop management (see Table 3.6). The requirements for water irrigation and use of fertilisers in clay soils are lower than sandy soils. Because of its high moisture content, clay soils will compact under "heavy traffic" conditions. Also the drainage capacity should before the harvest. Clay soils remains saturated with water after the spring thaw and after heavy rains.

Table 3.6 Some characteristics of clay and sandy soils

Characteristic	Clay soil	Sandy soil
Drainage capacity	Poor drainage	It drains easily after a rain
Handling	Easily worked	Difficult to work with high moisture content
Water retention capacity	Higher	Lower
Nutrient holding capacity.	Higher	Lower, use of fertilisers is required
Warms up	Very slow in the spring, can delay seeding	Easily in the spring

Biomass quality: Results from a study conducted in the Netherlands with switchgrass and *Miscanthus* grown in sandy and clay soil have shown clearly the influence of the soil texture in the ash content. It was found that higher levels of ash (2 to 3 times) can be obtained in biomass sown in clay soil compared to sandy soil (Elbersen et al., 2001) (see Figure 3.1). Also the results from a Scandinavian study by Pahkala et al (1996) cited by Samson and Mehdi, (1998) found that silica levels in reed canarygrass are highly influenced by soil type; silica levels were 1.3% on sandy soil, 1.9% on organic soil and 4.9% on clay soils. In Denmark, Sander (1997) has concluded that there is a clear tendency to increasing content of silica with increasing content of clay in the soil. On the other hand he found that the content of K and Cl shows no relation between soil types.

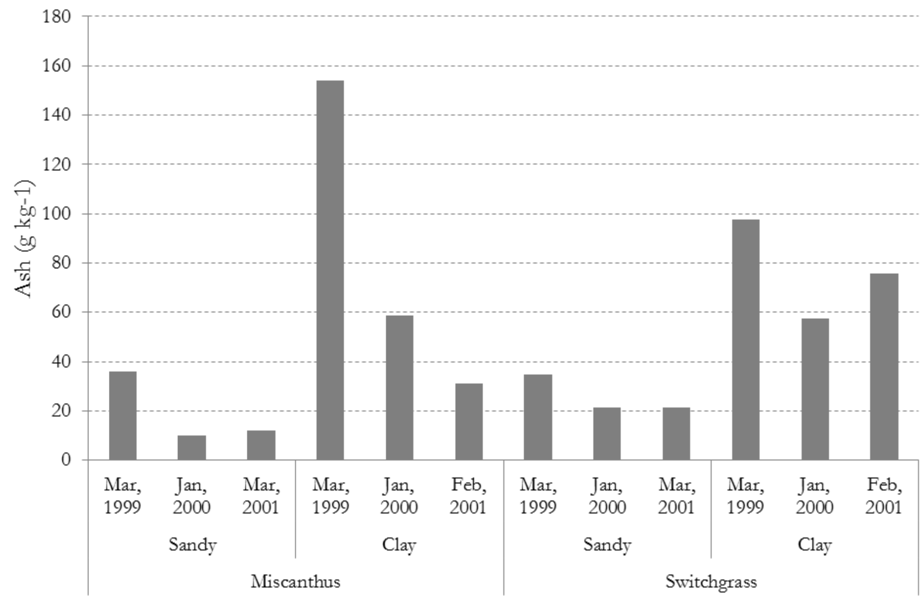

Figure 3.1 Influence of the soil type in the ash content of *Miscanthus* and Switchgrass in the Netherlands
Source: (Elbersen et al., 2001)

3.3.4 Use of fertilizers

Description: The quality of biomass in terms of ash content and mineral nutrients as K and Cl is affected by the type and amount of fertiliser used (Bakker and Elbersen, 2005). Using cultivation trials of straw with Cl –free fertilizer, Sander (1997) shows that there is positive correlation between Cl dose applied with the fertilizer and the Cl content in biomass. Other experiments with reed canary grass have shown similar results (Landström, 1996). Usually, the potassium required by plants is supplied as KCL or also it can be applied K_2SO_4 instead of KCL to decrease the Cl content in biomass (Sander, 1997). Nevertheless, when the weather conditions and the harvest time are taking into consideration, the dose of K fertilizer applied will not affect the content of K and Cl in biomass (e.g. delaying the harvest will allow natural leaching of K and Cl)

Biomass quality: Figure 3.2 and Tables 3.7 and 3.8 present some examples of the results found by Sander (1997) and Landström (1996) related to the effects of the dose and type of fertilizer on biomass quality.

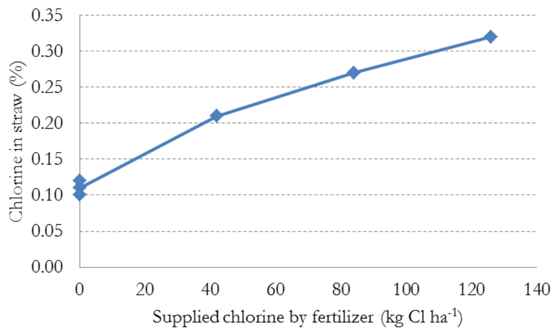

Figure 3.2 Chlorine in straw as a function of Cl supply to the field
Source: Sander, 1997

Table 3.7 Example of results from straw trial with chlorine-free fertilizer

Fertilizer dose (kg/ha)			Content in straw (% DM)	
K	Cl	S	K	Cl
137	126	0	0.82	0.32
137	84	20	0.80	0.27
137	42	40	0.74	0.21
137	0	60	0.95	0.11
68	0	30	0.83	0.12
0	0	0	0.77	0.10

Source: Sander, 1997

Table 3.8 K and Cl concentration in reed canary grass fertilized with different K salts[1]

	KCl		K_2SO_4		Ash	
	August	Spring	August	Spring	August	Spring
K (% DM)	1.13	0.26	1.20	0.25	1.12	0.25
Cl (% DM)	0.71	0.09	0.38	0.08	0.36	0.08

Source: [1]Landström et al. (1996) Average of all experiments with reed canary grass fertilized with K salts as 100 kg K ha^{-1}

It can be observed from Figure 3.3 that using higher doses of Cl supplied through fertilizer, the content in straw increases noticeable. However, when the K dose from fertilizer is increased, the K content in biomass does not describe the same behaviour as Cl content (Table 3.7).

The influence on the type of fertilizer on biomass quality is presented in Table 3.8. There is an increase by 86% of Cl content in biomass harvested in August (from 0.38 to 0.71 % DM) when KCl fertilizer is applied instead K_2SO_4 fertilizer. However, if the biomass is harvested in spring, there are no differences in K and Cl content related to the type of fertilizer applied. In this case, predominated factors influencing biomass quality are the harvest time and the weather conditions.

3.4 Harvesting phase

3.4.1 Delayed Harvest

Description: This method consists in the extension of the harvesting dates until the growing season has ended. The crop is left standing in the field and only after winter or autumn seasons the senescent plants (dry biomass) are harvested. During this period of time ash content and nutrients in biomass are reduced. It occurs mainly due to two factors: i) natural leaching of easily soluble material by rain, dew, mist and fog and ii) translocation of nutrients from the stem and leaf to the rhizome system. In this way, delay harvest method let dry biomass with suitable fuel characteristics for thermal conversion purposes (Bakker and Elbersen, 2005), as a consequence of the removal of Cl and K. Also a large proportion of nutrient can be recirculated which reduces the fertilization costs (Landstöm et al, 1996)

Special conditions should be considered when this method is applied. The soil moisture will allow the harvesting operations, especially after winter when the snow is melted and the soil is dry. Also, it is important to consider the time preparation of the field for the next crop.

Biomass quality: Different studies carried out with *Miscanthus*, Reed Canary Grass and Switchgrass have shown the changes in biomass quality by delaying the harvesting. (See Table 3.9). The delay in the harvest has positive effects in the ash melting temperature. In reed canary grass, the ash melting temperature can be increase from 1074°C in crops harvested between July and October to 1404°C in spring or delayed harvest (Burvall, 1997). The values are comparable or higher than wood fuels (Hadders and Olson, 1996 and Burvall, 1997). In addition, the energy value can be increase from 18.2 to 19.1 (GJ t^{-1}) in switchgrass. The information available in Table 3.9 does not show a clearly defined effect of delayed harvest in the energy value for Reed Canary. However, Heinsoo et al (2011) reported that the energy content of reed canary grass growth up in Estonian was higher in spring than in autumn or summer harvest (17.07 GJ t^{-1}, 16.77 GJ t^{-1} and 16.71 GJ t^{-1}, respectively). Other experiments with three verge grass samples in The Netherlands presented an improvement in the energy value.

The most significant effect of the delayed harvest method can be observed in the reductions of both potassium and chloride which are undesirable elements for thermal conversion. Different authors have highlighted that these reductions are due to the translocation in vivo and leaching of nutrients after maturation. In switchgrass (Table 3.9) the level of K can be reduced at 84% or higher comparing fall harvest (0.38 – 0.95 g kg^{-1} dry matter) with spring harvest (0.06 g kg^{-1} dry matter). For both experiments with reed canary grass presented at Table 3.9, K level was decreased (75%) in delayed harvested biomass. The same behaviour for K concentrations in reed canary grass can be observed in different plant fractions such as stem (78%) and leaf (75%) (Landström et al, 2003 and Burvall, 1997). K losses in *Miscanthus* the are up to 83% (ranging from 10.1 g kg^{-1} to 1.7 g kg^{-1} dry matter) while the average K content in verge grass samples, was decreased by 84% (Elbersen et al., 2002).

Table 3.9 Effects in biomass quality by delaying the harvest time in switchgrass, reed canary grass and Miscanthus

Unit	Wood Pellets[1]	Switchgrass[1]		Reed Canary Grass [2] Autumn (August)		Reed Canary Grass [2] Spring (Apr-May)		Reed Canary Grass [3]		*Miscanthus* [4] Dec		*Miscanthus* [4] Feb		*Miscanthus* [5]		Verge grass[6] De Wieden		Verge grass[6] Weerribben		Verge grass[6] Baarle-Nassau	
		Fall harvest	Spring harvest	Stem	Leaf	Stem	Leaf	Summer (Jul-Oct)	Spring (Mar-May)	Stem	Leaf	Stem	Leaf	Dec	April/ May	Fall harvest	Winter harvest	Fall harvest	Winter harvest	Fall harvest	Winter harvest
Energy (GJ t^{-1})	20.3	18.2-18.8	19.1					17.9	17.6	18.5	18.9			--	--	18.1 [7]	18.9 [7]	18.9 [7]	19.1 [7]	19.0 [7]	19.1 [7]
Ash (% DM)	0.6	4.5-5.2	2.7-3.2	4.2	8.5	3.4	6.6	6.4	5.6	2.6	2.5	17.9	25.7	3.1	1.0	6.8	5.8	9.4	14.8	9.6	9.3
N (%)	0.3	0.46	0.33	0.6	2.3	0.7	1.9	13.3	8.8	1.9	4.5	1.9	7.6	--	--	1.47	1.51	1.32	1.06	2.51	1.67
S (%)	--	--	--					1.7	0.9	1.1	1.1	1.0	1.1	--	--	0.19	0.13	0.15	0.09	0.26	0.13
Cl (%)	0.01	--	--	0.5	1.1	0.1	0.1	5.6	0.9	4.5	0.8	1.0	1.1	3.3	0.2	0.31	0.08	0.28	0.02	0.68	0.02
K (%)	0.05	0.38-0.95	0.06	0.9	1.6	0.2	0.4	12.3	2.7	15.0	4.3	8.3	6.6	10.1	1.7	5.2	1.4	3.3	0.5	20.7	1.3
Ash melting temperature (°C)	1100-1200	--	--					1074	1404	--	--	--	--	--	--						

Source: [1] Samson et al 2005 (Canada) [2] Landström et al, 2003 (Sweden) [3] Burvall, 1997 (Sweden) [4] Lewandowski and Kircherer (1997) – (Gerrmany) [5] Flojgaard (Denmark)
[6] Elbersen et al., 2002 (Netherlands) [7] The value correspond to the LHV- lower heating value -(dry and ash free)

The harvest time effect on Cl concentration can be observed in reed canary grass which had reductions by 84% (from 12.3 g kg^{-1} to 2.7 g kg^{-1} dry matter), *Miscanthus* at 94% (from 3.3 g kg^{-1} to 0.2 g kg^{-1} dry matter) and verge grass by 89% average. Different behaviour was found by Lewandowsky and Kircherer (1997) in plant fractions of *Miscanthus*. From December to February the Cl and K concentrations in the stem decreased (from 4.5 g kg^{-1} to 1.0 g kg^{-1}) while for leaf decrease was not observed (0.8 g kg^{-1} to 1.1 g kg^{-1}). It is probable that the harvest time was not enough to allow the leaching out of these nutrients. Generally the harvesting is carried out in the early spring (April to May) and not at the end of the winter (February).

According to the information in Table 3.9, ash content is slightly decreasing in reed canary grass (28%) and switchgrass (12.5%). The plant fractions of *Miscanthus* show the same behaviour described for Cl and K, where leaf has higher ash content in the late harvested biomass (from 24.7 g kg^{-1} to 25.7 g kg^{-1}. However, the results reported by Flojgaard show reductions on the ash content at 68% in the late harvested *Miscanthus* biomass.

Reductions on the nitrogen concentrations in late harvested biomass can be observed in Table 3.9. N concentration in biomass for thermal conversion systems is not a critical problem. Higher contents in biomass produces NOx emissions which are harmful for the environment and which requires special management. The reduction of the N content means the reduction in combustion system cost due to emission control (Lewandowsky and Kicherer, 1997)

Delaying harvest can cause important losses of plant matter as well as the physical loss of leaves which reduces yields considerably. Also the loss of organic matter can produce an increment in the total ash. Delayed harvest, however, reduced biomass yields of Miscanthus by 35% (Lewandowski and Heinz, 2003).

Costs

Hadders and Olsson, 1997[4] have estimated the costs[5] of energy production in Sweden with reed canary grass harvested in the late summer and delayed-harvest to be about 9.9 USD Gj^{-1} and 6.9 – 7.9 USD Gj^{-1} (1USD=7.2 SEK at 2010) respectively. This means that the delayed harvest costs of reed canary grass are at least 19% lower than the late summer harvesting. Comparing these values with the costs of energy production using wood chips in smaller district heating plants (6.0 – 6.9 USD Gj^{-1}), the costs for late summer harvest are 140 – 160% and for delayed harvest are 100 – 120% of that for wood chips (Hadders and Olsson, 1997).

[4] *The original values cited in the reference were updated to values at 2010 using the consumer price index (CPI)*
[5] *Assumptions for estimation of the costs: 1)delayed-harvest using square-bale technique and 2) late summer using round bales and drying outdoor stack (square bale technique for handling is cheaper but is not appropriate use it in summer harvesting since the bales cannot easily be dried (Hadders and Olsson, 1997)*

According to Samson et al., (2005), the costs of switchgrass production in Eastern Canada projected at 2010 were in fall harvesting \$88 – 103 USD ton^{-1} and spring harvesting \$82-109 USD ton^{-1}(1 USD = 0.9705 CAD at 2010. The delayed harvest costs of switchgrass are at least 19% lower than the spring harvest.

Figures 3.3 and 3.4 show the distribution of the costs for switchgrass and reed canary grass biomass. These Figures are not comparable due to production costs depends on the local conditions in which the economic analysis is carried out. However harvest and transport operations are the higher cost , representing by 50 % approximately of the total costs. One of the effects on delayed harvest method is the reduction of the demand for fertilization, which implies lower production costs.

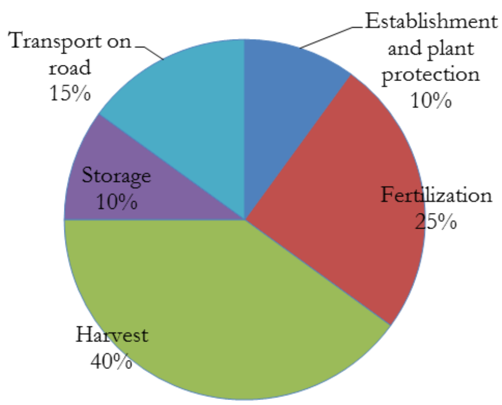

Figure 3.3 Distributions of the production costs of spring harvested reed canary grass in Northern Sweden

Source: Hadders and Olsson, 1996

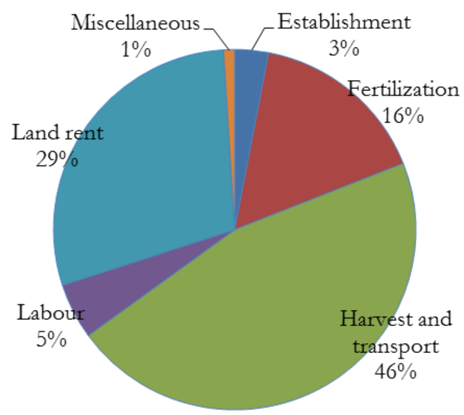

Figure 3.4 Distribution of the production costs of delayed harvested switchgrass in Eastern Canada

Source: Samson et al 2005(ppt presentation)

Girouard et al., 1998 reported that the costs of delaying the harvesting (50 USD ton^{-1}) was found to be 17% higher than the cost of fall harvested switchgrass (32 USD ton^{-1}). The delayed harvest was found to be 19% less expensive than the case for short rotation forestry willow (62 USD ton^{-1}).

Table 3.10 shows the analysis of the strengths, weaknesses, opportunities and threats for the delayed harvest method

Table 3.10 SWOT analysis of the method: onsite leaching

Strengthens	Weaknesses
- Dry and storable biomass - Lower transport costs - Reduction of the energy demand for drying - Low ash content - High content of fibre/lignocellulose - Positive nutrient recycling (N. K, and Cl) - Good regrowth in spring - Reduction of emissions of environmentally harmful substances during combustion such as of Cl and nitrogen (N)	- Losses of material in the field Harvesting should be done in favourable weather conditions and when the soil will be dry enough to allow harvesting operations.
Opportunities	**Threats**
- Reduction on the fertilization costs - Improved biomass quality for thermal conversion	- There is not yet market for dry biomass - Reduction of the field preparation time for subsequent crop - The energy demand in spring and afterwards is lower, then harvested biomass requires being storage. It will cause biomass decomposition by microbiological activity, increases the fungi spores and dry matter losses - The biomass producer faces a conflict between yield and quality optimisation

Source: Elbersen, ppt presentation

3.4.2 Natural leaching

Description: Leaching refers to the removal of soluble material from plants through the percolation of water. Leaching can be accomplished mainly in two ways: 1) natural leaching by rain, dew, mist and fog and 2) onsite-leaching with controlled conditions (Jenkins et al, 2000).

Natural leaching is defined as the removal of soluble material by rain, dew mist and fog. According to Tukey (1970) many substances can be leached from plants and include: inorganic nutrients (macro and micro nutrients), organic substances (free sugars, peptic substances and sugar alcohols), aminoacids, vitamins, alkaloids and phenolic substances. Inorganic nutrients in plants such as K, Ca, Mg, and Mn are usually leached in greatest quantities (Tukey, 1970). Furthermore, different authors have reported lower ash content in moist climates and moist seasons or after a rain in comparison with dry climates. Some of the constituents of ash with important implications in thermal conversion systems such as potassium and chlorine can be easily removed from biomass due to their solubility in water. Some plants only need to be wetted to be leached. Leaching processes can remove 80% of the potassium and 90% of the chlorine in plants (Jenkins, 2000)

There are numerous factors affecting quality and quantity of leached substances:
- Type and nature of the plant and plant fraction (stem, branches, flower and fruits)
- Age of the leaf, young plants are less susceptible to leaching than dead plants (senescence). As the maturity of the leaf increases, the susceptibility to loss nutrients also increases.
- High temperature may increases leaching losses from some mature leaves
- Intensity and volume of rain. Also has influence the content of salts on rain water.
- Time of exposition (leaching losses increases as a function of time). Dew, fog, and light rain of long duration are more effective in leaching substances than compared with heavy rain of short duration.

Biomass quality:
The changes in biomass quality by natural leaching can be observed in short time of exposition to rainfall. Tukey (1970) reported that after 24 hours the loss of K in mature biomass may be 80 percent or greater. Other studies suggested changes in periods of less than 72 hours with reductions of 83 percent of the initial potassium content for rice straw (Bakker and Jenkins, 1996). Similar results have been reported for switchgrass. The reduction of potassium in biomass increases the ash melting temperature.

Costs
The components of the cost for natural leaching of biomass include mainly: field collection, and transportation costs.

Field collection cost: depend on the type of operation (swathing, raking, baling and roadsiding) and the equipment used for harvest operation. Depending on the type of harvesting systems for field leached rice straw, the costs are ranging from 114 USD ha^{-1} to 204 USD ha^{-1}, as it is show in Table 3.11. In some cases, harvest operations may be done directly by growers or by contractors. Bakker and Jenkins (2003) have suggested costs of 31.5 USD Mg^{-1} for collection of leached rice straw. This means an increment of 100% approximately on the collection cost for crude straw (16.6 USD Mg^{-1}) (See Table 3.11)

Table 3.11 Capacities and costs for three harvesting systems for field leached rice straw in California

Description	Capacity (tonnes hr-1)	Cost operation (USD t-1)	System 1	System 2	System 3
Swathing (4.8 m wide)	11.1	9.24		X	
Swathing (4.8 m wide)	16.7	6.16			X
Raking (6 m wide)	7.5	7.34	X	X	X
Raking (12 m wide)	15.3	3.86	X	X	
Baling (large rect bales)	17.1	12.92	X	X	X
Bankout bales	32.0	1.57	X	X	X
Roadside bales	27.9	5.84	X	X	X
		Total collection costs (USD t^{-1})	31.53	40.78	33.83
		Expected yield (tonne ha^{-1})	5.0	7.0	5.6
		Costs per ha (USD ha^{-1})	114	204	136

Source: Bakker and Jenkins, 1996. The values were updated at 2010

Transportation costs: it depends on the amount of biomass transported and the transport distances. According to Bakker and Jenkins (2003) the average costs of a short-ton of biomass (1 Mg= 1.1 short tons) transported 32 km distance may be 8.67 USD Mg^{-1}. For longer distances, it can be observed incremental transportation cost at 0.14 USD Mg^{-1} Km^{-1}.

Comparison of incremental cost of natural leaching vs centrally leaching

Table 3.12 shows the comparison of cost for natural leaching and on-site leaching reported by Bakker and Jenkins (2003). From the economically point of view, the costs of natural leaching strategy (42.4 USD Mg^{-1}) are 12.5% lower than the industrial leaching (47.7 USD Mg^{-1}) (Bakker and Jenkins, 2003).

Table 3.12 Comparison of incremental fuel costs for naturally leached rice straw and centrally leached straw

	Natural leaching (USD Mg^{-1})	Industrial leaching (USD Mg^{-1})	Difference natural leaching-industrial leaching (USD Mg^{-1})
Collection costs	31.53	16.56	14.97
Transportation	8.67	8.67	0
Straw leaching			0
- Leaching + dewatering	0	12.10	-12.10
- Leachate treatment	0	6.97	-6.97
- Increased fuel input	0	2.11	-2.11
Conversion cost			0
- NOx management	0.31	0.31	0
- Ash handling	1.92	1.0	0.92
Total	42.40	47.72	-5.32
Fertilization costs	5.13	20.36	-15.23
Total (incl. nutrient replacement costs)	49.45	69.08	-19.63

Source: Bakker and Jenkins, 2003. Values in the Table were updated at costs for 2010

The differences between both strategies are in the collection cost (100% higher for natural leaching) and the additional costs for the treatment processes required in the industrial leaching

(21.2 USD Mg^{-1}). One of the advantages of natural leaching is the recycling of nutrients which means the reduction on the use of fertilizes for the next crop and consequently the costs. If the fertilization costs are taking into account, the costs of natural leaching (49.5 USD Mg^{-1}) are 40% lower than those for the industrial leaching (69.1 USD Mg^{-1}) (Bakker and Jenkins, 2003).

Table 3.13 shows the analysis of the strengths, weaknesses, opportunities and threats for the natural leaching method

Table 3.13 SWOT analysis of the method: natural leaching

Strengthens	Weaknesses
- Effective removal of potassium and chlorine due to their high solubility in water - Nutrient recycling at the field crop - Decreases requirements for fertilizers. - Removal of potassium increases ash melting point in leached biomass - There is no extra water consumption in the process besides the water provided by natural precipitation	- Loss of dry matter by rainfall and microbial action (Bakker and Jenkins, 1996) - Leaching by natural rainfall cannot be controlled. For instance the intensity, frequency and quantity of water. - The harvesting operations after leaching require specific field conditions. The soil moisture content can difficult the operations.
Opportunities	**Threats**
- Historical rainfall data in the study area can be used to determine the probability of rainfall for the harvest time. Thus the natural precipitation will be not a limiting factor	- Unpredictability of the occurrence of rainfall and meteorological conditions - Reduction of the field preparation time for subsequent crop

3.4.3 Strip harvesting

Description: This method consists in the selective harvesting of panicles or grain without cutting the straw. The straw is left standing in the field after grain harvest. The straw is collected later in the season to allow the leaching K and Cl by natural precipitation

Biomass quality: There is not specific information about this method related to the biomass quality. The effects on biomass quality may be similar to those described for natural leaching and delayed harvest.

Cost

Bakker and Jenkins, 1996 have estimated the costs of strip harvest method for field leached rice straw in California. The cost calculations considered field operations such as: swathing, raking, baling, bankout bales and roadside bales. The estimated cost was 33.83 USD t^{-1}. This value is comparable with the costs of traditional field operation system where the straw is left as stubble and collected later (31.53 USD t^{-1}). However the expected yield will be higher for strip harvest (5.6 tonne ha^{-1}) than conventional harvest method (5.0 tonne ha^{-1}). In consequence the cost per ha will increases by 19% (114 USD ha^{-1} for conventional harvest and 136 USD ha^{-1} for strip harvest).

Table 3.14 shows the analysis of the strengths, weaknesses, for the strip harvesting method

Table 3.14 Strengths and weaknesses of strip harvesting method.

Strengthens	Weaknesses
- There is no removal of stubble - Decreases contamination of biomass with soil and other materials. - Positive recycling of nutrients - Decrease use of fertilizers	- Flattening of biomass caused by machinery will make difficult the harvesting of biomass. - Requires special conditions of soil moisture to the harvest operations

Source: Bakker and Jenkins, 1996

3.5 Pre-processing

3.5.1 On-site leaching or wash

Description: The leaching of biomass is carried out at the site of the power plant under controlled conditions (Jenkins et al, 2000). This mechanical treatment is mainly done in three steps (see Figure 3.5). In the first step, biomass is pre-treated in a hammer mill for its size reduction to less than 50 mm. Then it is washed with water at 60-80 ºC. Second step consists in the mechanical dewatering for reduction of moisture content by about 50%. Finally, in the third step the biomass is dried using steam. The steam and the waste water from the leaching process can be recovered and used as a fertiliser (Knudsen, 1998).

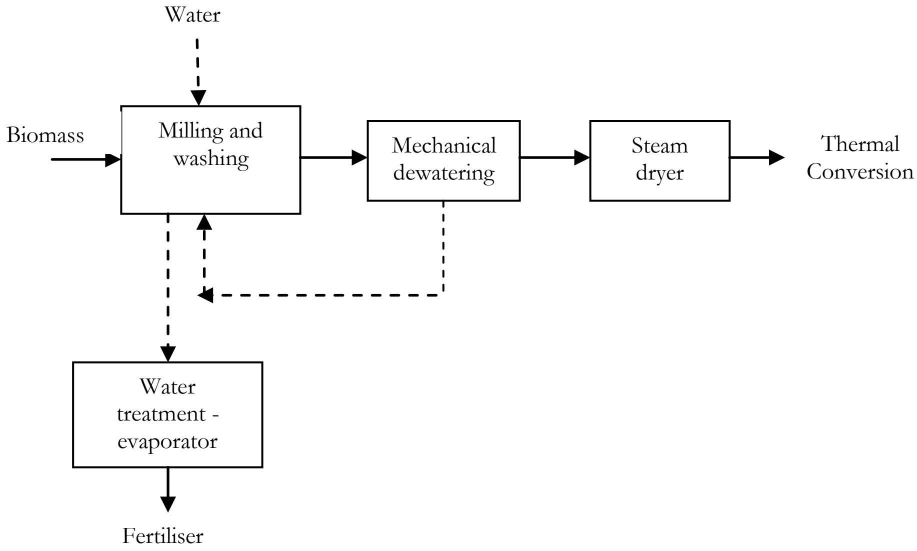

Figure 3.5 on-site wash process of biomass
Source: Adapted from Knudsen et al, 1998

Biomass quality: Leaching biomass is an effective way to reduce ash content, alkali metals (K, Na), chlorine and sulphur before its utilisation for thermal conversion. These components are removed at greatest quantities from biomass due to their high solubility in water. Knudsen et al, 1998 shows that the release of K and Cl in wheat straw is a fast reaction and the equilibrium can be reach within 10 -15 minutes (see Figure 3.6). Also that the removal efficiencies of Cl and K can be higher than 95%.

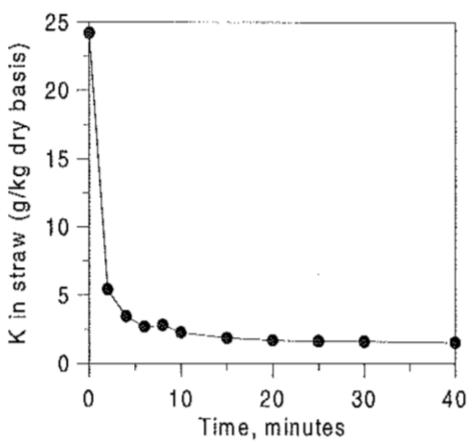

Figure 3.6 Batch leaching experiment with wheat straw at 60 °C
Source: Knudsen et al., 1998

Different leaching experiments have been done by different authors at the lab scale . Turn, (1997) experimented with banagrass (Pennisetum purpureum) at laboratory scale (Hawaii) applying sugar-processing technology to the removal of alkali metals. The test included fine comminution and multi-step dewatering. The results shown substantial reductions in ash (45%), K (90%), Cl (98%), S (55%), Na (68%), P (72%) and Mg (68%) (see Table 3.15). Also, was observed a reduction on the moisture content of fresh herbaceous biomass from 70% to 50% (Turn et al, 1997)

Other experiment at the lab scale using wheat straw was conducted by Arvelakis et al, (2001). The aim of this research was to study the effect of leached wheat straw in a bubbling fluidized bed combustion system (BFB). The leaching resulted in the removal of alkali metals, 53% of Cl and 30% of the ash content. The higher heating value was increased by 6%. The S concentrations showed to be less sensitive to the leaching process. Despite these results, the combustion tests showed that the effect of leaching on the ash thermal behaviour is not enough to prevent ash related problem, although the problems were less compared with those from the combustion tests with the untreated wheat straw material (Arvelakis et al, 2001).

Jenkins et al, (1996) assessed the changes on biomass quality (rice straw and wheat straw) using different leaching techniques (see Table 3.13) at the lab scale. The results showed that the ash content in both type of biomass (rice straw and wheat straw) was reduced by each of the treatments used. For rice straw the relative reduction in total ash ranged from 6 to 9% while for wheat straw the decrease in ash content was by 50% approximately.

Cl concentrations are also decreased by 92% (from 0.74 to 0.06 %DM) for the soaked rice straw and by 50% (from 0.74 to 0.38 % DM) for the sprayed method. For wheat straw soaking process decreased the Cl concentration by 90% (from 2.02 to 0.21 % DM). The N concentration does not seem to be affected by washing. An important effect of the washing straw was the increase in the fusion temperatures of rice straw and wheat straw. In rice straw the ash fusion temperature was increased from 900-1000 °C (untreated straw) to 1600 °C (washed straw). The same behaviour can be described for ash temperature of wheat straw which was increased from 800 °C to 1000-1250°C by washing. These results imply a reduction in the fouling effect in boiler; however the assessment was done in furnaces at the laboratory scale.

Results at full scale experiments suggested that leached rice straw (blended at 20%) is technically feasible to be used in conventional power plants employing different combustion technologies such as a stoker –fired travelling grate, circulating fluidized bed (CFB) and a Suspension- fired unit (Jenkins et al, 1999)

Table 3.15 Different compositions of untreated and leached biomass

Biomass characteristic	Wheat straw[1]		Banagrass[2]				Rice straw [3]			Wheat straw [3]	
	Untreated	Leached	FC-UP	FC-P	FC-PRP	JC-PRP	Untreated 0[a]	Sprayed 1[b]	Soaked 5[c]	Untreated 0[a]	Soaked 5[c]
Moisture (% DM)	7.75	6.89	65.6	52.1	44.7	49.3					
Ash (% DM)	6.22	4.38	3.94	3.05	2.69	2.66	18.63	17.59	17.10	12.78	6.45
Nitrogen (% DM)	0.506	0.44	0.6	0.48	0.41	0.31	0.52	0.47	0.48	0.68	0.64
Sulphur (% DM)	0.222	0.19	0.1	0.06	0.05	0.05	0.09	0.07	0.06	0.39	0.09
Chlorine (% DM)	1.05	0.49	0.58	0.29	0.09	0.02	0.74	0.38	0.06	2.02	0.21
Gross calorific value (MJ kg^{-1})	18.5	19.62									
HHV(MJ kg^{-1})			18.2	18.3	18.7	18.6					

Source: [1] Arvelakis et al., 2001 (Denmark), [2] Turn et al, 1997 (Hawaii) [3] Jenkins et al, 1996 (California, USA)

Notes: FC-UP: Forage chopped unpressed
FC-P: Forage chopped pressed
FC-PRP: Forage chopped pressed-rinsed-pressed
JC-PRP: Jeffco cut, pressed-rinsed-pressed HHV: Higher heating value
[a] Untreated, milled (19 mm) sample not subjected to washing and precipitation
b Laboratory washed, 100 g whole straw, hand sprayed for 1 minute with tap water
c Laboratory washed, 100 g whole straw, submerged in 7L distilled water, 24 h

Costs

According to Knudsen et al, 1998 the straw washing process has implied total net loss by 5.3% on electrical efficiency. The losses are distributed in: straw extraction (0.6%), mechanical dewatering (0.3%), wastewater evaporation (0.7%), straw drying (1.0%), loss of organic material in wastewater (2.2%) and miscellaneous (0.5%). These losses have impact in the total cost of the on –site leaching system. Table 3.16 presents the incremental cots of the technology estimated for the pretreatment of rice straw in California (Bakker and Jenkins, 1996). The total cost is 36 USD dry t^{-1}, which 43% corresponds to the wastewater management and 29% are due to leaching and mechanical dewaterin processess.

Table 3.16 Incremental fuel costs due to on-site leaching system (in USD)

System component	Costs per tonne (USD/dry t)	Percentage of total cost (%)
Fuel handling incl. particle size reduction	3.47	9
Leaching + mechanical dewatering	10.42	29
Leachate treatment + recycling (screening, membrane sep)	15.75	43
Water (0.045 USD m^{-3})	0.32	1
Labour (2 operators, full time)	3.89	11
Total direct costs	33.85	93
Loss of fuel (6% of 30 USD $tonne^{-1}$)	2.50	7
Total costs	36.36	100%

Source: Bakker and Jenkins, 1996

Bakker and Jenkins, (2003) have estimated the cost for onsite leaching by 69.08 USD Mg^{-1}. These costs included values for collection (24.0%), transportation (12.6%), straw leaching (31.0%), NOx (0.5%) management, ash handling (1.5%) and fertilization costs (29.5%) (See Table 3.12). In comparison with the natural leaching, the cost for industrial leaching is 40% higher.

Table 3.17 shows the analysis of the strengths, weaknesses, opportunities and threats for the onsite leaching method

Table 3.17 SWOT analysis of the method: onsite leaching

Strengthens	Weaknesses
- Effective removal of potassium and chlorine due to their high solubility in water - Removal of potassium increases ash melting point in leached biomass - Process operation can be controlled (time of leaching, quantity of water) - Technically suitable for conventional boilers when is blended with wood	- There is extra water consumption in the process that needs treatment and disposal - Requires extra area for operations on site - There is a loss in the electrical efficiency which can be reflected in the operational costs. - Dewatering and drying can become more difficult and expensive
Opportunities	**Threats**
- Leachate may be used for land irrigation allowing the recycling of nutrients	

3.5.2 Biorefinery – air separation of plant fractions

Description: As was mentioned in previous chapters, the ash content and minerals in biomass is variable in different plant fractions. The leaves have higher silica and ash content than stem. One way to improve biomass quality is separating them using air separation techniques. This dry fractionation method has been tested for reed canary grass (delayed in the harvest) that will be used in the pulp industry (Hemming, 1998). The process consists in two main steps. First, the biomass is chopped into smaller pieces in a hammer mill. Second the chopped biomass is conducted through a separation tunnel where leaves and dust are separated from the stem fraction by the airflow. About 20% of the material is removed in this process (Finell, 2003 and Hemming, 1998). The separated plant fraction (leaf and leaf sneaths) could be used as a bio-fuel or could be returned to crop as a fertilizer allowing the recycling of nutrients and decreasing the fertilization costs.

Biomass quality: There is no documented information related to the changes in biomass quality that will be used for thermal conversion purposes.

Cost: There is no documented information related to cost of this method. Table 3.15 shows the SWOT analysis

Table 3.18 SWOT analysis of biorefinery method: air separation of plant fractions

Strengthens	**Weaknesses**
- Improved biomass for thermal conversion system - Lower ash content and reduced levels of potassium and chlorine. - Not produces wastewater	- Losses of biomass in the process - There is no documented information related to the requirements of equipment, and energy and material consumption during the process.
Opportunities	**Threats**
- The separated plant fraction can be used as a fertilizer or as a valuable biofuel	- Lack of information about biomass quality and costs

4 Conclusions

The results shows that improving biomass quality upstream at the production chain reduces the presence of unwanted ash and mineral content by controlling different factors at the growing, harvesting and processing phases. These elements contribute with the deposit formation (slagging and fouling) and corrosion of boilers and heat exchanger during combustion process.

According to the literature review and the inventory of documents, some methods such as delayed harvest, natural leaching, and on-site leaching accounts with numerous experiments at different scales, with different types of biomass and reporting from different authors. Other methods such as strip harvest, dry fractionation are lacking of information about the changes in biomass quality and the technical aspects for their implementation.

In general terms, there is a lack of information related to the costs. It is required an economic analysis that considers not only the production cost but the benefits of these methods such as the positive nutrient recycling, the decrease in the amount of fertilizers. Further research need to be carried out to explore the economically and technically feasibility in the energy market.

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Knudsen NO, Jensen PA, Sander B, Dam-Johansen K. (1998) "Possibilities and evaluation of straw pretreatment", Biomass for energy and industry, 10th European Conference and Technology Exhibition, Wurzburg, Germany, pp224-228

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Annex 1 Inventory of documents and references related to methods/technologies to influence biomass quality for thermal conversion

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
Arvelakis S., Vourliotis P, Kakaras E., and Koukios E.G. (2001), "Effect of leaching on the ash behaviour of wheat straw and olive residue during fluidized bed combustion" Biomass and Bioenergy vol 20, pp 459-470.	- Wheat straw (Denmark) and olive residue (Greece)- Mediterranean region- - Straw pre-treatment leaching- Lab scale (CFB)									X					X
Bakker R.R., Jenkins B.M. and Williams R.B. (2002)" Fluidized Bed Combustion of Leached Rice Straw" vol 16, pp356-365	- Biomass type: Rice straw blended with wood/almond shell -Untreated and natural leached - Lab scale Fluidize bed combustor - Sample: Northern California - Biomass quality						X						X		
Bakker R. R., and Elbersen, H. W. (2005) "Managing ash content and quality in herbaceous biomass: an analysis from plant to product", 14th European Biomass Conference, 17-21 October 2005, Paris, France.	- Biomass production chain (plant fraction, type, growing conditions, harvest time, handling systems, pre-treatment - Biomass quality and ash content		X	X	X	X	X			X					
Bakker, R. R. and Jenkins, B. M. (1996) "Feasibility of fuel leaching to reduce ash fouling in biomass combustion systems" Proceedings of the Nineth European Bioenergy Conference, Copenhagen, Denmark, 24–27 June 1996	- Natural leaching (precipitation) - Mechanical leaching (on site), Mechanical dewatering, Reverse osmosis, Thermal drying - Analysis of technical and economic feasibility - Sample: California						X			X	X				
Bakker, R. R. and Jenkins, B. M. (2003) "Feasibility of collecting naturally leached rice straw for thermal conversion", Biomass and Bioenergy, vol25, pp597-614.	- Rice straw - - Natural leaching and harvest - Rain probability - Straw composition - Economic analysis - costs comparison with industrial leaching - Sample: California					X	X			X					

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
Beale, C.V., and Long, S.P. (1997), "Seasonal dynamics of nutrient accumulation and partitioning in the perennial C4-grasses Miscanthus X Giganteus and Spartina Cynosuroides", Biomass and Bioenergy, Vol 12 No. 6 pp 419-428, Great Britain	- Miscantus x giganteus and S cynosuroides - Seasonal variation in nutrient concentration (N, P and K)	X				X									
Brand M.A., Bolzon de Muñiz G.I., Ferreira W. and Brito J.O. (2011) "Storage as a tool to improve wood fuel quality", Biomass and Bioenergy, vol 35, no7, pp2581-2588	- Wood (Pinus taeda L. and Eucalyptus dunnii) - Storage time (immediately, 2, 4, 6 months storage) - Harvest in four weather conditions. - Moisture content, gross and net calorific value, ash content and solubility - Brazil					X									
Burvall, J. (1997) "Influence of harvest time and soil type on fuel quality in reed canary grass *(Phalaris Arundinacea L.)*", Biomass and Bioenergy, Vol 12, No. 3, pp149-154	- Reed Canary Grass - Harvest time (Summer and delayed harvest) - Soil composition - Biomass quality data - Swedish			X		X									
Christian, D.G., Riche, A.B., and Yates, N.E. (2008), "Growth, yield and mineral content of *Miscanthus x giganteus* grown as a biofuel for 14 successive harvests" Industrial Crops and Products, Vol 28, pp 320-327, United Kingdom	- *Miscanthus x giganteus* - Biofuel crops - Growing conditions (silty clay loam soil) - Effect of N fertilizer on N, P, and K offtake			X		X									
Demirbas, A. (2005) "Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues", Progress in Energy and combustion Science, vol31 pp171-192	- Biomass quality - Biomass combustion - Related problems														x
Elbersen H.W., Christian D.G., El Bassam N., Sauerbeck G. and Alexopoulou E. (2001) "Switchgrass nutrient composition" Final Report FAIR 5-CT97-3701 'Switchgrass" chapter 4 pp23-34	- Switchgrass and Miscanthus - Relation nutrients and growing conditions - Netherlands, UK, Germany, Greece - Biomass quality data		X	X		X									

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
EUBIONET, European Bioenergy Networks (2003) Biomass co-firing - an efficient way to reduce greenhouse gas emissions, Finland	- Boiler operation - Biomass quality														X
Fox, G., Girouard, P., and Syaukat Y., (1999) "An economic analysis of the financial viability of switchgrass as a raw material for pulp production in eastern Ontario", Biomass and Bioenergy, vol 16 pp 1-12.	- Biomass: Switchgrass - Economic Analysis - Paper production - Ontario, Canada														
Hadders, G., and Olsson, R. (1997) "Harvest of grass for combustion in late summer and in spring" Biomass and Bioenergy, Vol. 12, No. 3, pp. 171-.175, 1997, Great Britain	- Reed Canary Grass - Fuel quality and removal of nutrients - Harvesting Technique - Cost - Sweden					X									
Heinsoo, K., Hein K., Melts, I., Holm, B., and Ivask, M. (2011) "Reed canary grass yield and fuel quality in Estonian farmers' fields" Biomass and Bioenergy, vol 35, pp. 617-625	- Reed Canary Grass - Delayed harvest (late autumn and spring) - Growing conditions (Soil type, use of fertilizers) - Estonia			X	X	X									
Hernandez J., Mitre A.J., Gonzalez, J.A. Itoiz C., Blanco F., Alkorta I. and Garbisu C (2001) "Straw quality for its combustion in a straw-fired power plant" Biomass and Bioenergy vol 21, no4, pp249–258	- Wheat and barley straw - Natural Leaching and harvesting time - Samples collected after rain events - Navarra, Spain					X	X								
IEA Bioenergy (2007) "Potential Contribution of Bioenergy to the Word´s Future Energy Demand", United Kingdom.	General information														
IEA Bioenergy (2009) "Bionergy – The Impact of Indirect Land Use Change", summary and conclusion from the IEA Bioenergy EXCo63 Workshop, United Kingdom	General information														

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
IPCC, Intergovernmental Panel on Climate Change (2011) "IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation"	General information														
Jenkins B.M., Mannapperumaa J.D., and Bakker R.R"Reverse Osmosis of a Biomass Leachate for Water and Materials Recovery", *Fuel Processing Technology*" (submitted)	- Rice straw - Pilot membrane leaching - estimation of costs						X			X					
Jenkins, B. M., Bakker R. R and Wei, J. B. (1996) "On the properties of washed straw" Bionmass and Biomergy, vol 10,. no4, pp177-200. Great Britain	- Rice straw and wheat straw - Ash composition different types of biomass - Different harvest time - Natural and mechanical leaching - California					X	X			X					
Jenkins, B. M., Bakker, R.R., Williams, R. B., Bakker-Dhaliwal, R., Summers, M.D., Lee, H., Bernheim, L.G., Huisman, W., Yan, L.L., Andrade-Sanchez, P. and Yore, M. (2000) "Commercial Feasibility of utilizing rice straw in power generation" Proceedings Bioenergy, Buffalo, New York.	- Rice straw and rice straw blended with wood - Full scale (Stoker-fired traveling-grate and circulating fluid bed (CFB) boilers) - Natural leaching - Economic Impacts. Incremental costs - California						X						X		
Jenkins, B.M., Williams, R.B., Bakker, R.R.,Blunk, S., Yomogida, D.E., Carlson,W., Duffy, J., Bates, R., Stucki, K. and Tiangco, V. (1999) "Combustion of Leached Rice Straw for Power Generation" Proceedings of the Fourth Biomass Conference of the Americas, Pergamon, Elsevier Science, Oxford, UK,, pp1357-1363.	- Leached straw and blend it with urban wood and agricultural wood, shells, and pits, and for the suspension unit with rice hulls. - Full scale (stoker-fired traveling grate, circulating fluidized bed (CFB), and suspension fired unit) - California					X	X								X
Jorgensen, U., and Sander, B. (1997) "Biomass requirements for power production- how to optimise the quality by agricultural management", Biomass and Bioenergy, Vol 12, No. 3, pp. 145-147. Great Britain	- Power generation from biomass in Denmark, workshop experiences and conclusions - Denmark														

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
Knudsen NO, Jensen PA, Sander B, Dam-Johansen K. (1998) "Possibilities and evaluation of straw pretreatment", Biomass for energy and industry, 10th European Conference and Technology Exhibition, Wurzburg, Germany, pp224-228	- Straw - Straw wash and pyrolysis and char wash - Mechanical leaching (straw wash-dewatering and drying) - Denmark									X				X	
Landstöm	-		X		X										
Lewandowski, I., and Kicherer A. (1997) "Combustion quality of biomass- practical relevance and experiments to modify the biomass quality of *Miscanthus x giganteus*" European Journal of agronomy, Vol 6, pp. 163-167	- *Miscanthus* - Biomass quality - Influence of location, fertilizer and harvest date on quality - Germany		X	X		X									
Lewandowski, I., and Heinz, A. (2003) "Delayed harvest of miscanthus—influences on biomass quantity and quality and environmental impacts of energy production" European Journal of Agronomy, vol 19, pp. 45–63.	- *Miscanthus* - Influence of delayed harvest - Life cycle Assessment LCA - Biomass quality - Germany			X											
Livingston W.R. (2007) "Biomass ash characteristics and behaviour in combustion, gasification and pyrolysis systems" Draft Final report, Technology & Engineering, Doosan Babcock Energy Limited, Report No: 34/07/005 Issue No.: 1	- Biomass ash quality - Behaviour of ash in different combustion systems														
Paulrud, S., and Nilsson, N. (2001) "Briquetting and combustion of spring-harvested reed canary-grass: effect of fuel composition" Biomass and Bioenergy Vol 20, pp. 205-35	- Reed Canary Grass - Spring harvesting and delayed harvest - Plant fraction (Leaf and stem) - Sweden		X			X									
Perlack, R.D., Wright, L. L. Turhollow. A.F. and Graham, R.L. (2005) "Biomass as a Feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual	General information														

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
supply".															
Reulein J., Scheffer K., Stülpnagel R., Bühle L., Zerr W. and Wachendorf M. (2007) "Efficient utilization of biomass through mechanical dehydration of silages", Proceedings of the 15th European Biomass Conference & Exhibition, Berlin, Germany, 2007, pp1770–1774. Florence, Italy.	- Maize silage - Mechanical dewatering - Blend straw and maize - Germany									X			X		
Samson, R. and Mehdi, N. (1998) "Strategies to reduce the ash content in perennial grasses", Research Reports R.E.A.P., Canada.	- Perennial grass - Biomass quality, silica content, ash content - Canada	X	X	X		X									
Sander, B. (1997) "Properties of Danish biofuels and the requirements for power production", Biomass and Bioenergy, vol12, no3, pp177-183	- Straw and wood chips - comparison of species, variety, growing conditions, fertilizer - Biomass quality - Denmark		X	X	X		X								
Summers, M.D. (2001) "Using Rice Straw for Energy Production: Economics, Energetics and Emissions", California, USA	- Rice straw - Harvest/utilization - comparison between burning and harvest - Costs analysis and energy use - California														
Telmo C. and Lousada J. (2011) "Heating values of wood pellets from different species" Biomass and Bioenergy, vol 35, no7, pp2634-2639	- Wood (different species) - Higher Heating Value is analysed - Portugal		X												
Turn S.Q., Kinoshita C.M. and Ishimura D.M. (1997) "Removal of inorganic constituents of biomass feedstock by mechanical dewatering and leaching" Biomass and Bioenergy, vol. 12, no 4, pp241 -252.	- Banagrass - Mechanical dewatering and leaching - Biomass composition - Hawaii						X			X					

Reference	Description	Plant type	Plant Fraction	Soil type	Use of fertilizers	Delayed harvest	Natural leaching	Strip harvesting	Addition chemicals	Mechanical leaching	Biorefinery –Dry fractionation	Hydrolysis	Mixing biomass	Pyrolysis and char wash	Conversion systems
Woli K.P., David M.B., Tsai J., Voigt T.B.,Darmody R.G. and Mitchell C.A. (2011) "Evaluating silicon concentrations in biofuel feedstock crops Miscanthus and switchgrass", Biomass and Bioenergy, vol 35, no7, pp2807-2813	- Miscanthus and switchgrass - Soil type an composition - Illinois		X	X											

Annex 2 Classification of the soils

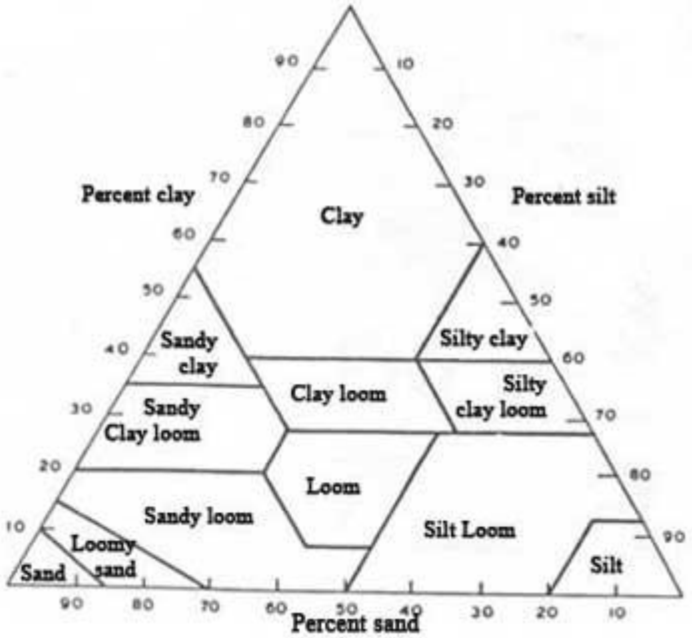

Figure A2.1 Soil triangle. Relationship between contents of clay, silt and sand in determining the different kinds of soil

Source: http://www.microbiologyprocedure.com/soil-the-natural-medium-for-plant-growth/physical-properties-of-soil.html. Physical Properities of Soil
Accessed at July, 2011