

Torrefied Bamboo for the Import of Sustainable Biomass from Colombia

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Abstract

The report presents the results of the technical, economic and sustainability assessment of the import of torrefied bamboo pellets from Colombia to the Netherlands as a biomass supply chain for electricity production. The specific case assessment is for the bamboo species *Guadua angustifolia*. Additionally to *Guadua*, alternative species (*Guadua amplexifolia*, *Bambusa vulgaris*, *Chusquea subulata*, *Dendrocalamus strictus*) have been identified and subjected to a preliminary technical assessment.

The technical evaluation results show that the bamboo species *Guadua angustifolia* is a good candidate for fossil fuel (coal) replacement in power plants, especially after it undergoes pre-treatment such as dry torrefaction that improves grindability of the material, or torwash that in addition removes ash elements such as Cl and alkalis that cause fouling and deposition problems during thermal conversion. Furthermore, several other bamboo species (e.g. *Bambusa vulgaris*, and *Dendrocalamus strictus*) could be included in the fuel portfolio of modern pulverized fuel power plants after a certain pre-treatment process.

Bamboo presents common characteristics with many other biomass feedstocks regarding heating value and chemical composition. It has the potential to be a sustainable feedstock in the bio-based economy, not only for energy purposes but also for the chemicals and materials sectors. Bamboo has some advantages over other lignocellulosic feedstocks such as: high land productivities (10-40 ton/ha-year) and higher biomass densities (500-600 kg/m³) which results in reduced production and transport costs.

In the coffee region of Colombia a potential of 400 to 1,800 kton_{dry} could be produced annually from natural stands or from the establishment of plantations of *G. angustifolia*, which corresponds to a fuel potential between 250 to 1,000 MW_{th}. The potential of other bamboo species, and regions in the country, has not been assessed. When calculated along the complete supply chain, GHG emissions reductions are above 70% when compared to coal-based electricity in the Netherlands. Additionally, the bamboo chain has the potential to comply with the additional sustainability criteria from the certification system NTA8080 and the EC recommendations for solid biomass. The LCA results show a superior environmental performance of the bamboo chain when compared to the coal-based reference.

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Summary

The report presents the results of the technical, economic and sustainability assessment of the import of torrefied bamboo pellets from Colombia to the Netherlands as a biomass supply chain for electricity production. The base case assessment considers the bamboo species *Guadua angustifolia*. Additionally to *Guadua*, alternative species have been identified (*Guadua amplexifolia*, *Bambusa vulgaris*, *Chusquea subulata* and *Dendrocalamus strictus*) and subjected to a preliminary technical assessment. Up to date, there are no studies on the use of the bamboo species *Guadua angustifolia* in the heat and power sector.

The technical evaluation included torrefaction tests (dry and wet), as well as combustion and gasification tests. Issues such as pre-treatment options, as well as slagging and fouling under standard power plant conditions were studied to evaluate this novel biofuel.

The Sustainability assessment was based on the sustainability requirements framed in the EC (2010)¹ and in the certification system NTA8080. The evaluation considers two scenarios: the use of residual streams from forest management and the use of bamboo from a bio-energy crop. The complete biomass chain is assessed in its relationship to the goals in reducing greenhouse gas emissions. Complementary information is generated by means of a Life Cycle Assessment to estimate additional potential environmental impacts on air, soil and water.

From the evaluation of the complete biomass chain the following conclusions and recommendations can be formulated:

- Bamboo has the potential to be a sustainable feedstock in the bio-based economy, not only for the energy but also for the chemicals and materials sectors
- Bamboo presents common characteristics with many other biomass feedstocks regarding heating value and chemical composition. Bamboo has some advantages over other lignocellulosic feedstocks such as: high land

¹ Report from the commission to the council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity; heating and cooling.

productivities (10-40 ton/ha-year) and higher biomass densities (500-600 kg/m³) which can result in reduced production and transport costs.

- In the coffee region of Colombia an annual potential of 400 to 1,800 kton_{dry} annual could be produced from natural stands or from the establishment of plantations of *G. angustifolia* which corresponds to a fuel potential between 250 to 1,000 MW_{th}. The potential of other bambo species, and regions in the country, has not been assessed
- The techno-economic potential of the biomass chain for the bio-based economy differ according to the species, maturity stage, production site and cultivation practices (e.g. fertilizer use), harvesting alternatives (e.g. selective harvesting vs. clear cutting), etc.
- Torrefaction improves the physical qualities of the fuel, such as grindability and moisture content. Torwash removes salts and minerals from biomass that cause fouling and deposition problems during thermal conversion. Pre-treated *Guadua angustifolia* is a high quality solid fuel with an elemental composition and heating value comparable to clean wood.
- The combustion tests revealed that no severe technical obstacles exist for using pre-treated bamboo in large power plants as a partial coal substitution. Firing 100% bamboo is not recommended before extensive and dedicated trials are carried out for a specific boiler, mainly due to the increased alkali content of bamboo compared to clean wood.
- Several other bamboo species (e.g. *Bambusa vulgaris* and *Dendrocalamus strictus*) could be included in the fuel portfolio of modern pulverized fuel power plants.
- Entrained flow gasification of 100% guadua exhibits a low slagging potential due to high silica oxide content in the ash. This could implicate a drawback for entrained flow gasification; however this could be beneficial for other thermal conversion processes (down draft gasifiers; PF combustion). Nevertheless co-feeding torrefied bamboo with low rank coal (alkali-, iron- or ash-rich) can be advantageous in entrained flow gasification.
- The overall economic model indicates that torrefied bamboo pellets could cost between 5-8 €/GJ (2012) at the port of Rotterdam, depending on the source and local logistics strategies. This price range is within the current price of white pellets, therefore there is a potential for the economic competitiveness of the bamboo chain. Detailed feasibility studies need to be performed for each specific business case.
- GHG emissions reductions are above 70% when compared to coal-based electricity in the Netherlands, when calculated along the complete supply chain. The results are dependent on the cultivation and harvesting strategy.

- The bamboo chain has the potential to comply with the sustainability criteria formulated in the certification system NTA8080 and the EC recommendations for solid biomass.
- The LCA results indicate the superior environmental performance of the bamboo chain compared to the coal-based reference. This applies for all impacts categories with the exception of acidification and photochemical oxidation. Both exceptions mainly stem from emissions related to interoceanic transport fuel usage and the potential use of fertilizers. These potential negative impacts are common to biomass chains. However, transport related impacts are lower for bamboo than for other biomass feedstocks (for the equivalent transport distances), due to its high density. Reduction of potential impacts related to fertilizers use could be accomplished by an integrated system with:
 - Biofertilizers use which are produced from the bamboo leaves as well as from other sources available in the region.
 - Recycling of minerals resulting from the processing steps, in particular if hydrothermal (Torwash) pre-treatment is applied where a stream rich in minerals is produced.
 - Soil properties improvement via alternatives such as biochar production and use in the plantations could be explored.
- Bamboo is not included in the list of the default biomass chains considered by the EC, therefore it needs to be “demonstrated” that the GHG emissions reduction is at least 50-70% of the fossil-based route. There are no default values in EU-RED for bamboo forest/plantations, the GHG emissions reductions data needs to be demonstrated, therefore monitoring activities are required.
- The macro monitoring of bamboo production issues should include: biodiversity, preservation, land use, food security, social well-being and local prosperity, and specifically for bamboo also the competition with existing utilization markets, i.e. furniture production. In certain countries competition with this existing market is not considered to be an issue since the added value for this market is much higher than for energy use. Additionally, the access to international markets of finished bamboo products from Colombia is very limited as the major global supplier is China; therefore the opening of new markets (local and international) and product diversification would highly benefit the bamboo sector.
- The interest in bamboo as an alternative feedstock is increasing rapidly. However, the end use of the feedstock and the supply chain development requires the direct involvement of the private sector as well as the support of public institutions in both the producing countries as well as end use countries. The development of the supply chain requires an active role of all actors involved either in the international and/or national markets. The participation of end users in any follow up initiative is a must.

Additional relevant issues for the supply chain development are:

- The recognition of bamboo as a biomass source for different applications in the local and international market.
- The Colombian public institutions (ministry of environment and ministry of agriculture) should develop a regulatory framework that clearly defines bamboo either as an agricultural resource, a forestry resource or an agro-forestry resource.
- Multidisciplinary expertise on bamboo production, pre-treatment, conversion and system assessments are of key importance in the successful integration of bamboo in the bio-based market in Europe and other regions.

1

Introduction

Biomass is expected to play a major role in the transition to sustainable bioenergy production in the world. It is anticipated that in 2050 biomass could supply 30% of the total global energy consumption. Most of the energy will be produced via thermal conversion processes (combustion and gasification). The biomass used will be a combination of biomass residues, mixtures of biomass, waste and specially cultivated bio-energy crops.

With respect to maximizing the biomass share in the energy sector, biomass trade will become important, and regulations must be formulated and applied in the sustainable production of the various biomass streams in conjunction with positive social, economic and environmental impacts. Moreover, the associated logistics and technologies need to be optimized in order to simplify biomass trade and supply.

Bamboo has the global potential to become a sustainable biomass source for renewable fuels and materials production. As a resource it may total more than 36 million hectares worldwide (Lobovic, 2007). Recently bamboo has received increasing attention because of its easy propagation, vigorous regeneration, fast growth, high productivity and quick maturity. Bamboo can be an efficient user of land and produces more biomass per unit area than most tree species (Kumar, Ramanuja Rao I.V. & Sastry, 2002). Typical growth rates are between 10-40 ton/ha-year, depending on the species. Bamboo can be harvested annually without depletion and deterioration of the soil (Lobovic, 2007) and can grow in marginal land that is not suitable for agriculture or forestry, or as an agroforestry crop. Bamboo is also seen as a material with huge potential for poverty alleviation and livelihood development in producing countries. Bamboo represents an important natural resource traditionally used to build long-lived products such as houses, furniture, handicrafts, veneers and flooring. A significant amount of it is not suitable for manufacturing products and is available from processing sites, plantations and forest resource management. These residues can be used for bioenergy and materials production, providing a potential economic use for this material.

The alternative production of bamboo as a bioenergy crop would generate local jobs and income for the rural sectors. Natural areas of non-disturbed forest, generally associated to fragile ecosystems, could also be prevented from deforestation, which

would guarantee their existence and allow the preservation of biodiversity in the areas of influence (Riano, 2002).



Guadua angustifolia is a woody bamboo species, which is native to Latin America, particularly the regions of Colombia and Ecuador, although it grows in other regions. *Guadua angustifolia* is considered to be one of the three largest species of bamboo, and one of the 20 most used species worldwide (Londoño, 1998). In Colombia and particularly in the coffee region, *Guadua angustifolia* represents an important natural resource traditionally used by farmers to build long-lived products such as houses, furniture, handicrafts, veneers and flooring (Camargo, 2006). A significant amount of it is not suitable for manufacturing products and is available from processing sites and from forest resource management. These residues could be used for bioenergy production, providing a potential economic use for this material.

Up to date, there are no studies on fuel properties of the bamboo species *Guadua angustifolia*. The technical issues related to the fuel pre-treatment and end use are part of the techno-economic and sustainability assessment of the complete supply chain. The assessment of this alternative biomass chain aims at innovation and technology development, while promoting and marketing sustainable biomass.

1.1 Scope and outline of the report

This report presents the results of the assessment of bamboo as a biomass supply chain for bioenergy production in the power industry.

The ultimate goal of the chain assessment is to address the suitability and options to adapt this promising fuel to the existing power industry. This requires in-depth knowledge on the crop production, the sustainability assessment of bioenergy chains, the technical issues related to fuel behaviour in thermal conversion systems, and optimum pre-treatment techniques and conditions.

Chapter 2 presents the overall project description, methodology and the assessed base case. Chapter 3 describes the overall aspects of bamboo as a global biomass resource, the potential species and current state in Colombia. Chapter 3 also presents the main crop characteristics and the physical and chemical properties of the selected species. Chapter 4 describes all performed test and results achieved during torrefaction. Chapter 5 reports the technical evaluation of the fuel properties based on co-firing and gasification tests. Chapter 6 describes the economic evaluation of imported torrefied bamboo pellets from Colombia to the port of Rotterdam. Chapter 7 presents the sustainability assessment of the biomass chain including a screening LCA. Finally Chapter 8 presents the conclusions and recommendations.

2

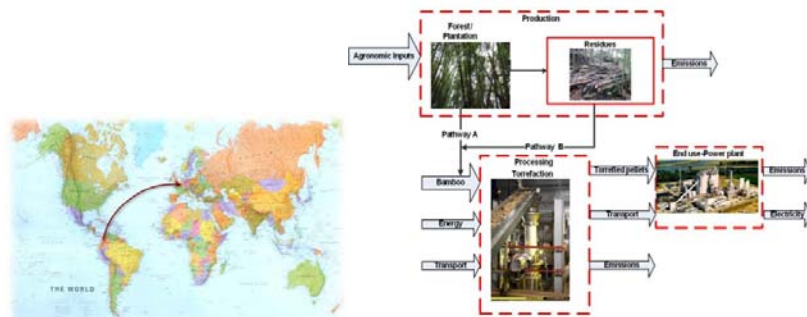
Analysing the potential of bamboo as a solid fuel

2.1 Project description

This work forms part of the project “Torrefied bamboo pellets for sustainable biomass import from Colombia”. The project aims to assess the techno-economic potential and the sustainability of the import of torrefied bamboo pellets from Colombia to the Netherlands as a biomass supply chain for bioenergy production. The specific case assessment is for the bamboo species *Guadua angustifolia*. Additionally, alternative species have been identified and subjected to a preliminary technical assessment.

The assessment covers the complete chain from biomass cultivation & collection and the upgrading via torrefaction in Colombia and the export of the torrefied bamboo pellets to be used as solid fuel in The Netherlands for electricity generation.

Figure 1: Biomass chain



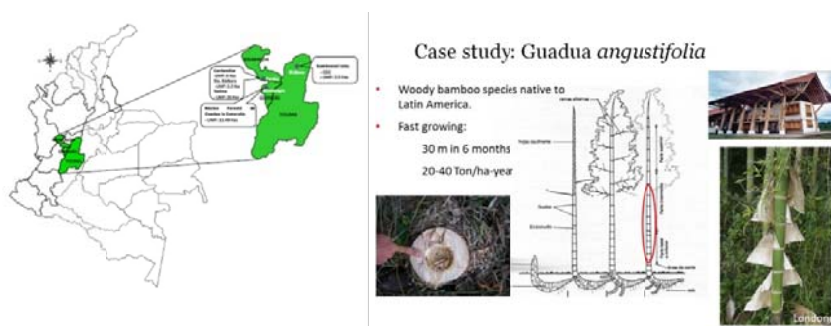
2.2 Methodology

The project combined the knowledge and expertise of ECN and the project partners during the assessment of the whole chain of bamboo cultivation and collection, via torrefaction/upgrading to application as biofuel. The consortium had a multidisciplinary structure, with the Colombian partners: the Technological University of Pereira and the Colombian Bamboo Society playing a key role in providing and collecting essential information as experts on bamboo. The European partners, the Energy research Centre of the Netherlands and the Imperial College of London provided the technology development and sustainability assessment. ECN expertise on torrefaction and combustion, as well as system assessments are of key importance for the complete chain evaluation.

The country of origin for the assessed bamboo species is Colombia; a country of 114 million ha (Mha) with an ample diversity of climate, soil, geology, topography, vegetation cover and land use. The major 5 natural regions are: the Caribbean region, the Pacific region, the Andean region, the Amazonian and the Orinoco regions. Colombia has coastal areas with access to both the Pacific and Caribbean Sea, which allows international trade with all continents. (See a detailed map in Appendix **Figure 86**).

The base case involves the coffee region which is located in the Andes region (**Figure 2**). This region covers about 6 Million Ha and is an area with a strong cultural identity related to the production of coffee and the presence of the bamboo species *Guadua angustifolia*. Coffee is the main agricultural activity followed by plantains and pastures for husbandry.

Figure 2: Base case. Map Source (GFA Consulting Group, 2005)



Within the area there is a group of farms which have been certified by the Forest Stewardship Council (FSC). The Corporative for the sustainable management of guadua CORGUADUA has 5 members (or units) with an up to date certified area of 96 ha. The experience of CORGUADUA is used to identify the barriers and opportunities with FSC certification and with other certification schemes which would apply to solid biomass production, such as NTA8080. The experience and knowledge gained by the certified farms in the coffee region could be reproduced in other regions of the country with potential for bamboo production.

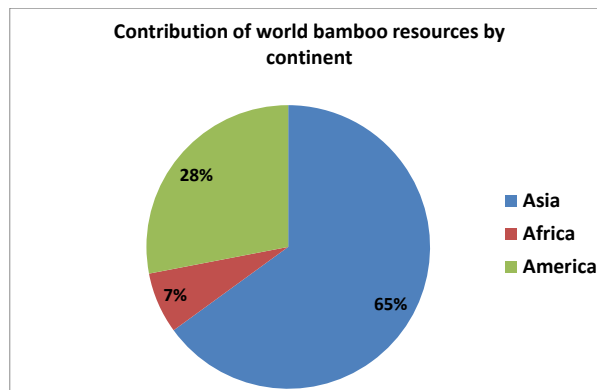
3

Bamboo as an alternative biomass resource

3.1 Bamboo as a global resource

Bamboo as a global resource may total more than 36 million hectares, of which 65% in Asia, 28% in the Americas and 7% in Africa (Lobovic, 2007). Assuming a low value for potential harvesting of 10 ton /ha-year, at least 360 million tons of bamboo could be sustainably harvested globally each year.

Figure 3: Contribution of world bamboo resources by continent. (Lobovic, 2007)



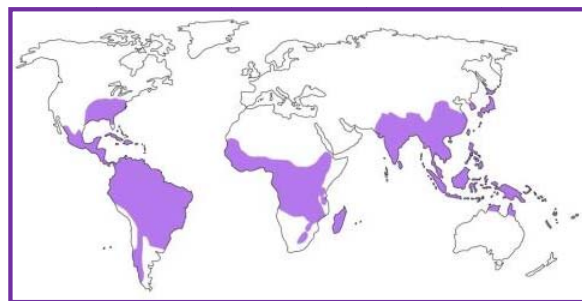
In Asia, the major bamboo producing countries are India (almost 11.4 million hectares) and China (over 5.4 million hectares), followed by Indonesia (2 million hectares) and the Lao People's Democratic Republic (1.6 million hectares). The total area of bamboo reported by five African countries (Ethiopia, Kenya, Nigeria, Uganda, Tanzania) makes up over 2.7 million hectares. Latin America has no reliable data on the bamboo area at the regional level. Information exists in some countries, but it is insufficient, scattered

and at times contradictory. The most reliable report estimates 11 million hectares of bamboo area in the region (Londoño, 2001). Lack of reliable data on bamboo resources in Latin America is partially explained by the current low economic value of bamboo at the continent. Many people regard bamboo as a weed and do not yet appreciate its huge economic potential for development and poverty alleviation. Although the resources of native species are abundant, their exploitation is limited to mostly low-end, low-profit, traditional non-mechanized manufacturing. In Brazil, Colombia and Ecuador, bamboo plays a more conspicuous economic role. In these countries, small-scale cultivation of commercial bamboo is limited to a few native (*Guadua angustifolia*, *Guaduaamplexifolia*) and introduced species (*Bambusa vulgaris*, *Bambusa tuldoidea*, *Phyllostachys aurea*) (Lobovic, 2007).

3.2 Bamboo plant

Bamboo belongs to the Gramineae family and has about 90 genera with over 1,200 species. Bamboo is naturally distributed in the tropical and subtropical belt and is commonly found in Africa, Asia and Central and South America. Some species may also grow successfully in mild temperate zones in Europe and North America.

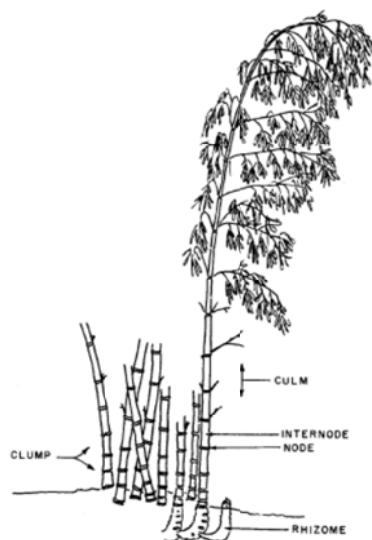
Figure 4: Bamboo global natural distribution



Bamboo is an extremely diverse plant, which easily adapts to different climatic and soil conditions. Dwarf bamboo species only grow up to a few centimetres (cm), while medium-sized bamboo species may reach a few metres (m) and giant bamboo species grow up to about 30 m, with a diameter of up to 30 cm. Bamboo stems are generally hard and vigorous, and the plant can survive and recover after severe calamities, catastrophes and damage (Lobovic, 2007). In the subfamily Bambusoideae (Poaceae) both woody and herbaceous bamboos are found, although only the woody bamboos have economic potential (Gielis, 2005).

Bamboo use and trade has been growing rapidly in recent years. Bamboo is becoming popular as an excellent substitute for wood in producing pulp, paper, board and charcoal. It is widely used in construction, either in its natural form or as a reconstituted material (laminated boards and panels) (Lobovic, 2007). Shoots from some species are fit for human consumption. All parts of the plant have traditional and potential applications, see (Figure 5).

Figure 5: Clump of common bamboo (*Bambusa vulgaris*) with parts labelled, picture source (Francis, 1993). Table: Overall bamboo current and some potential applications.



Plant section	Current and some potential applications
Culm	Finished products: housing, flooring, furniture, paper, charcoal, activated carbon, fibre composites, textiles, feedstock for lignocellulosic biorefineries.
Leaves	Left in the field as fertilizer, and/or collected for animal feed, production of extracts, medicines.
Branches	Chopsticks, tooth picks, poles.
Roots	Food

Different from trees, the width of the bamboo culm is already determined during its sprouting, and does not increase in diameter afterwards (de Vos, 2010). **Table 1** presents the main differences with trees.

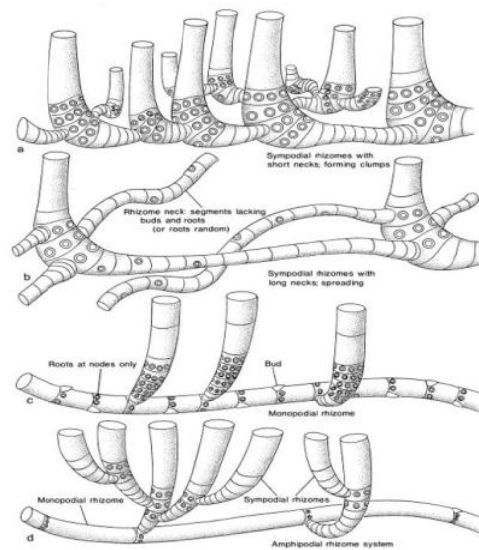
Table 1: Bamboo vs. trees

Bamboo	Tree
Regenerates itself after harvested. Does not need replanting.	Does not regenerate itself.
Culm or stalk is mainly hollow, cylindrical and segmented.	Solid stalk and not segmented.
No bark or central heart. The hardest part is the area of the periphery and is in the outer.	Has bark and aged cells form the hardened heart of the tree which is in the centre.
No cambium tissue and culm diameter does not increase with age.	Has cambium tissue and stalk diameter increases with age.
There is no radial communication.	There is radial communication.
It grows extremely fast (30 m at 6 months), which make it the fastest growing lignified plant in the planet.	It grows slowly in height and diameter.
Associated growth, forming a network of rhizomes, where an individual depends on the other and its use affects the rest of the community.	It grows as an individual, independent, and its use does not affect the community.

Bamboo shoots and culms grow from the dense root rhizome system. There are two main categories of rhizomes: monopodial and sympodial. Monopodial rhizomes grow horizontally, often at a surprising growth rate, explaining their nickname 'runners'. The

rhizome buds develop either upward generating a culm, or horizontally, with a new tract of the rhizomal net. Monopodial bamboos generate an open clump with culms distant from each other and can be invasive. These are usually found in temperate regions and include the genera *Phyllostachys* and *Pleioblastus*. Sympodial rhizomes are short and thick, and the culms above ground are close together in a compact clump, which expands evenly around its circumference. Their natural habitat is tropical regions and these are not invasive (Lobovic, 2007).

Figure 6: Bamboo Rhizomes and forest. Sources (Guadua Bamboo, 2012), (de Vos, 2010), Londono X.



Monopodial bamboo (*Phyllostachys pubescens*, Moso) (de Vos, 2010)



Sympodial bamboo (*Guadua angustifolia*) (Pict: Londono, X.)

Bamboo is the most important non-timber forest product, which is in many countries the most important material for construction, especially in rural areas. Although most bamboo stands correspond to small patches, the resource represents an essential alternative for improving the livelihood of rural communities (Lobovikov et al., 2007).

3.3 Bamboo as a biomass source

Bamboo presents common characteristics with many other biomass feedstocks regarding heating value and chemical composition (Daza C.M., 2011). Literature presents a wide range of values of biomass fractions, and was collected from different sources (Chen, 2011; Kwong, 2007; Scurlock, 2000; Vassilev, 2010) that refer to bamboo species other than *Guadua angustifolia*. **Table 2** lists typical properties compared to wood and other alternative feedstocks. Detailed chemical compositions of the species analysed within this project are presented in section 3.6.

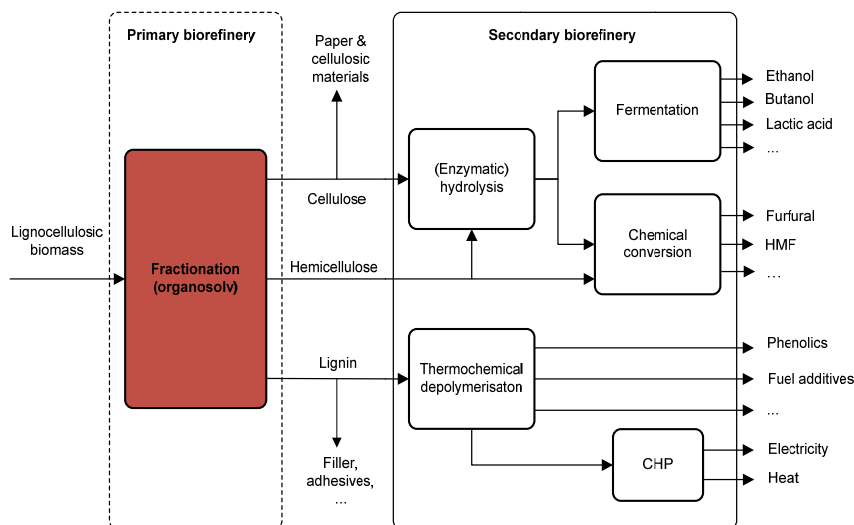
Table 2: Properties of bamboo vs. other biomass feedstocks. Sources (Chen, 2011; Kwong, 2007; Scurlock, 2000; Vassilev, 2010)

Feedstock		Bamboo culm	Cane Bagasse*	Wheat straw*	Wood
HHV (dry)	MJ/kg	17-20	18-20	16-19	17-20
Density	kg/m ³	500-700	150-200	160-300	200-500
Yield	Ton dwt/Ha-year	10-40	7-10	6-12	10-20
Overall composition (dwt %)					
Cellulose		40-60	35	38	50
Hemicellulose		20-30	25	36	23
Lignin		20-40	20	16	22
Others**		2-10	20	10	5

* Data is taken from (Brown, 2003). **Includes proteins, oils, mineral matter such as silica and alkali

As a biomass resource bamboo has the potential to be a feedstock not only for the energy, but also for the chemicals and materials sector. Different initiatives for the development of new applications and the production of high added value products (for example activated carbon) are found in literature (Choy, 2005; Krzesinska, 2009; Krzesinska, 2006; Mui, 2010) As a lignocellulosic feedstock, it could be used in the development of sugars and lignin based bio refineries (Li, 2012a; Li, 2012b)

Figure 7: Lignocellulose biorefinery concept (van Haal, 2013)



In terms of overall techno-environmental performance, the use of bamboo as a lignocellulosic feedstock presents advantages over other lignocellulosic feedstocks. These include high land productivities and higher biomass densities, which result in reduced production and transport costs. Additionally, the production does not require the use of seeds, use of plastics for baling, and requires no or little amounts of fertilizer use. These are key factors in the environmental performance of biorefinery concepts along the complete chain (LignoValue project consortium, 2011).

3.4 Native and exotic species in Colombia

In Colombia more than 100 bamboo species have been registered. The Andean region has the largest quantity and greatest diversity of woody species reported until now. The departments (states) with the highest woody bamboo diversity are Norte de Santander, Cundinamarca, Cauca, Valle del Cauca, Antioquia, Huila, Nariño and Quindío. The majority of species belong to *Chusquea* genus (30%), with the rest of the species belonging to the genera *Arthrostylidium*, *Aulonemia*, *Elytostachys*, *Merostachys*, *Neurolepis*, *Rhipidocladum*, *Guadua* and *Otatea* (Guadua Bamboo, 2012).

Despite species diversity only *Guadua angustifolia* has a considerable economic value up to date. The role of other species on the local economy is low. Therefore more

information on this species is available, since it is the most abundant and utilized, and it has characteristics which permit utilization for different purposes. In Colombia an area of about 51,000 ha is reported to be covered by forest dominated by the bamboo species *Guadua angustifolia* from which about 90% are natural forest and 10% are cultivated. Only in the coffee region (Caldas, Quindío, Risaralda, Valle del Cauca and Tolima), 28.000 ha have been registered (Kleinn, 2006).

Within this project several alternative existing species in Colombia (native and exotic) have been selected as potential biomass sources, based on following criteria:

- Sympodial species
- Potential high biomass productivity
- Culm size
- Growth site: height above mean sea level (amsl), topography and annual rainfall

Table 3 present the list of selected species which can grow at different sites (amsl), and could potentially be produced for the local or international market. Each of them are briefly described in the paragraphs below.

Table 3: Selected Sympodial bamboo species (This project)

Bamboo species	Native (N) Exotic (E)	Altitude Amsl	Culm	Average Culm Diameter (cm)	Average wall thickness (cm)	Culm length range (m)	
<i>Guadua angustifolia</i>	N	900-1600	Hollow	15	3	15	30
<i>Guadua amplexifolia</i>	N	0-1000	Solid	8	-	10	20
<i>Chusquea subulata</i>	N	2200-2800	Solid	7	-	3	10
<i>Bambusa vulgaris</i>	E	0-1500	Hollow	10	2	8	20
<i>Dendrocalamus strictus</i>	E	0-800	Solid	6	-	6	20

The Technological University of Pereira, carried out a study to determine the biomass content (**Figure 8** and **Figure 9**). The Figures below presents the average biomass distribution per plant section. It is observed that there are significant differences on the distribution between species and plant maturity stage. These are relevant when analysing the economic potential of processing each plant part for any given species as well as the comparison of alternatives.

Figure 8: Average aboveground biomass distribution per plant section of the selected species

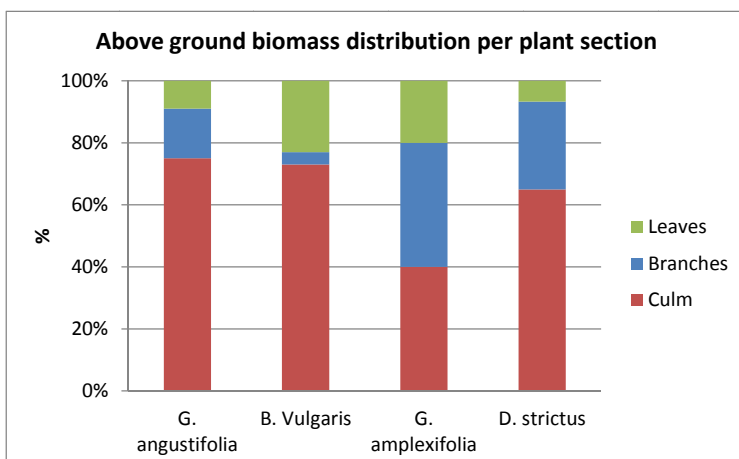
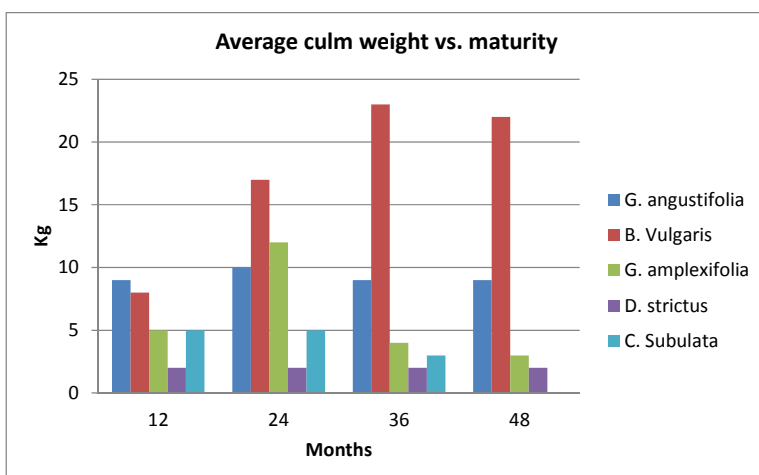


Figure 9: Average culm weight vs. maturity stage of the selected species



The properties of bamboo according to maturity stages are described in section 3.5.

- *Guadua angustifolia*

It is the most used species, therefore the most studied in Colombia and some countries in the Americas where it also grows, like Ecuador and Venezuela. In the Americas, the Guadua genus is distributed from Mexico to South America and the *Guadua angustifolia* (*G. angustifolia*) is one of the 33 species of this genus. Native from Venezuela, Colombia, Ecuador, Peru and Panama, it forms part of the tropical forest of America and it's principally located in the Andean region of Colombia, Ecuador and Venezuela, especially between the Inter-Andean valleys (Garcia, 2004); (Londoño, 1990).

Figure 10: *Guadua angustifolia*. (Pict Londono, X.)

- Woody bamboo species native to Latin America.
- Fast growing:
 - 30 m in 6 months
 - 20-40 Ton/ha-year



G. angustifolia is a rapid growth monocotyledon that increases its height up to 21 cm per day (Riano, 2002). The most outstanding aspects of the different research studies indicate that the culms of guadua emerge from the ground having a diameter between 6 to 22 cm. They reach their final height in the first 6 months of growth, and come to maturity when they are 4 to 6 years old. The life cycle of guadua culms is approximately 11 years. However, this cycle may vary depending on site conditions and management, and thus the cycle varies between 5 and 11 years (since the shoots appear to the dry maturity stage).

G. angustifolia has many applications in the daily life of rural inhabitants: these include musical instruments, domestic utensils, handicrafts, furniture, tools and even farm infrastructure. Nowadays crafts and furniture made of *G. angustifolia* have modern and innovative designs and processing industries are a source of employment. *G. angustifolia* is a material with good structural properties, such as its strength/weight ratio, which surpasses that of most woods and has been compared to steel and some high-tech composites. Its capacity to absorb energy and allow for higher bending strength makes this bamboo an ideal material for seismic-resistant constructions (Gnanaharan, 1994)). Its specific density (which is important in building materials) is 750-800 grams/cm³.

Growing conditions

It grows in places with a height above mean sea level (amsl) between 500 to 1800, rainfall of 1200 - 2500 mm per year, temperature between 18 °C and 24 °C, and 80 - 90% relative humidity. It adapts well to extreme rainfall conditions of Colombian tropical rain forests (more than 10,000 mm per year) but cannot withstand extreme drought (< 800 mm year) (Londoño, 1998; Riano, 2002)

Different studies have been carried out to define those environmental factors that influence the growth and quality of guadua culms (Camargo, 2006; Garcia, 2004); these results demonstrated that the guadua has a wide geographic distribution (Camargo, 2007a)). The reported optimal growing conditions are presented in **Table 4**.

Table 4: Optimum variables and factors for *Guadua angustifolia* growth (Camargo, 2007a)

Environmental Factor	Variable	Optimum Range
Topography and elevation	Elevation (masl)	1,200-1,500
	Slope (°)	0-20
Climatic	Precipitation (mm/year)	1,800 – 2,600
	Relative Humidity (%)	75 – 85
	Temperature (°C)	19.5 – 22.5
	Solar Brightness (hours/year)	1,800 – 2,200
Soil	pH	5.8 – 6.1
	Effective depth (m)	>1
	Organic Matter (%)	>5
	Total porosity (%)	>50
	Natural Draining	good
	Al (meq in 100g of soil)	0.06 – 0.03
	K (meq in 100g of soil)	0.12 - 0.15

G. angustifolia forest also plays an important role in carbon sequestration. According to (Arango, 2010)), the total carbon stored by natural guadua stands with an average density of 4050 culms per ha is of 126±41,7 ton per Ha with about 85% corresponding to aboveground biomass (culms, branches and leaves) and 15% to belowground biomass (rhizome). For plantations with an average density of 7700 culms per ha, the total carbon stored is of 24,6±5 ton per ha with 86% of aboveground biomass and 14% of belowground biomass. In the other hand soil carbon under guadua stands and bamboo plantations measured at 0,5 m of depth, was estimated in 544±125 ton per ha in average (Arango, 2010).

- *Guadua amplexifolia*

It is native from southern Mexico to northern Colombia and Venezuela, from 0 to 1000 masl. In Colombia it mainly grows in the Atlantic Cost and is called “Guadua Carrizo” or “Cañabrava” (Judziewicz, 1999). It is quite vulnerable for certain insects and not recommended for construction (Hidalgo, 2003; Hidalgo, 1981).

The most common applications are: wood for beams, ridges, ceilings, fences and hedges. In furniture it is used for doors, windows, chairs and beds. In the lagoon of Tamiahua its widely used for “charangas” a kind of fishing art that consists in putting lines of logs in the water to hold the nets (Gutierrez, 2005). The solid culms and huge biomass production capacity result in a large potential for the pulp and paper industry; comparable to the Asian species *Bambusa vulgaris*.

Figure 11: *Guadua amplexifolia*. Source: F. Castaño, ECOPLANET BAMBOO, 2012



- *Bambusa vulgaris*

Bambusa vulgaris is original from the tropical areas of Asia. It is the world's most widely cultivated bamboo in the tropical and subtropical regions. In America it has adapted to different types of soil and climate from Mexico to Uruguay and the Caribbean Islands (Londoño, 2004).

Despite its non-straight culms is the most used bamboo. The culms are used as boat masts, rudders, outriggers, poles, oars, and to transport all kinds of objects such as fences and as tutors. The culms are sometimes used as temporary beams. In Cuba the culms provide raw material for the construction industry and bamboo furniture. In Brazil is used for the production of paper pulp. New shoots are very bitter and rarely suitable for human consumption; sometimes leaves of *B. vulgaris* are used as fodder (Dransfield, 1995).

The shoots grow rapidly and can develop culms of 3-4 meters high in two weeks, reaching a maximum height of 20 meters in 3 months. On average a mature clump produces 3-4 new culms per year and has between 50 to 90 culms per clump. Shoots that emerge at the end of the rain period grow faster and are taller than those that emerge when the rain period starts. A mature green culm of *B. vulgaris* weighs 16 kg, its branches 5 kg and its leaves 3 kg, while the walls of the internodes are thicker in the basal portion (Dransfield, 1995).

Bambusa vulgaris culms of two years old are used for paper pulp production, due to the fibre length (Mejia, 2009). These are also used for construction and handicraft purposes in India. The longevity of the culm is comparable to the best wood species. Laboratory studies and pilot tests of the African species indicate its potential value, especially for the mixture with hard wooden pulps (Seethalakshmi, 1998). There are also records of studies for this species as a fuel for energy generation, as a result of the low ash content, the favourable alkali index and high calorific content (Rousset, 2011).

Figure 12: *Bambusa vulgaris* plantations in Brazil. (Source: Colombian bamboo society)



- *Chusquea subulata*

Chusquea subulata is a native bamboo species from central Ecuador and the Central Cordillera of Colombia. In Ecuador this species grows in the departments of Imbabura and Pichincha; and in Colombia in the departments of Tolima and Quindío, between 2,260-2,800 meters above sea level and often on steep slopes in upper montane forest. Among its most common uses are the manufacturing of baskets, adornments, hats, mats, house construction and forage (Ulloa, 2011).

There is little or no information on this species to date, and reported data is from Ecuador and Colombia (Tolima). As part of the activities of this project, a field study allowed to generate information to get a better understanding of the ecology of this important bamboo species.

Chusquea subulata has culms ranging from 4 to 10 cm in diameter, and 3 to 10 meters tall, erect at the base, arching toward the apex; the internodes are solid, deeply sulcate above the bud/branch complement, glabrous or pubescent.

Figure 13: *Chusquea subulata*. Source (Lopez, 2011)



Due to its solid culms up to 10 meters tall and 10 cm in diameter, it could be a good biomass source. It has a medium density of 7052 culms/ha, a net wood production of 296 m³/ha per year and a volume of wood per culm of 0,04 m³ (Lopez, 2011). *Chusquea subulata* is one of the tallest bamboo species that grows at the altitudes above 2000 masl. It is a bamboo species with specific potential for elevated carbon sequestration and protection of hydric sources.

- *Dendrocalamus strictus*

Dendrocalamus strictus is a native bamboo species that grows in India, Nepal, Bangladesh, Burma (Myanmar) and Thailand. Its culms reach 6 to 20 meters tall and 2.5 to 9 cm in diameter. They are solid or with small lumen, glabrous when young, becoming yellowish when old. The culms of *D. strictus* are widely used in Southeast Asia and India, primarily in construction, furniture, mats, baskets, canes, agricultural implements, rafts and woven products. In India this bamboo is still the main source of paper pulp. In Thailand it is an important species for bamboo board industry. The shoots and seeds are edible, while the leaves are used for fodder (Dransfield, 1995).

Dendrocalamus strictus occurs naturally in tropical and subtropical regions of Southeast Asia. The annual optimum temperature for growth is between 20-30°C, although it can withstand extreme conditions as low as -5°C and as high as 45°C. Mature plants often are resistant to frost, but could result in mortality amongst young plants. Optimal conditions of annual rainfall are between 1,000-3,000 mm, with 300 mm per month during the growing season. However *D. strictus* bamboo is drought resistant and grows quite well with rainfall between 750-1,000 mm per year. It prefers low relative humidity and is found from sea level up to 1,200 meters, particularly on slopes with dry and cool conditions. It grows in all soils that has good drainage; preferably sandy clay soil on rocky subsoil with a pH between 5.5-7.5. *D. strictus* grows well in open, deciduous and mixed forests (Dransfield, 1995).

The production figures for the culms of *D. strictus* in India vary widely and depend on many factors. A crop of 400 plants/ha can produce 3.5 tons of culms per hectare annually. A natural forest of *D. strictus* with 200 plants/ha can produce 2.8 tons of culms per hectare annually but production is usually lower. In well-managed natural farming in India yields of 17 tons of green culms per hectare can be obtained with hoeing, thinning and use of fertilizers (Dransfield, 1995).

Several common names are: Solid bamboo, Bamboo from Calcutta (Europe and the Americas); Buloh batu (Malaysia); Myinwa (Burma-Myanmar); S'ang (Laos); Phai-sang (Thailand); Bans and Karail (India)(Dransfield, 1995).

Figure 14: *Dendrocalamus strictus*.



3.4.1 Current state of bamboo forest in Colombia

About 1,200 species of bamboo have been registered globally; from these 440 native species are registered in America (Hidalgo, 2003)) and 95 in Colombia (Londoño, 1990). As mentioned in section 3.4, up till now only the woody species *G. angustifolia* has been studied and represents an important natural resource in Colombia, and particularly in the coffee region.

The *Guadua* has been traditionally used by farmers to build products such as houses, furniture, handicrafts, agglomerates, veneers and flooring.



After the last *G. angustifolia* inventory, 28,000 hectares were estimated in the coffee region (Kleinn, 2006) mainly corresponding to natural stands. At a national level about 51,000 hectares are reported to be covered by *G. angustifolia* species dominated forests, from which about 90% are natural forests and 10% are cultivated.

In the coffee region, commercialised timber and timber used for domestic applications comes from the natural forest located in the pacific coast. In the coffee region most of the forests were eliminated long time ago particularly for agricultural purposes. As a result, small fragments of forests dominated by *G. angustifolia* are currently the remnants of natural forest.

Guadua bamboo forests are an important refuge of biodiversity where more than 400 woody species have been identified. Besides, these provide a habitat to about 50 birds species and 18 mammals (bats), which fulfil important ecological functions (CIEBREG, 2008). Some specific studies on richness of vegetation species are referred in (Calle, 2008) and (Ospina, 2002) and for birds in (Fajardo, 2008).



These forest are highly fragmented and most of the patches are not larger than 5 hectares (Camargo, 2010). Landscape metrics are an evidence of fragmentation, with small patch area, high values of edge and shape index larger than 1, indicating a predominant elongate shape (**Figure 15**) which is in ecological terms a factor contributing to the so called edge effect.

Figure 15: Fragments of Guadua bamboo forest included in a matrix of pastures and pineapple crops. Coffee region of Colombia (Camargo, 2010)



Fragmentation of these forests has implications for silviculture, because larger areas of guadua stands would be required to meet demands. Currently, a number of farmers conduct improper management in the small Guadua areas to avoid costs for forest planning and technical assistance. Although most of the culms harvested are used for domestic applications and the intensity of harvesting is usually low, the silvicultural practices to obtain these culms are inappropriate.

Domestic harvest sometimes causes damage and contributes to increased susceptibility of Guadua stands, as well as to a decreased productivity (**Figure 16**). In addition, culms harvested under these conditions are usually of inferior quality. Better profits would be obtained when the technical process for harvesting is properly applied.

Figure 16: Degradation of Guadua bamboo forests associated to domestic harvesting



As previously mentioned, most of the timber used in the coffee region originates from natural forests of the Colombian pacific coast. Nevertheless, guadua is the most harvested species to obtain wood for different applications. Some reports show that between 2000 and 2004 roughly 2,420,000 culms of guadua were logged from 2,500 hectares (Moreno, 2006). Although it represents that about 90% of guadua stands were not harvested in this period of time, Guadua bamboo forests have been significant for consolidating enterprises (Held, 2005) and have improved the possibilities for expanding markets to Europe.

Information related to harvesting of guadua has not been registered after 2004. Based on the number of requested harvesting permissions and the poles of guadua sold in timber stores, it is known that commercialisation continues to be high. The coffee region is the major supplier of guadua poles and products to other regions of the country where consumption is high.

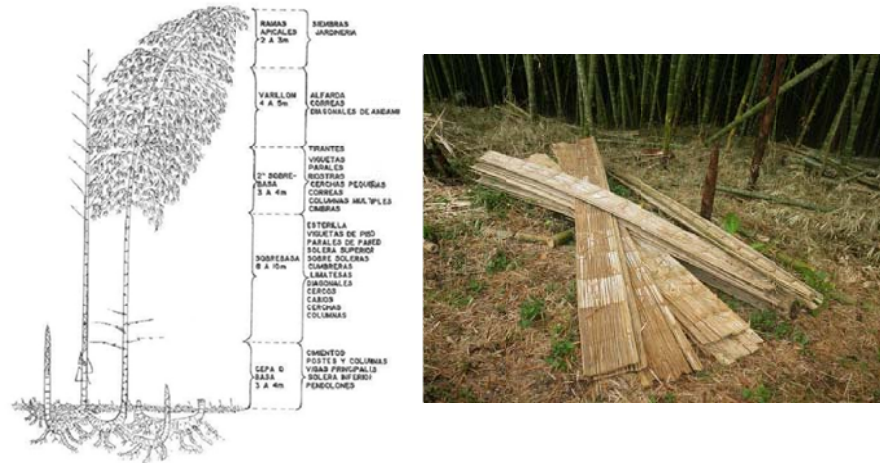
It is important to point out that the harvesting of guadua forest consists of the extraction of a fraction of mature culms. A significant number of standing culms with different stages of maturity therefore remain in the guadua forest under proper silvicultural management.

Because of the guadua culms characteristics, logging is usually conducted by using machetes and sometimes chainsaws. During harvest a fraction of mature and over-mature guadua culms are harvested, subsequently each culm is usually divided in four pieces according to the market possibilities. The base of the culm (approximately the firsts 3 meters of height) the so called “cepa” is frequently considered as a domestic product and is employed for fences. The next part (about 3 to 9 meters of height) the so called “basa” has the higher commercial value and therefore is used for different applications. The next piece is the so called “sobrebasa” (about 9 to 15 meters of height) and is usually manually opened for making mats or “esterilla” (See **Figure 17 b**). The last part of the culm is the so called “puntal” that is also used in domestic applications, especially as support in some crops such as plantain, banana or tomato.

Most of the businesses associated with the market for guadua culms involves “basa” and therefore this piece has the highest price. The “cepa” and “puntal” in addition to domestic use, also offer workers in charge of harvest (guadueros) a possibility to

generate some income when these products are required by other farms. Lastly, despite the low price the use of “esterilla” is significant because it can be commercialised by guadueros at the local markets.

Figure 17 a & b: a. *Guadua angustifolia* plant section and products (CATIE, 2004) . b. Esterilla

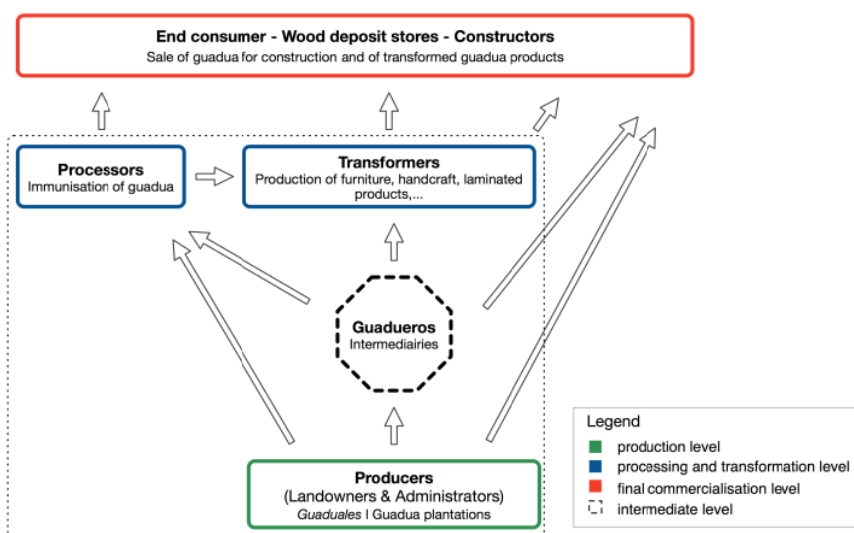


3.4.2 Value chain operators and institutions

Both operators and institutions that play a significant role in the forest policy affecting the exploitation and trade of guadua are presented in **Figure 18** and **Figure 19**. A comprehensive description of operators and institutions in the value chain of guadua is presented by (Retz, 2010).

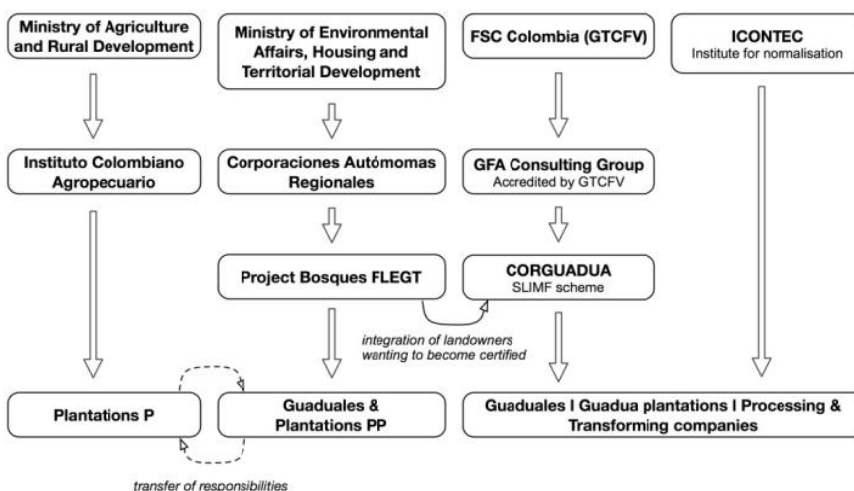
Figure 18 illustrates the different operators and the production flows between them, which form the interconnections between the different levels of production, intermediate transfer, processing and transformation to final consumption.

Figure 18: Operators in the Guadua sector in the coffee region. Source: (Retz, 2010).



The institutions also contribute to this value chain through their services for mainly producers and guadueros. The latter are landless men that organise the harvest and transport, and are an essential link between producers and other actors higher up in the chain. They play a pivotal role in the value chain by being the intermediate liaison between the various levels in the chain. The guadueros commercialise Guadua by selling it to other merchants (who in their turn sell to end users) or by having their own wood deposit shop. They also work in the guadua forests doing all kinds of heavy physical tasks such as clearing the under forest and cutting the culms (Retz, 2010).

Figure 19: The institutional context of the Guadua sector (Retz, 2010).



The production of the natural resource, guadua, is supervised by two different Colombian Ministries: The Ministry of Agriculture and Rural Development and the

Ministry of Environmental Affairs. The Ministry of Agriculture and Rural Development is responsible for registering, managing and providing technical assistance to commercial guadua plantations. These commercial plantations are relatively scarce in Colombia, since the natural guadua forests or guadua plantations of the type protection and protection-production (protectora and protectora-productora) are widely dispersed and fragmented. These are registered and managed by the CARs (Regional environmental authorities) under the Ministry of Environmental Affairs (Retz, 2010).

Both Ministries developed their own policy regarding the guadua, which resulted in the absence of one unified policy. Some operators in the chain advocate concentrating these different responsibilities under the Ministry of Agriculture and Rural Development. This would turn guadua into a crop like any other without restrictions on the exploitation of this natural resource.

Various production systems of guadua are identified and this categorisation is used in the policy framework implemented by the CARs.

The natural guadua forests (guaduales) have not been planted and appear in their natural state. These guaduales fall under the Ministry of Environmental Affairs, and subsequently under the regulatory authority of the CARs.
Plantations protectora-productora (PP) are plantations established with the purpose of protecting the natural guadua forests as well as for commercial extraction of guadua. Sometimes respondents, when talking about plantations PP, use the term reforestation. Establishment of these plantations has been promoted and supported by the CARs in their reforestation program (Ministry of Environmental Affairs).
Plantations productora (P) have been established solely with the purpose of commercial exploitation and fall under the Ministry of Agriculture.

All natural guadua forests and plantations PP or protectora (with a protective function solely) have to be registered at the CAR within the department where the natural or planted guadua forest is located. Landowners/administrators of natural guadua forests and Guadua plantations PP or protective purposes have to comply with the Unified Norm (UN). Only plantations with purely commercial purposes (plantations P) can be exploited without authorisation from the CARs (Castaño y Moreno, 2004) as these are subject to the authority of the Ministry of Agriculture and Rural Development (ICA).

Prior to official exploitation of the guadua forests) under the CARs, their state has to be assessed² by the CARs to determine the appropriate harvest quantity and intensity, and issue permits accordingly. The harvest quantity cannot exceed 35% of the commercially exploitable guadua culms in the forest. This extraction limit is determined by the UN and has the purpose to assure that the extraction of guadua is environmentally sustainable (CARDER, 2008a) and protect the guadua resource from further deterioration due to illegal overexploitation of this resource. The CARs issue permits for harvesting and transport of the guadua; the harvested and transported quantities and

² According to the UN, people who wish to exploit their guadua resource have to submit a Technical Study for volumes between 20–200 m³ or a Management Plan when exploiting volumes exceeding 200 m³. The elaboration of this plan is done in close collaboration with professionals of the CARs. This study or plan is conducted only once, but has to be revised regularly to maintain its validity relating to the guadua forest or plantation (Castaño y Moreno, 2004).

frequencies are monitored and deducted from the submitted plan. With this permit system the CARs aim at guaranteeing sustainable harvest and mobilisation of guadua, and reduce illegal activities.

The institutional and regulatory framework for the guadua sector in Colombia poses a barrier for market development based on the exploitation of natural forest. A permit is a time consuming process, which is the result of corruption and bureaucratic barriers. This discourages the small operators to manage and use the resource, while simultaneously encouraging illegal logging.

Some operators argue that the responsibility of this resource should be transferred to the Ministry of Agriculture and Rural Development to simplify the management and exploitation of guadua forests. This has economic and environmental consequences. In economic terms this means that the extraction restriction of 35% is not in vigour any more, adhering the same exploitation rights to guadua as any other agricultural crop (e.g. potatoes or maize). This measure turns guadua extraction into a potentially more profitable forest activity. Environmentally, this means there is no institutional control anymore on the conservation of this natural resource, but some actors in the value chain of guadua argue that abolishing the 35%-restriction will not automatically result in overexploitation of guadua. The extraction regime inherent to a commercial guadua plantation, with the objective of economic viability, supposedly avoids overexploitation of the guadua. This reasoning would be similar for guadua forests. Some respondents believe that commercial exploitation of guadua is required to protect it from deterioration and extinction. Additionally, they argue that guadua is a “weed”, a grass that grows fast and abundantly if not maintained regularly (Retz, 2010).

Guadua forest certification

The process of forest certification for guadua bamboo forest in Colombia started in 2002 in the framework of the project “Manejo Sostenible de Bosques en Colombia” funded by the German Organisation for Technical Cooperation (GTZ). The forest certification has been promoted under the principles of the Forest Stewardship Council (FSC), consequently specific standards were elaborated for Guadua stands, due to particularities associated with these kind of forests. In the first stage, forests from 5 farms and one organization were certified. Subsequently a Bosques FLEGT (Forest Law Enforcement, Governance and Trade) project was conducted between 2006 and 2010 with focus on new areas, including those related to initiatives of Units of Forest Management (UFM) that represent a scheme of integration of forest from different farms. Currently it is also possible to commercialise transformed guadua products with the stamp of FSC.

Furthermore a strategy of forest governance for Colombia has been developed during the Bosques FLEGT project. The aim of this project was to improve legality and governance for contributing to the sustainable management, increment of productivity and commercialisation of forest resources from small farmers. The management of guadua bamboo forest is now carried out following the principles of a standard Norma Unificada para el manejo de guaduales naturales (UN), which defines the guidelines for adequate management in the framework of legislation. Moreover, the Terms of Reference for the Management and Harvesting of Guadua Stands (TRMHGS) were also

deploy this norm, which allows the guarantee of proper management of guadua stands, even if certification of FSC has not been obtained.

Forest governance

The strategy for forest governance for Colombia has been developed during the Bosques FLEGT project. This project was formulated and led by the environmental authority (CAR) of Risaralda, or CARDER (Corporación Autónoma Regional de Risaralda). The project also involved others states (Quindío, Tolima and Norte de Santander) and their respective CAR (CRQ, Cortolima, Corponor). As mentioned before, the aim of the project was to improve legality and governance for contributing to the sustainable management, increment of productivity and commercialisation of forest resources from small farmers. Apart from defining the scope and expected results of the project, the first step involved assuming the concepts of governance and governability based on the definitions from the World Bank (World Bank 2006).

Within the project following achievements were highlighted:

- Different stakeholders from all links of production chains were collectively involved in formulating the **forest management Norms**. As a result of this process, the unified Norm for management of natural Guadua stands and the TRMHGS were adjusted. At this moment, the Norm and the TRMHGS are only applied in the coffee regions states. However, the Ministry of Environmental Affairs considers applying these in the entire country.
- **To approve the Guadua forest harvesting**, optimisation of the process to obtain permissions for forest harvesting is recommended by means of **time reductions**. This option was revised within each CAR for each step of the process and could result in a time reduction of about 30%.
- **Legal forest management**: For a proper management of Guadua stands, technical assistance was provided to 619 farms or 2,360 hectares under Guadua forest. Consequently these stands are now managed under lineaments established in the Norm and TRMHGS.
- **Voluntary forest certification for small farmers**: The process of forest certification started earlier in the framework of the project “Manejo Sostenible de Bosques en Colombia”. The forest certification has been promoted under the principles of the Forest Stewardship Council (FSC). In addition, specific standards were elaborated for guadua stands. In the first stage, about 26 ha from 5 farms and one organization were certified. During the Bosques FLEGT project, an additional 27 hectares and an enterprise were certified. Currently it is also possible to commercialise transformed Guadua products with the stamp of FSC.
- **National strategy of forest prevention, monitoring, control and alertness**: The objective of the strategy is to establish guidelines and actions to articulate the preventive, juridical, administrative and operative aspects. These correspond to the process of the prevention, monitoring, control and alertness associated to guadua forest management.

- **Intersectorial agreement for legal timber in Colombia:** The Bosques FLEGT project promoted an intersectorial agreement to purchase the use of legal timber. The agreement was signed by 23 public and private organisations in the country. Additionally, specified agreements were signed by individual states (Caldas, Risaralda, Quindío, Tolima and Norte de Santander). As part of this agreement, a successful campaign was launched to raise awareness amongst purchasers with respect to timber legality.
- **Strengthening of forest control and alertness:** the state committees of forest control and alertness were strengthened by means of institutional coordination,. As a consequence, activities of control and alertness increased 136% between 2007 and 2009 and infractions increased with 39%. Nevertheless, timber confiscation decreased with 9%. However, a survey showed that 96% of purchasers would only accept legally produced timber.
- **Operation of forest solution centres:** Those farmers involved in the project, received machinery and tools to improve their production capability. Furthermore two forest business offices were opened to contribute to improving the market possibilities.
- **Support to enterprises of timber transformation.** Technical assistance and consultancy was provided to enterprises of timber transformation. Consequently, 17 enterprises managed to increase their employment by 63%, the productions of transformed products by 43% and income by 55%.
- **Conformation of Forest Management Units (FMU).** FMUs were suggested as a result of forest planning process, and a proposal for the establishment of a FMU was consolidated within the Bosques FLEGT project. FMU initiatives were considered for three different states , being a FMU with 260 hectares of Guadua for Risaralda, 156 hectares for Quindío and 103 hectares for Tolima were defined. Each proposed FMU was qualified in terms of potential guadua production, farms that could be integrated into the FMU and operation schemes. Biophysical and socio-economic aspects were also integrated during characterisation of the proposed FMU.

Legislation, silvicultural practices and strategies of forest management have considerably contributed to the improved situation of the guadua sector in the coffee region of Colombia. The key issues for the development of guadua sector are almost all consolidated in policies, while instruments and tools are provided for better management of guadua stands. Stakeholders that are involved in each link of the production chain have been provided with tools, technical assistance, certification schemes and a proper legislative framework. Besides these improvements, efforts should now focus on further development of market options.

Guadua bamboo forests supplied products to timber market in the coffee region as well as in other regions of Colombia during several decades. Stakeholders received profits and the guadua production chain has sustained economy activity in the region, which were at times affected by problems with others products such as coffee. The possibilities to obtain different products at the harvesting site also led to important

social effects. All aspects associated with integral chain management have been considered and increased sustainable development is foreseen for the near future.

3.4.3 Planning of guadua bamboo forests in the coffee region

Estimates for the land capability and potential areas for establishment of guadua plantations in the coffee region (approximate total area of the region is 5.8 million hectares) have been previously reported by (Camargo, 2007a). A total of 24 variables were used for the analysis develop of a model for land capability. These variables were associated to five factors, which represent site conditions: topography, climate, soils, landscape ecology and socio-economics. By using a simple decision model based on the above mentioned five factors, it was feasible to define four classes of land capability: low, marginal, moderate and high (**Figure 20**). Only 2% of the evaluated total area (470,000 hectares) resulted to have a high capability for guadua production, with sites located close to urban centres. The main limitation for guadua production was the lack of access roads and the absence of a local market. Furthermore areas above 2000 meters of elevation were immediately excluded, because guadua does not grow well under these conditions (**Figure 21**).

Figure 20: : Estimated land capability for the establishment of commercial Guadua stands in the Coffee region of Colombia

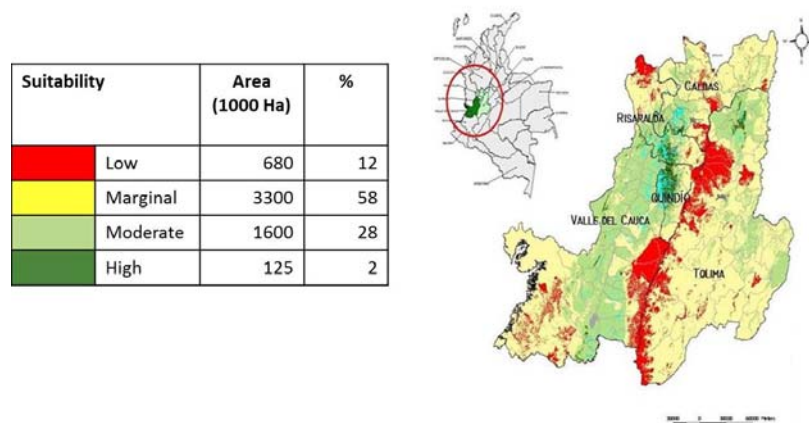
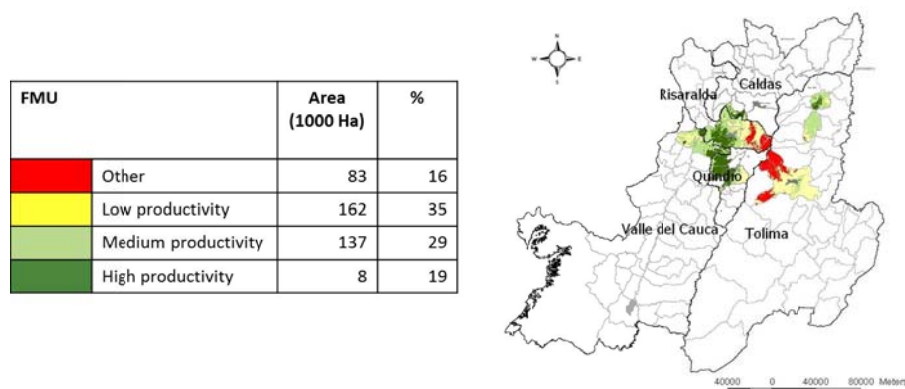


Figure 21: Definition of Forest Management Units (FMU) for guadua bamboo forest in the coffee region of Colombia.



Regarding Forest Management Units (FMU), areas defined at the category of high productivity represented 19 % of the total area analysed. Due to the characteristics of FMU in this category, it is feasible to develop intensive programs of forest management, since all aspects confirm a favourable level. Other FMU, with categories of moderate and marginal productivity, could potentially become of high productivity. This can be achieved when harvest volumes increase and if conditions such as access are improved.

Guadua stands located within FMU were qualified in terms of productivity, quality and as potential protected areas. Consequently, the conformation of a FMU is an important strategy to promote the management of small guadua stands. The fragmented pattern and small size of guadua stands could be a drawback. However, these forest areas are to be included as a part of FMU and integrating these can therefore be an opportunity for better forest management and a reasonable strategy of forest planning. Moreover, management and marketing of guadua culms will then be incorporated within a FMU plan, in accordance with specific characteristics of FMU.

Within the FMU it is possible to have productive areas without affecting other vegetation types or agricultural areas, such as the production of coffee, bananas and fruit crops.

Figure 22: Guadua forest close to banana production



3.5 Bamboo properties

The physical and chemical characteristics of bamboo largely depend on species, cultivation site, age, and section of the plant. This section presents an overview of the main properties of bamboo based on literature data as well as results that were obtained during this project, being detailed chemical analyses of selected bamboo species.

3.5.1 Maturity stages

The maturity of bamboo culms is the result of a primary growth process through which the culms reach the maximum diameter and elongation of the internodes, and afterwards harden up through the lignification (Liese, 1998). The elongation occurs during the first months, although maturity is only reached at a later stage (Judziewicz, 1999). For bamboo species the lignified fibres found in the wall provide the internal support and are responsible of the hardness of the culm (Liese, 1998), which has a composition of around the 50% of parenchyma, 40% fibres and 10% of vascular bundles (Liese, 1998).

When bamboo inventories are carried out, the structure of stands can be represented according to the percentage of culms in different stages of maturity (Arias.L.M., 2008; Camargo, 2006). Culm maturity and culm quality are closely related to each other; culm quality can be expressed through physical and mechanical properties which change with the maturity, this relationship has been studied by (Gritsch, 2004). However, the maturity of the culms has been traditionally determined in accordance to its external characteristics such as colour, the presence of lichens or fungus (Londoño, 1998);(Camargo, 2006). The characteristics that traditionally define culm maturity are shown in **Table 5**.

Table 5: Characteristics of guadua culms according to the different stage of maturity (adapted from (Camargo, 2006)).

Stage of maturity	Illustration
Shoots This state begins since the new culm emerges until it reaches its maximum elongation. The shoots are always protected by caulinar leafs (Londoño, 1998)). Time in this stage is about 6 months.	
Young It begins when the caulinar leafs fall. The colours of the culms are intense green and the development of branches and foliage (Londoño 1998). Time in this stage is from 11 to 15 months.	
Mature This state is characterized by the change of colour from the culm from intense green to opaque green, becoming grey as lichens and fungus grow over its surface. In this stage the culm is available to be harvested (Londoño 1998). Time in this stage is between 17 and 20 months.	
Over-Mature The culm starts to decay and pink fungus appear on its surface. (Londoño 1998). However these culms can also be harvested for commercial purposes. Time in this stage is from 60 to 88 months.	
Dry The culms become yellowish and the branches and leafs dry out. This is the last state of maturity and afterwards the culms die. These culms are harvested but usually don't have commercial value. Time in this stage is between 9 and 10 months.	

3.5.2 Anatomy, fibres, sugars and maturity

Unlike trees where it is possible to relate the age with its dimensions expressed through dendrometric characteristics such as diameter or the height, bamboo species as guadua reach their maximum elongation in their early stage of maturity (Camargo, 2006); (Judziewicz, 1999). However, during these first months only small changes can be observed as a result of the meristematic maturation within the internodes (Liese, 1998).

According to (Liese, 1998), the chemical and structural patterns of culms are more significant when correlated to the age, because the percentage of hemicellulose and cellulose have a tendency to decrease in older culms. (Liese, 1998) also found an increase in the thickening of the fibres of the wall during the maturing of the culms of *Phyllostachysviridi-glaucsesen*. Furthermore (Xiaohong, 2005)also observed variations in the thickening of fibre within culms with the ageing, increasing quickly during the first four years and then diminishing.

According to (Liese, 1998), the properties of culms are determined by the anatomical structure. Culms have nodes that provide transversal interconnections and internodes where the cells are axially oriented. Inside the nodes there is an intense ramification of the vessels and the phloem. These start to curve radially towards the interior and provide the transversal conduction through the nodal diaphragms, in a way that all the parts of the culms appear intertwined.

The external part is formed by two epidermal layers, being the intern thickener and highly lignified. While the more external ones are covered by a skinned layer with wax on top of it. The internal parts have a great number of cells of esclerenquima, which prevent the lateral movement of the liquids. The passages for liquid penetration are in principal the unions of the culms (Liese, 1998).

The anatomical structure of culms is determined by the form, size and number of vascular bundles. In the periphery zone of the culm the vascular bundles are smaller and numerous, in the internal parts these are large and more scarce (Gritsch, 2004).

According to (Londoño, 2002) the tissues in guadua culm show a defined pattern of distribution, both horizontally and vertically. The parenchyma and the conductive tissue are more abundant in the inner part of the wall, while in the outer part the presence of fibres is significantly larger. In a vertical direction, the quantity of fibres increases from the base to the top, while the parenchyma decreases. On average the culm of guadua is formed by 40% fibre, 51 % parenchyma and 9% vascular tissue.

Figure 23: Anatomical structure of *Guadua angustifolia* culm: a. transversal section; and b. detail of vascular bundle. (Londoño, 2002)

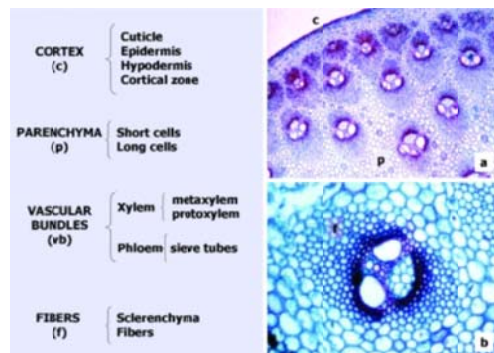


Figure 24: Cross section of *Guadua angustifolia* culm. Cortex; b. detail of stomata; c. detail of silica cell (100X) (Londoño, 2002)

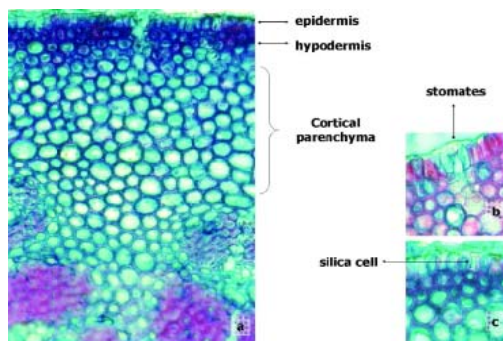
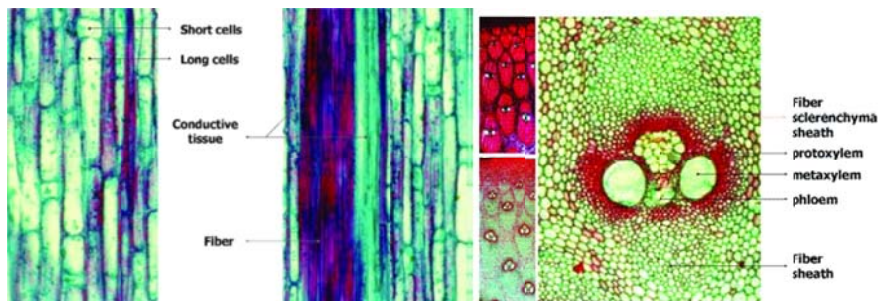


Figure 25: A. Longitudinal section. B. Vascular bundle detail (Londoño, 2002)



Londoño et al. (2002) found that the fibres are characterized by its thin, long and sharpened shape in both extremes, and are sometimes bifurcate. Its longitude has influence over the strength of the culm and the possibilities of using it for paper pulp. Leaf sheaths of hipostomatic fibre surround the vascular bundles (phloem and xylem)

and these are different in size, form and location, depending of the species, age and its location on the culm.

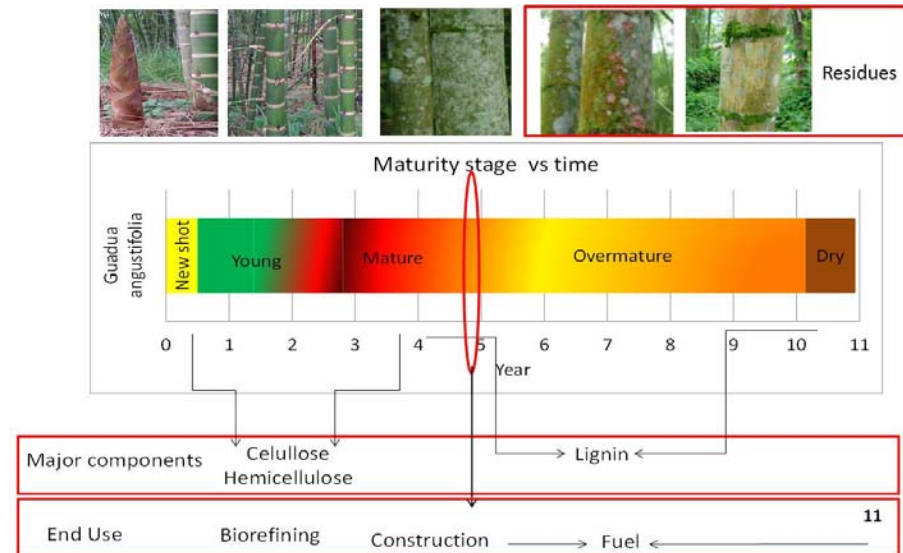
According to (Liese, 1998) the age of the culm is also related to the storage and mobilization of carbohydrates. In the young culms starches are not stored because these are easily consumed in metabolic processes. However, in the old culms grains of starch can be observed in the cells of the fine tissue of the parenchyma.

The lignin regulates the hydration of the hydrophilic molecules within the cellular walls of plants and additionally contribute to the strength and protection against attacks of pathogens and herbivores [Mosquera, 2010]. For industrial purposes, lignin content is highly relevant to define the proper use of culms.

Carbohydrates and lignin can be used to describe the association between the chemical content of the culms and its maturity. The carbohydrate content tends to increase up to three years of ageing after which it decreases. Lignin on the contrary tends to increase with the time and highest values are reached between 4 and 5 years. These results also contribute to the understanding about changes in physical and mechanical properties that vary in a similar fashion like lignin. For this reason, the quality expressed in terms of strength can be explained through the lignification process that occurs during the first 4 years after the culms emerge. Furthermore upon decreasing carbohydrate content the culms are less susceptible to insect attacks.

The information related to composition and maturity stages is of great importance for decision making during management of guadua forest, and to identify current and potential applications within different sectors (see **Figure 26**).

Figure 26: Feedstock potential for different applications according to maturity stage {Daza, 2013 55092 /id}



The figure above illustrates the potential applications in a bio-based economy in accordance with the maturity stage when guadua culms are harvested.

3.5.3 Physical-mechanical properties and maturity of the *G. angustifolia* culm

Physical and mechanical properties of bamboo culms vary according to the species, the stage of maturity, the method employed for culm selection before harvesting and site conditions {Camargo, 2006 54665 /id}. The optimal stage of maturity for construction applications, is close to five years ageing. This age was identified based on compression and shear strength test results. However, as a proper and realistic practice the labelling of culms just after these emerge is recommended; after five years the labelled culms can be harvested.

According to the research conducted by the Universidad Tecnológica de Pereira about **“Technologies to define the maturity of the *G. angustifolia* culm: a contribution to the forestry development of the Colombian coffee region”** several conclusions on maturity and properties of the culms were drawn:

- The compression and shear strength are directly related with the maturity of guadua culms. Values for these properties increase with ageing and peak at about 60 months. This is also confirmed in the norm NTC 5300 which indicates that maturity is reached after 60 months ageing.
- Physical and mechanical properties of guadua culms are comparable with those of tree timber species employed for structural applications such as pine, teak or saman.
- The hardness and wood density were measured, although these variables did not show any correlation with ageing.
- Changes in physical and mechanical properties of culms, as well as the chemical composition illustrate the potential use of culms for different purposes at different stages of maturity (see **Figure 26**).

3.6 Chemical composition

Different culm samples of 5 selected species have been analysed with respect to the chemical composition. These samples were collected from different sites in Colombia, mainly from botanical gardens and collections. The selection criteria of the species are presented in section 3.4. The results from the biochemical analyses and the proximate ultimate analyses are presented in **Table 6**, **Table 7**, and **Table 8** and are compared with selected agricultural residues (wheat straw) and wood feedstocks (willow).

3.6.1 Culm composition

Selected species of culm samples were subjected to a different set of analyses at ECN and the results are presented in **Table 6**. The Technological University of Pereira, carried out a study to determine the lignin content of the six bamboo species considering different stages of maturity; these results are presented in **Table 7**.

Table 6: Biochemical analyses of bamboo species

Specie		<i>Guadua angustifolia</i> ^a		<i>Bambusa vulgaris</i> var.	<i>Dendrocalamus strictus</i>	<i>Guadua amplexifolia</i> ^a Presit
Maturity stage		Young	Mature	Mature	Mature	Mature
Extractives	Water (ash free)	7.74	5.63	15.03	9.26	15.35
	Ethanol	2.96	1.25	1.42	1.19	2.26
	Total	12.23	10.21	18.02	11.97	21.21
Polysaccharides	Arabinan	0.66	0.60	0.69	0.67	0.59
	Xylan	16.38	13.95	16.62	15.34	13.47
	Mannan	0.00	0.00	0.00	0.00	0.00
	Galactan	0.23	0.14	0.16	0.14	0.24
	Glucan	41.29	40.21	36.04	36.60	32.16
	Rhamnan	0.00	0.00	0.00	0.00	0.00
Lignin	AIL ³ - ash	20.27	23.72	21.22	24.80	19.17
	ASL ⁴	0.90	1.00	0.87	0.82	1.09
Ash	As (% dw)	4.04	5.25	2.91	5.69	4.43

Table 7: Acid Insoluble Lignin content for the selected bamboo species at different stages of maturity

Species	Age (months)	Lignin (%)	SD
<i>Bambusa vulgaris</i>	24	23.8	1.4
<i>Bambusa vulgaris</i>	36	23.3	0.4
<i>Bambusa vulgaris</i>	48	23.9	1.2
<i>Guadua amplexifolia</i>	24	28.9	1.6
<i>Guadua amplexifolia</i>	36	29.0	1.5
<i>Guadua amplexifolia</i>	48	25.9	0.1
<i>Dendrocalamus Strictus</i>	24	28.9	0.5
<i>Dendrocalamus Strictus</i>	36	26.7	0.7
<i>Dendrocalamus Strictus</i>	48	31.1	1.4
<i>Chusquea Subulata</i>	36	31.6	1.7
<i>Chusquea Subulata</i>	36	25.9	1.4
<i>Chusquea Subulata</i>	36	22.6	1.1
<i>Guadua angustifolia</i>	24	23.7	2.34
<i>Guadua angustifolia</i>	36	22.7	2.35
<i>Guadua angustifolia</i>	48	29.3	2.50

³ AIL: Acid insoluble lignin

⁴ ASL: Acid soluble lignin

According to the results, the insoluble lignin in the culm of bamboo species varied between 20% and 30%, which places bamboo at the high end of the normal range of 11-27% reported for non-woody biomass and appears to more closely resemble the ranges reported for softwoods (24-37%) and hardwoods (17-30%). This would suggest that bamboo should have similar physical properties and uses as conventional softwoods and hardwoods. Its high lignin content contributes to the relatively high heating value of bamboo, and its structural rigidity makes it a valuable building material (Scurlock, 2000).

Similarly, the glucan content of 32-42% is comparable to the reported cellulose content of softwoods (40-52%) and hardwoods (38-56%). The cellulose content in this range make some bamboo species a useful feedstock for paper production and processes that convert cellulose to fuels and chemicals (Scurlock, 2000).

The higher lignin contents were observed between 36 and 48 months ageing. This is also consistent with the values registered by Mosquera et al, 2010 for *Guadua angustifolia* between 20% and 38%.

3.6.2 Proximate ultimate analyses

Samples of mature culms of selected species were subjected to proximate and ultimate analyses at ECN, of which the results are presented in **Table 8**.

The proximate analysis and heating value of the bamboo species are comparable to wood. However, the ash content of bamboo is higher than wood and roughly lies in between clean wood and herbaceous material. The ash composition of a solid fuel determines its suitability for thermal conversion; certain ash properties such as the formation of low melting solutions can have detrimental effect on the process. The major inherent ash forming elements in biomass include Si, Al, Ca, Mg, Na, Fe, K, S, and P. Some of these, such as K/Na and Cl cause operational problems such as slagging and fouling in power plants. The high potassium (K) content of bamboo is a known precursor of slagging, fouling and corrosion related issues, as well as agglomeration in fluidized bed systems.

The physical and chemical properties of untreated bamboo as an alternative to coal generally do not meet the stringent fuel specifications of most thermal conversion processes, which holds for most biomass streams with increased ash content. Co-feeding of biomass in pulverized coal-fired power plants and entrained flow gasifiers requires a very small particle size after grinding. Bamboo, like other woody and herbaceous biomass, is tenacious and fibrous, which makes it difficult and expensive to grind. The poor grindability of biomass is one of the limiting factors for large scale biomass introduction. Furthermore its characteristics with regard to handling, storage, degradability and energy density are not favourable in comparison with coal. To an important extent these problems can be solved by pre-treating the biomass in order to increase energy density, grindability and storage capability.

Table 8: Proximate and ultimate analyses of selected bamboo species and other biomass feedstocks

Bamboo species/ other	<i>Guadua angustifolia</i>	<i>Guadua amplexifolia</i>	<i>Dendrocalamus strictus</i>	<i>Bambusa vulgaris</i>	<i>Chusquea subulata</i>	Wheat straw	Wood Willow
Age (years)	5	NA	NA	NA	NA	NA	NA
HHV (MJ/kg)	18.35	18.78	18.73	19.05	18.56	16.57	19.35
Proximate & ultimate (mass fraction %, dry fuel)							
Volatiles	74	74	75	76	74	71	81
ash @ 815°C	4.9	3.8	5.6	2.7	6.9	7.8	1.5
C	47.00	47.00	47.00	48.00	46.10	43.82	44.70
H	5.90	6.00	5.90	6.10	5.40	5.28	5.70
N	0.70	0.80	1.20	0.60	0.80	0.42	0.20
O	42.00	43.00	41.00	43.00	42.20	43.31	46.15
S	0.07	0.19	0.16	0.05	0.13	0.11	3.00
Cl	0.11	0.09	0.04	0.02	0.12	0.27	0.01
Ash composition (mg kg ⁻¹ fuel, dry fuel)							
Si	16453.0	6209.0	21105.0	7570.0	20259.6	20271.0	69.1
Na	6.3	11.8	13.5	5.0	13.5	48.3	127.2
K	10684.0	16402.0	3656.0	6907.0	7158.4	15466.0	1420.0
Cl	1086.0	859.0	438.0	213.0	1205.0	2682.0	100.0
S	736.0	1861.0	1579.0	548.0	1283.0	1100.0	30000.0
As	< 1.4	< 1.4	< 1.4	< 1.4	< 1.4	1.0	0.7
Cd	< 0.1	< 0.1	0.1	< 0.1	< 0.1	0.3	1.9
Cr	1.1	1.1	1.3	1.0	3.0	4.7	2.1
Cu	2.6	3.0	5.4	2.2	9.5	3.7	3.1
Pb	< 0.6	< 0.6	< 0.6	< 0.6	2.1	0.0	1.9
Zn	8.0	22.3	32.7	7.5	31.6	28.7	61.8
P	869.0	1283.0	1786.0	892.0	2766.2	1030.0	651.0
Mg	253.0	290.0	1617.0	225.0	481.9	642.0	378.0
Al	8.5	13.0	5.0	5.9	20.8	109.9	18.9
Ca	260.0	380.0	346.0	215.0	379.5	2282.0	3899.0
Ti	0.5	0.6	0.3	0.5	1.2	1.4	2.1
Mn	2.6	7.4	7.0	4.2	8.9	28.1	12.0
Fe	16.0	20.2	21.7	16.5	53.7	114.6	30.0
Sr	2.1	1.7	1.0	0.6	4.8	8.2	14.4
Ba	2.4	1.2	0.9	0.7	2.9	42.2	1.2

4

Pre-treatment

The basic notion underlying pre-treatment technologies is that the bulk of the biomass and waste streams are not directly available in proximity of the conversion processes, and that the low bulk densities and biodegradability make transport to and storage at these sites relatively expensive. Furthermore the wide variety of biomass and waste streams does not match with the rather narrow range of fuel specifications for feeding systems and conversion processes under consideration.

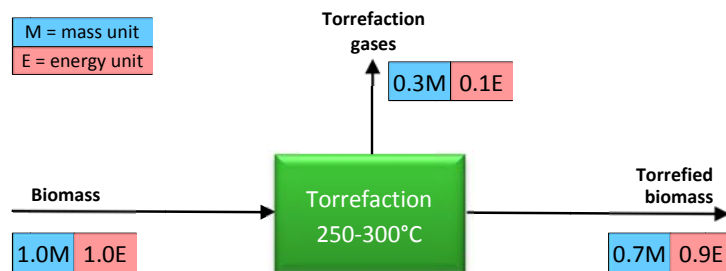
The use of conventional densification technologies as a sole pre-treatment step already offer several advantages. At present, wood pellets are amongst the most desirable solid fuels to be used in biomass-to-energy conversion. The uniform shape and relatively high volumetric energy density is advantageous in transport and logistics, as well as during the conversion into energy products such as electricity and heat. However, wood pellets require dedicated, closed storage and direct co-milling and co-feeding together with coal in pulverised coal-fired power plants is limited to low shares.

Moreover, the production of these pellets is costly and energy consuming, particularly for biomass other than clean sawdust. As such the scope for pre-treating bamboo is wider than densification only, and also takes into consideration thermal pre-treatment by means of torrefaction or alternatively hydrothermal pre-treatment by means of Torwash.

4.1 Torrefaction

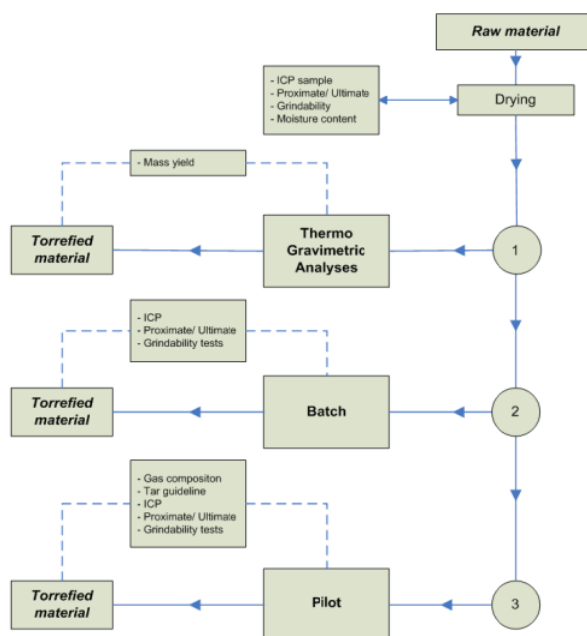
Torrefaction is a promising biomass pre-treatment technology that can be applied to further enhance the biomass quality by addressing the issues mentioned above. Torrefaction is a mild thermal pre-treatment technology used for the upgrading of biomass into a high quality solid fuel. It is performed at temperatures between 250-300 °C in the absence of oxygen. Figure 27 shows a typical torrefaction mass and energy balance for dry biomass. From the dry biomass fed into the process, typically 70 wt% is retained as the solid product, which represents 90% of the original energy content.

Figure 27: Typical mass and energy balance for torrefaction



To determine the influence of torrefaction on bamboo fuel properties, an experimental program was set up as shown in **Figure 28**. It starts with small scale Thermo Gravimetric Analysis (TGA) experiments, to get a first impression of reaction behaviour and mass yield at different torrefaction temperatures. The outcome of these TGA tests are subsequently used as input for batch experiments, where larger amounts of torrefied material are produced. These materials were subjected to proximate/ultimate analyses, as well as the determination of properties like mass and energy yield, lignocellulose composition and milling behaviour. Based on the results of the batch experiments, the optimum temperature for continuous pilot-scale moving bed experiments were selected. The properties of the materials that were produced during these continuous tests were also determined. Furthermore, the continuous nature of the tests allowed extensive characterization of the gases that were produced during torrefaction.

Figure 28: Set-up of the experimental torrefaction program

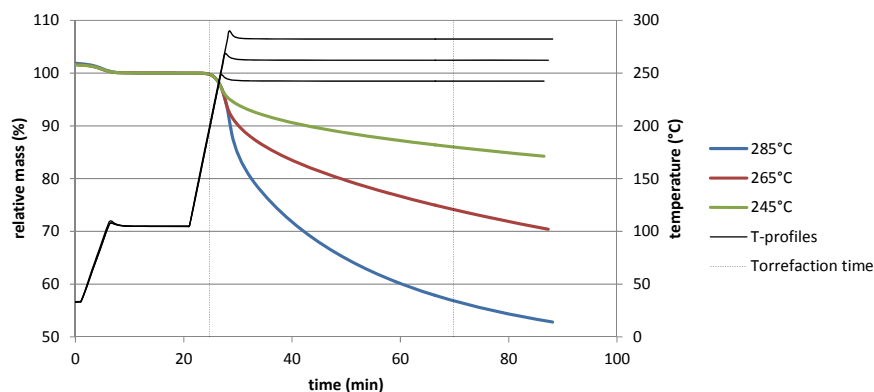


4.1.1 Thermo gravimetric analyses

Thermo Gravimetric Analysis (TGA) comprises a small-scale experiment to determine the mass loss and reactivity of a material under well-controlled conditions. The TGA experiments were performed using a Mettler Toledo TGA850. This TGA850 has a temperature range between room temperature up to 1100 °C and is equipped with water cooling. It has an adjustable heating rate of 0.1-50 °C per minute and a measuring range between 0 and 2 gram. An automated temperature program allows programming of different time versus temperature profiles.

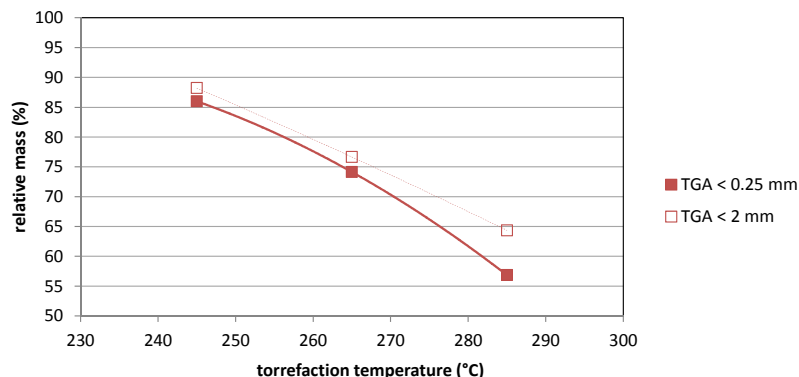
TGA measurements have been performed on both finely ground bamboo (< 0.25 mm) and coarser pulverised bamboo pieces (< 2 mm) using a standard temperature program to reach torrefaction temperatures of 245, 265 and 285°C. In Figure 29 the temperature profiles are shown together with the relative mass for the different measurements. The vertical dotted lines enclose the effective torrefaction residence time of 45 minutes. From an efficiency point of view a mass loss in excess of 30% is undesirable; therefore it was decided to perform the batch scale torrefaction tests at relatively low temperatures (<270 °C).

Figure 29: TGA measurements on finely ground bamboo at different temperatures



The TGA measurements on finely ground bamboo (< 0.25 mm) have been repeated using larger bamboo particles (< 2 mm) and resulted in mass yields up to 6 % points higher at 285 °C (the dotted line in Figure 30). The use of 2 mm bamboo particles leads to a more accurate resemblance with the mass transfer rates that are obtained during batch and pilot torrefaction tests.

Figure 30: Mass yield from TGA measurements with finely ground bamboo and bamboo pieces



4.1.2 Batch scale torrefaction

Batch torrefaction tests were performed in a fixed-bed or batch reactor (Figure 31). The reactor consists of a vertical cylinder with internal diameter of 16.5 cm and effective length of 100 cm. The bed is divided in three sections to distinguish possible differences in torrefaction behaviour across the bed height. Each section is supported by a gas distribution plate.

The reactor is directly heated by supplying preheated nitrogen through a distributor plate at the bottom. In addition, trace heating is applied to compensate for the relatively large heat losses via the reactor vessel that are typical for small-scale equipment. The off-gases are transported to an incinerator. The gas and tracing temperatures as well as the nitrogen flow are computer controlled and all temperatures, pressures and flows are logged to allow for in-depth analysis.

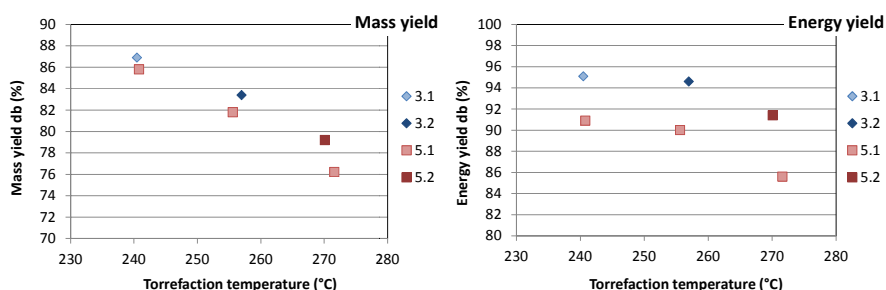
Figure 31: Batch scale torrefaction reactor



Tests in the batch reactor have been performed with *Guadua angustifolia* bamboo pieces at temperatures of 240, 255 and 270 °C. The mass and energy yields for these torrefaction tests are presented in Figure 6, where the first number of each series

represents the age of the bamboo (3 or 5 years), and the second number represents the batch from which the bamboo was obtained. The main differences between the two batches should be the thickness of the bamboo pieces, with the first batch containing pieces of typically 4.0 x 4.0 x 2.0 cm compared to 4.0 x 4.0 x 1.5 cm for the second batch.

Figure 32: Mass and energy yields versus the maximum temperatures during torrefaction



The presented mass and energy yields are given at the average temperatures over the entire height of the batch reactor, which deviates slightly from the defined set-points. A small temperature increase during torrefaction is typically observed, as result of the exothermic nature of the process. For bamboo this exothermic behaviour is already observed at 240 °C, and the effect increases with increasing torrefaction temperature.

However, the stronger thermal effect for bamboo compared to woody biomass is not related to different torrefaction reactions, but to the higher volumetric energy density for bamboo, and as such the higher thermal load in the torrefaction reactor. The energy content of bamboo is relatively similar to woody biomass (typically 18 MJ/kg dry basis) (Table 9), however the bulk density of woody biomass is approximately 40% lower than bamboo (see Table 2).

Table 9: Proximate and ultimate analyses results of untreated and torrefied bamboo

	Ash	H ₂ O	Volatil	C	H	N	O	HHV
	%	%	%	%	%	%	%	MJ/kg
bamboo	(db)	(ar)	(db)	(db)	(db)	(db)	(db)	(db)
3yr old untreated ^[1]	4.3	9.2	77	46	6.0	0.29	44	18.6
5yr old untreated ^[1]	5.4	10.5	75	47	5.9	0.33	43	18.7
3yr old torrefied (240°C)	5.2	0.8	72	48	5.6	0.24	40	20.1
3 yr old torrefied (255°C)	6.2	0.2	68	51	5.6	0.26	37	20.8
5yr old torrefied (240°C)	7.9	0.7	69	49	5.6	0.41	38	19.8
5yr old torrefied (255°C)	6.8	0.1	68	50	5.6	0.37	37	20.5
5yr old torrefied (270°C) ^[1]	7.1	0.2	65	52	5.6	0.35	35	21.0

^[1] Based on analyses of 2 or more samples from different batches

The batch reactor tests could be conducted with rather constant temperature profiles, which resulted in torrefied bamboo samples with a uniform quality (Figure 33).

Figure 33: Torrefied bamboo from the batch reactor tests

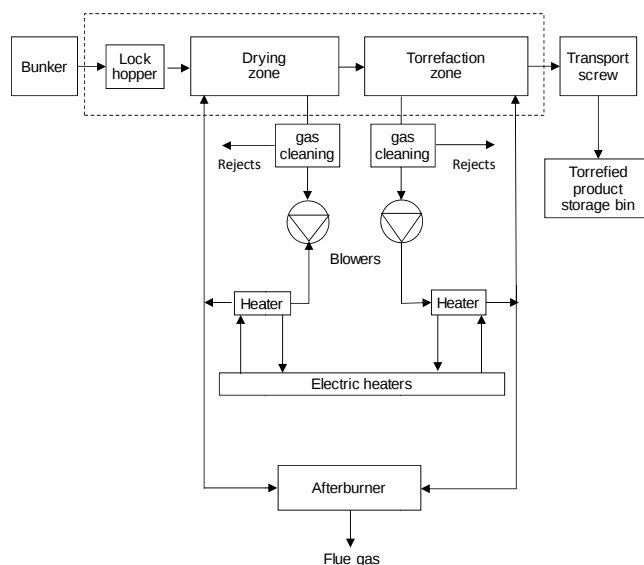


4.1.3 Continuous pilot scale torrefaction

An important part of the experimental torrefaction program were tests using the continuous pilot plant with a production capacity of 50 -100 kg per hour. This plant provides the most realistic results with respect to product quality, reactor control as well as the production and combustion of torrefaction off-gases. The pilot plant at ECN is based on a moving bed technology with direct heating of the biomass materials by recycled product gas (torgas). The same technology is used by ECN and Andritz in the demonstration plant in Denmark, which forms the basis for the future commercial plants to be supplied by Andritz.

A simplified process flow diagram is given in Figure 34. It shows that the chips are fed to the reactor via a bunker and a lock-hopper system that simultaneously prevents that gasses escape from the reactor or that oxygen enters the reactor. The reactor is divided into two parts: a drying section and a torrefaction section. In the drying section the chips are dried (bone-dry) and preheated. The drying heat is supplied to the drying section via a co-current drying gas loop, which is heated electrically at pilot scale to allow for sufficient flexibility at this relatively small throughput.

Figure 34: Torrefaction pilot plant process flow diagram



After drying, the chips enter the torrefaction section where these are heated up to the desired torrefaction temperature and kept at this temperature for a defined period of time. The temperature in the torrefaction section is controlled by a counter-current torrefaction gas loop, ensuring a well-controlled torrefaction temperature, a homogeneous temperature distribution and a well-defined torrefaction time. The torrefied chips are extracted at the bottom of the reactor by means of conveyer screws, and are stored in product bins. After cooling and deactivation the chips are stored in wooden boxes for further handling. The gasses that are produced during the

torrefaction process are combusted in a furnace. Pictures of the system are given in **Figure 35**.

Figure 35: Torrefaction pilot plant pictures



Chips are fed via bunker and belts



Lock hopper on top of the reactor



Product storage vessels



Torrefaction section of the reactor



Control room



Torrefied materials in warehouse

The torrefaction temperature setpoints were selected at 245, 255 and 265 °C, where the torgas inlet temperature was taken as the reference torrefaction temperature. It is not possible to determine the temperature inside the slowly moving bed. The throughput during the tests was constant and in line with earlier tests with woody biomass, i.e. approximately 50 kilograms per hour. During the test the bed height in the moving bed torrefaction zone was reduced with approximately 50% in order to prevent temperature excursions.

The test runs at these temperatures proceeded smoothly; there were no interruptions and lowering the biomass content of the reactor appeared effective to prevent any temperature excursions. The pilot plant was operated for a total duration of 75 hours. In Figure 36 the temperatures are given at three locations in the reactor. Since the bed height in the reactor was reduced, the thermocouples near the top and in the middle of the reactor were located above the bed. Therefore these measured the local torgas temperature, which is lower than the bed temperature due to the cooling effect of the fresh (dry) biomass of 160 °C that is fed to the torrefaction reactor from the top.

Figure 36: Temperature at different levels in the pilot torrefaction reactor

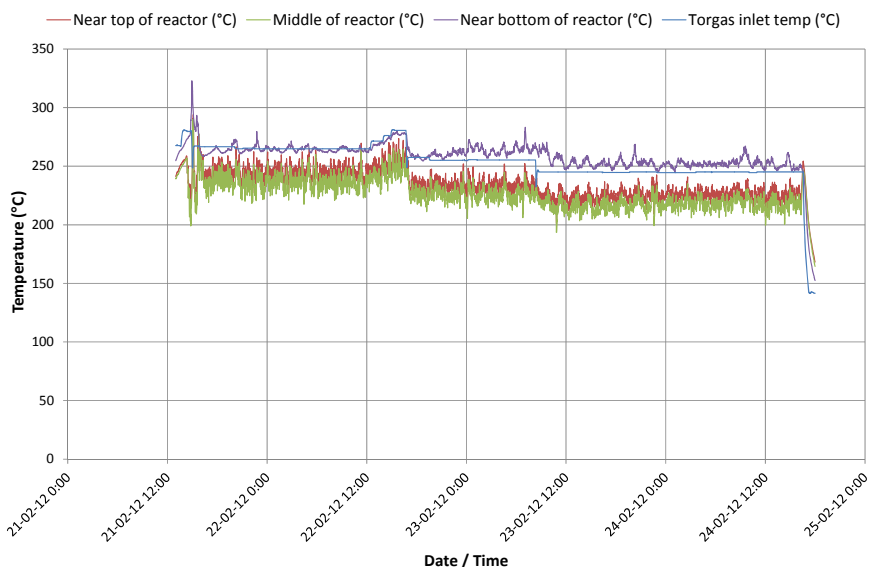


Figure 36 shows that the local temperature in the bed is higher than the temperature of the torgas inlet temperature, which indicates that exothermal reactions take place. In total 3,070 kg bamboo was fed to the pilot reactor, producing 2,002 kg of torrefied material including rejects (Figure 37).

Figure 37: Torrefied bamboo from the pilot torrefaction tests

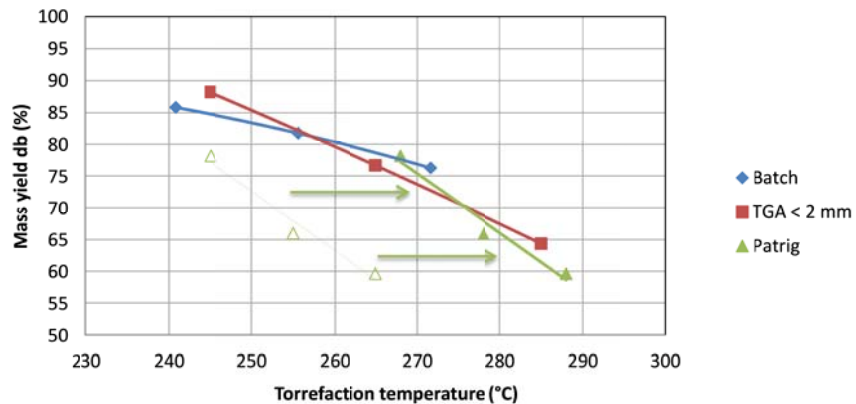


At the end of the batch reactor tests the bamboo pieces were manually removed, which reduces any disintegration of torrefied bamboo pieces to a minimum. During the pilot

scale tests the bamboo is removed automatically from the reactor via screw conveyors. This caused some disintegration of the bamboo as shown in Figure 37.

The colours of the bamboo pieces from the 270 °C batch reactor test and the extracted pieces of bamboo torrefied at 245 °C in the pilot reactor are comparable. Based on this observation and the comparison of mass yield curves (Figure 38) it was confirmed that the bed temperature in the pilot reactor has been higher than the defined setpoint based on the torgas inlet temperature. The actual bed temperature in the pilot reactor has been approximately 25 °C higher than the setpoint temperature. It should be noted that the residence time has been kept the same during TGA, batch and pilot experiments.

Figure 38: Mass yields from TGA measurements, batch and pilot scale torrefaction tests



4.2 Wet torrefaction: Torwash

Torwash is a technology to upgrade biomass, which integrates torrefaction with washing and drying. The technology is particular of interest for biomass streams that contain high alkali and chlorine content. These components typically cause fouling and corrosion problems during thermal conversion, therefore removing these from the biomass can be highly beneficial. Dry torrefaction typically slightly increases the alkali and chlorine content of the product, as a result of the decreasing organic content during torrefaction (see detailed chemical compositions in section 5.1).

Guadua angustifolia bamboo has a relatively high alkali and chlorine content compared to the other evaluated bamboo species. Therefore a screening Torwash test has been performed where torrefaction of wetted bamboo is combined with washing out the inorganic components. The basic idea of Torwash is that biomass is hydrothermally treated in a pressurized vessel, in order to facilitate torrefaction reactions in liquid water at elevated temperatures.

The screening Torwash test has been performed in an autoclave under elevated pressure at 200 °C. Biomass and water are manually placed in the vessel, after which

pressure and temperature are controlled and logged automatically. During the Torwash test the reactor is stirred to obtain optimal mixing of biomass and water. After the test the slurry is drained on a filter, with the remaining filter cake pressed into pellets as displayed in Figure 39.

Figure 39: Batch scale Torwash streams



A total of 1.3 kg bamboo has been torwashed in a 20 litre autoclave vessel at 200 °C for 30 minutes. The bamboo pieces had the same size as during the dry torrefaction, experiments, being 4 x 4 x 2 cm. During the test the material decomposed significantly and formed a ball of fibres on the stirrer. Torwash weakened the bamboo structure more severely than expected and the stirrer apparently had enough impact to break the links between the fibres. The few chunks surviving the Torwash test as one piece could be easily broken by hand.

The slurry obtained from the test drained very well on a filter, leaving a filter cake with 30% dry matter. Compared to other biomass feedstocks that were tested (mainly other grassy materials like straw and hay) this is quite high, a more commonly obtained value is 17%. The total recovery of solid material is 78%, which is also high compared to approximately 50% with grassy feedstocks. The liquid only contained 1% solids, for the more commonly used grassy materials this amounts 4% or more. This means that very little organic material dissolved in the water, on estimate only about 5% of the original dry input. In order to close the solids balance, 17% of the solid mass is missing and probably converted into H₂O, CO₂ or other components that evaporate, in the autoclave or later upon drying.

The cake was easy to compress at room temperature, producing mechanically dewatered cookies with 70% dry matter. The cookies do not expand when the pressure is released, although some expansion was observed upon further thermal drying.

Proximate and ultimate analyses results of the torwashed material are presented in **Table 10** (detailed analysis of fuel quality is presented in Chapter 5).

Table 10: Comparison of raw and wet torrefied (torwashed) *Guadua*

Fuel	Untreated <i>Guadua angustifolia</i>	Wet torrefied <i>Guadua angustifolia</i> (dried cookie)
Moisture %	12	0.06
Proximate analysis (mass fraction %, dry fuel basis)		
Ash @ 850°C	5.1	4.5
Volatiles	75	76
HHV (MJ/kg)	18.81	20.23
Ultimate analysis (mass fraction %, dry fuel basis)		
C	47	50
H	5.9	5.8
N	0.3	0.27
S	0.084	0.026
O	43	44
Ash composition (mg kg⁻¹, dry fuel basis)		
Na (± 7)	3	29.4
Mg (± 1)	218	15.9
Al (± 4)	10	20.61
Si (± 90)	12731	20121
P (± 15)	482	50.7
K (± 20)	9902	510
Ca (± 20)	252	396
Ti (± 8)	0.5	0.75
Mn (± 6)	2	2.1
Fe (± 4)	14	26.14
Zn (± 1)	6.3	2.7
Pb (± 20)	0	0.33
Sr (± 5)	2.2	1.2
Ba (± 5)	2.5	1.34
Cl (± 20)	1395	253

The heating value of the torwashed *G. angustifolia* was higher than that of the raw material. The pre-treated material contains lower concentrations of all its inorganic components, except for silicium (Si) and calcium (Ca). The removal of potassium (K) is 95% and of chlorine (Cl) is 78%. This is a drastic reduction of the inorganic elements that are considered critical to be able to use bamboo as a fuel. As a rule of thumb 500 mg/kg alkalis (K and Na) could be interpreted as a limit for fuels that will not cause any problem during co-firing in pulverised coal-fired power plants, and as such torwashed bamboo closes in on this value.

In addition to alkali removal the Torwash treatment of bamboo demonstrated the following promising results:

- Torwash breaks down the fibrous structure of the material and allows straightforward pulverization.

- A series of single test pellets was conducted, resulting in a pellet density of 1200-1300 kg/m³, which is somewhat higher than obtained for regular torrefied wood pellets, while significantly exceeding the material density and energy density of regular white wood pellets.
- As a result of the Torwash treatment mechanical dewatering is straightforward. On lab-scale, the resulting cake had a moisture content of only 30 wt%.
- The liquid stream is rich in minerals that could be used as fertilizer; this alternative will be further assessed in the near future.

Please note that these results are preliminary and need to be confirmed in larger scale continuous tests.

4.3 Densification

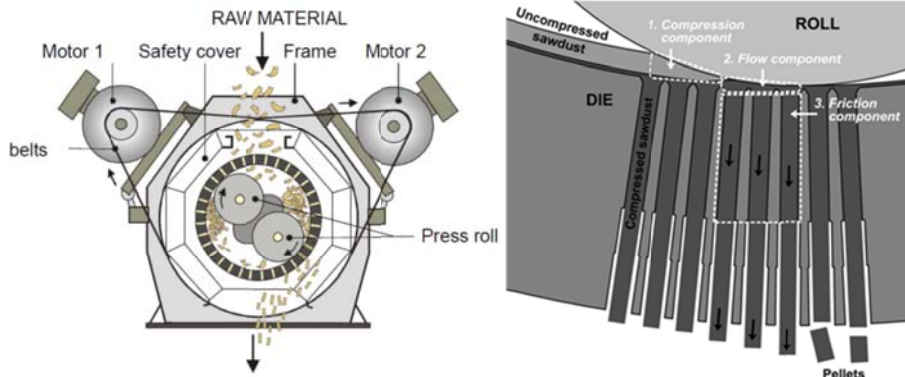
Biomass densification technologies such as pelleting and briquetting have been introduced to overcome the poor handling properties of untreated biomass, being its low bulk density and inhomogeneous structure-. In order to obtain a more standardized product with better handling properties, the torrefied and torwashed bamboo samples have been subjected to densification experiments. The focus during these experiments was mainly on pelleting since the global pellet market has developed quickly and conventional wood pellets are much more abundantly available than briquettes.

A biomass pellet plant typically involves drying and size reduction prior to the densification. Steam conditioning of the biomass is commonly applied to enhance the densification process through softening of the fibres. In case densification is difficult, binders might be added to improve the quality of the product. The lignin that is present as one of the main polymers in the biomass, acts as a binding agent. An increased lignin content typically results in improved pellet qualities and milder densification conditions. However, at the higher side of the temperature spectrum, lignin is partially converted or evaporated during (hydro) thermal pre-treatment and as such additional binders like starch may be needed.

• Pelletisation

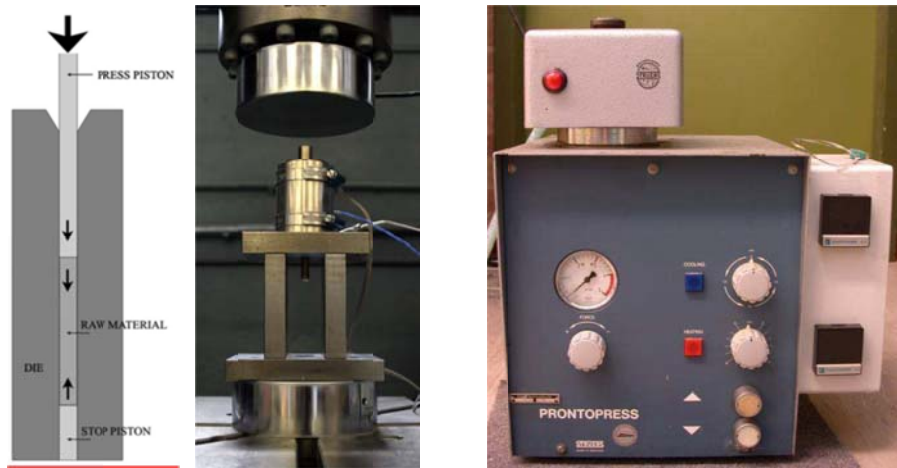
The most common pellet mill contains a ring die and is capable of producing large amounts of pellets with only limited wear of the dies. The ring die mill can be recognized by the circular "ring" shape of the extrusion die. The raw material is fed into the central chamber of the mill, where generally small wheels in the centre of the ring guide the die and force the raw material through the extrusion holes. The diameter of the pellet is determined by the die size, whereas the length is determined by the pellet quality (breaking) or an installed knife (cutting). The principle of a ring die pellet mill is illustrated in Figure 40.

Figure 40: Ring die pellet mill scheme (Stelte, 2012)



The quality of the pellet will depend on the used material, the (added) binder, die characteristics (diameter and length) as well as compression temperature. In an actual mill, the latter is indirectly controlled by changing the friction characteristics by adding steam or oil as lubricants, or by changing the die size. At lab scale, a single pellet press can be applied to investigate the effect of temperature on pellet quality more directly. In a single pellet press (Figure 41) the temperature settings during densification can be controlled more easily.

Figure 41: Single pellet press scheme and pictures (Stelte, 2012)



Experiments were carried out in a single-pellet Prontopress with a piston diameter of 17 mm, as shown in Figure 41. Material is fed batch wise and 3-6 grams of material can be pelletized per batch, depending on the specific weight of the material. The piston is surrounded by an oven, which allows the piston to be heated up to 300 °C. The pressure of the piston press is adjustable between 0 and 1700 barg.

The density after compression is presented as a function of the temperature in the Prontopress in Figure 42. In all cases, the bamboo was ground using a 4 mm sieve before pelleting. The pellets were produced during a timeframe of 2 minutes at a piston press pressure of 650 barg, without the addition of a binder. The curves of the untreated bamboo are slightly different; it was assumed that the bamboo from the

small initial batches for batch scale tests slightly differed from the bamboo from the large shipment sent for pilot scale tests. Furthermore the higher actual operating temperatures during pilot scale torrefaction tests (section 4.1.3) inhibit direct comparison with the batch experiments.

Figure 42: Pellet densities as a function of the pelletisation as well as torrefaction temperature

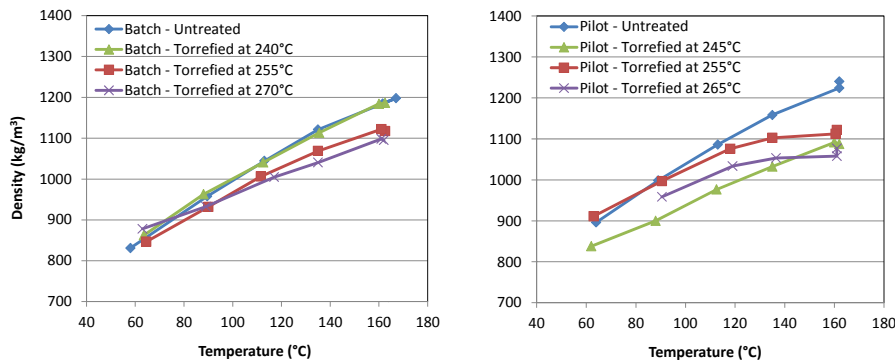


Figure 42 shows that due to torrefaction the density of the pellet reduces. The lignin present in the untreated or slightly torrefied bamboo acts as binder during pelleting, filling up the pores in the pellets and increasing the pellet density. At higher torrefaction temperatures part of the lignin is converted and/or evaporated.

It also can be observed that a higher die temperatures during pelleting can be beneficial. These higher temperatures result in improved lignin flowability in the pellet, although this effect tends to level off at temperatures that approach the torrefaction temperature.

Torwash material was also subjected to single press pelleting at 100-120 °C in the Prontopress. The density obtained was 1280 kg/m³, which is the highest found in all pelleting tests with bamboo. This is attributable to increased lignin retention in the bamboo due to the lower operating temperatures in the Torwash process (200 °C), even though the bamboo structure has been modified. The density of the Torwash pellet is among the highest densities (at this temperature range) ever observed during Prontopress tests at ECN.

In addition to the single pellet tests, bamboo also has been pelleted on a Farm Feed Systems Mini Press ring die mill. This mill with a maximum throughput of 20 kg/hour is constructed for pelleting powdered cattle feed and saw dust. Several dies were ordered with a single row of holes of 6 mm diameter and 15, 17.5, 20, 22.5, and 25 mm length. Figure 43 shows the pellet mill, the die and the control system.

Figure 43: Lab scale ring die pellet mill



With this mill several pelleting tests have been performed, first using fresh wood and later on untreated bamboo and torrefied bamboo. In Table 11 the tests are listed including information on torrefaction conditions, sieve fraction, die dimensions (length and diameter in mm), motor speed (die speed and feed rate on a scale of 0-10), production rate and moisture content of the feedstock (if determined).

Table 11: Tests performed with the lab scale ring die pellet mill (Bamboo: *Guadua angustifolia*)

Nr	Material	Fraction	Die	Speed	Production	Moisture
A	Wood	< 2.0 mm	20.0/6	6.5/1.0		
B	Wood + bamboo torrefied at 255°C	< 2.0 mm	20.0/6	7.5/1.0		
C	Bamboo torrefied at 255°C	< 2.0 mm	20.0/6			15 wt.%
D	Bamboo	< 2.0 mm	20.0/6	6.0/1.0	1.5 kg/hr	4 wt.%
E	Bamboo	< 0.7 mm	20.0/6			
F	Bamboo	< 0.7 mm	15.0/6	6.0/3.5	± 4 kg/hr	
G	Bamboo	< 0.7 mm	15.0/6	7.0/2.5		
H	Bamboo torrefied at 255°C	< 2.0 mm	15.0/6	6.0/4.0		15 wt.%
I	Bamboo torrefied at 255°C	< 2.0 mm	15.0/6	6.0/2.5		15 wt.%
J	Bamboo torrefied at 255°C	< 2.0 mm	15.0/6	6.0/2.5		4 wt.%
K	Bamboo torrefied at 255°C	< 2.0 mm	17.5/6	6.0/2.0		15 wt.%
L	Bamboo torrefied at 255°C	< 2.0 mm	17.5/6	6.0/2.0		4 wt.%

Tests started with fresh wood (unknown origin) with particles < 2 mm. Within an hour long and shiny pellets could be produced. A shorter die was used (20.0/6 mm), because it was planned to switch to torrefied bamboo after starting up. Torrefied wood pellets are normally produced using shorter dies, because of the increased friction in comparison with fresh wood.

The wood pellets were reasonably good, but when slowly adding torrefied bamboo (255°C, pulverised to < 2 mm and pre-mixed with 15 wt% of water) the pellets became darker and the quality decreased. The production speed reduced and after switching completely to torrefied bamboo the pellets were brittle and too wet. **Figure 44** shows pictures of the fresh wood pellets, the mixture pellets and the bamboo pellets.

Figure 44: Pellets from untreated wood, torrefied bamboo and a mixture of both (tests A to C)



Because of the poor quality of the bamboo pellets several parameters have been varied and also pelleting of untreated bamboo was attempted. With the untreated bamboo the pellet mill could be heated sufficiently without blocking and small partly shiny pellets were produced. The natural binding agent present in the untreated bamboo wood and the added water lubricated the die and the mill produced longer and shiny pellets (Figure 45 left). Rough estimates of the achieved densities were $\pm 1250 \text{ kg/m}^3$ (pellet) and $\pm 610 \text{ kg/m}^3$ (bulk).

After successful tests with untreated biomass, torrefied bamboo was gradually added to the fresh bamboo. The bamboo was torrefied at 255°C in the pilot torrefaction reactor. The mill produced more noise than with fresh bamboo, and the produced pellets were rather long and partly shiny, although the durability could still be slightly improved (Figure 45 right). The densities were estimated to be $\pm 1200 \text{ kg/m}^3$ (pellet) and $\pm 570 \text{ kg/m}^3$ (bulk).

Figure 45: Pellets from untreated as well as torrefied bamboo (test F and H)



In additional tests the same torrefied bamboo was used with the addition of 4 wt% water. Manually a lot of water was added to prevent the mill from blocking, but the pellet quality remained the same. Densities were estimated to be $\pm 1150 \text{ kg/m}^3$ (pellets) and $\pm 565 \text{ kg/m}^3$ (bulk). Some of the pellets obtained during these tests are shown in Figure 46. Due to the varying quality of the produced pellets (some pellets are longer and shiny, while others are short and dull) a longer die (17.5/6 mm) was used to increase the friction and as such the temperature during pelleting. Large amounts of

water were needed to prevent the mill from blocking and the produced pellets were rather long but remained dull. Changing to torrefied bamboo with only 4 wt% of water did not result in pellets with the desired quality.

Figure 46: Pellets from torrefied bamboo (tests I to K)



The manual addition of water prevented the mill from blocking, but not enough water could be added to realize an acceptable production capacity of at least 5-10 kg/hr. Too much water caused the biomass to get lumpy and block the mill. Premixing of the biomass with the right amount of water, i.e. about 12 wt%, should reduce the need for manual addition and increase production rates, nevertheless bridging of the wetted material in the feeding bin prevented this improvement.

• Briquetting

The torrefied bamboo from the pilot tests, together with the raw bamboo was sent to the Danish briquetting company C.F. Nielsen A/S for the production of bamboo briquettes.

The delivered materials have been pressed into briquettes of 60 mm diameter and different lengths. The briquetting process has not been optimized for this specific feedstock, but acceptable to good quality briquettes have been produced. No additives have been used besides water. **Table 12** presents more specific data on the briquettes.

Table 12: Briquetting parameters for raw and torrefied bamboo.

Parameter	Raw	Bamboo 245°C	Bamboo 255°C	Bamboo 265°C
Moisture a.r. (%)	10.2	4.8	5.0	4.9
Particle size – min (mm)	1x1	0.1x0.1	0.1x0.1	0.1x0.1
Particle size – max (mm)	10x3	10x1	5x1	3x1
Power consumption (A)	75	85	80	80
Briquette length (mm)	215	200	145	130
Density (kg/m ³)	1122	1047	944	904

Briquetting of the bamboo torrefied at 265 °C was not possible without the addition of water and preferably also a binder like lignin or starch, although the latter was not

attempted. The hydrophobic behaviour still displayed room for some improvements, however it should be noted that the production process has not been optimized and these improvements are considered perfectly feasible. In **Figure 47** pictures of the different briquettes are shown.

The overall quality of the briquettes and especially the briquettes from the 245°C torrefied bamboo was good. Consumer briquettes have densities of 1050 – 1100 kg/m³ and optimizing the briquetting process for torrefied bamboo could lead to even higher densities.

Figure 47: Briquettes from raw and torrefied bamboo.



5

Torrefied bamboo as an alternative to coal

Currently there are no studies on the application of bamboo species *G. angustifolia* in the heat and power sector and the few reported studies on bamboo as energy source (Kumar, Ramanuja Rao I.V.& Sastry, 2002; Lobovic, 2007) mainly refer to other species.

The technical issues related to the final fuel application are of high importance in the assessment of the complete supply chain. The quality and properties of bamboo as a potential biomass source differ according to the bamboo species, its maturity stage, applied cultivation practices, (e.g. fertilizer use), production site, and other factors that affect the specific properties of the material and hence its final application or conversion method.

This chapter presents results on the suitability of bamboo residues of the species *G. angustifolia*, both virgin and thermally pre-treated, as an alternative fuel feedstock for heat and power generation, either pure or in blends with coal. The evaluation includes: determination of specific fuel properties like the chemical composition and grindability, discussed in section 5.1. Additionally, actual combustion and gasification tests to demonstrate the behaviour of the bamboo in end-use utilization are discussed in sections 5.2 and 5.3 respectively.

5.1 Fuel properties

5.1.1 Chemical composition

Samples of *G. angustifolia* were received from FSC certified forest in Colombia.

G. angustifolia samples, not chemically treated, were obtained from a Forest Stewardship Council (FSC) certified forest located in La Esmeralda farm in Montenegro-Quindio, Colombia, in October 2011. The site has the following ecological conditions: an elevation of 1.200 meters above sea level, 2000 mm year-1 average precipitation, 24 °C average temperature and slightly acidic soils (ultisols).

The harvested *G. angustifolia* had different ages, i.e. 5 year old based on the common age when harvested for construction purposes due to its natural strength and 3 year old based on the average time when carbohydrates content decrease and lignin content increases (see section 3.5.2).

A quantity of 4,000 kg of 5 year old bamboo culms was obtained, with 4 to 6 m length and basal diameters of 0.2-0.3 m with an average wall thickness of 0.03 m. The vertical cutting distance above ground level was between 0.15 - 0.3 m. The top section of the culm and leaves were discarded. The average moisture content of a fresh sample was about 30%. The culms were transported to a pre-processing site where chips were cut to average dimensions of 0.05 m x 0.05 m x 0.03 m. The chips were then stored and sun dried in a greenhouse for about 6 weeks reaching a moisture mass fraction between 10 to 13 % in the material. The dried biomass was then shipped to the port of Rotterdam in containers.

The 5 year old samples were subjected to Torwash experiments in a 20 litre autoclave under elevated pressure and 200 °C (see section 4.2). The 3 and 5 year old samples were subjected to torrefaction experiments at atmospheric pressure and 240, 255 and 270 °C (section 4.1). Table 13 shows the results from the product characterization. From these results it is clear that torrefaction has no significant influence on the chemical composition of the material, despite of a slight increase in some minerals concentration. On the other hand, Torwash removes most of the alkali (in particular potassium) and chlorine, and as such the composition is almost compliant to the standards set by the Initiative Wood Pellet Buyers (IWPB) for conventional wood pellets.

Table 13: Fuel analyses of untreated, torrefied and torwashed *G. angustifolia* (Batch tests)

Age (years)	5: Mature					3: Young			IWPB Limits ⁵
Material	Torrefied					Raw	Torrefied		
	Raw	Torwashed	240 °C	255 °C	270 °C		240 °C	255 °C	
Ash @ 815 °C	4.7	4.5	7	6.1	6.3	3.7	4.6	5.6	1-3
Volatiles	77	76	69	68	65	77	72	68	
HHV (MJ/kg)	18.68	20.28	19.78	20.50	21.01	18.63	20.13	20.81	>16.50
Proximate & ultimate (mass fraction %, dry fuel)									
C	46.5	50	49	50	51.5	46.5	48	51	
H	5.9	5.8	5.6	5.6	5.55	5.95	5.6	5.6	
N	0.33	0.27	0.41	0.37	0.35	0.24	0.24	0.26	0.5-1.5
O	43	39	38	37	35	44	40	37	
S	0.09	0.03	0.07	0.07	0.07	0.05	0.04	0.05	0.15-0.4
Cl	0.14	0.01	0.12	0.14	0.11	0.06	0.05	0.07	0.05-0.1
Ash composition (mg kg ⁻¹ fuel, dry fuel)									
Si	13492	20121	25079	22921	22015	12005	16260	19330	
Na	3.4	29	5.4	3	3.1	3.7	2.7	4	
K	10539	510	10266	8868	10525	6401	6096	7530	
Cl	1362	120	1150	1377	1130	1150	548	1150	
S	868	260	691	714	705	492	447	509	
As	<0,68	<0,68	<0,68	<0,68	<0,68	<0,68	<0,68	<0,68	<2
Cd	<0,05	<0,05	0.05	<0,05	<0,05	<0,05	<0,05	<0,05	<1
Cr	1.4	1.3	0.8	0.7	0.8	0.6	0.6	0.5	<15
Cu	2.2	5.8	1.2	1.5	1.9	1.6	1.9	2.2	<20
Pb	<0,24	0.33	<0,24	<0,24	<0,24	<0,24	<0,24	<0,24	<20
Zn	5.2	2.7	8.6	2.6	4.3	3.4	3.6	4.5	200
Others ⁶	1152	747	1257	999	1095	1663	1704	1978	

5.1.2 Grindability

Since the torrefied bamboo should be co-fired in existing coal fired power plants it is important to compare the grindability of bamboo with coal. This will give an indication of the energy requirement for the grinding at the power plant and provides inside in the milling capacity for both materials. Grinding experiments were executed with untreated, torrefied and Torwashed bamboo; the results were compared with earlier grinding experiments with bituminous coal and torrefied willow.

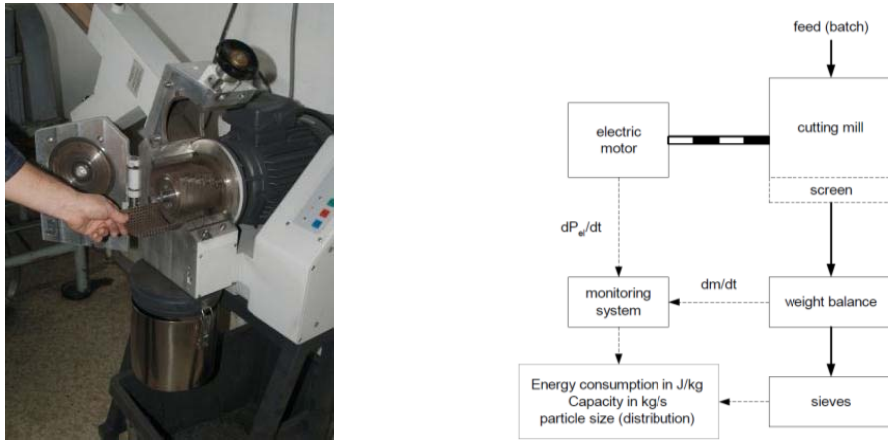
The cutting mill used for these tests is a Retsch SM 2000 heavy duty cutting mill powered by a 2.0 kW_e electrical motor (Figure 48) that runs at a constant speed. Disturbances that occur in the feed rate and feed properties which influence the speed

⁵ (Initiative Wood Pellet Buyers, 2012)

⁶ (P,Mg,Al,Ca,Ti,Mn,Fe,Sr,Ba)

of the motor are compensated by alterations in the power rate of the motor. Hence, the power rate at which the motor operates is a measure for the energy duty required to mill the feedstock. The power rate is registered by a monitoring system (Figure 48).

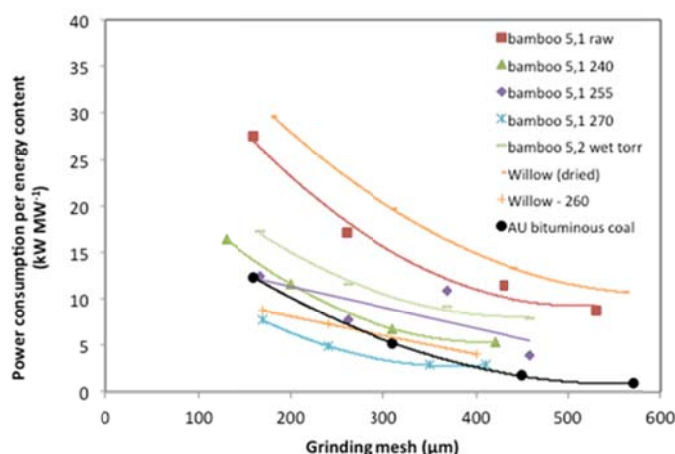
Figure 48: Retsch SM 2000 mill and schematic representation of the cutting mill facility



The feeding system of the mill is a funnel through which the feedstock is fed into the grinding chamber. In this chamber four cutting bars are mounted on the wall together with four series of hammers on the axis. Each series comprises eight individual hammers which are lined in jumped position from each other. The free distance between the bars and the hammers when passing the bars is 2 mm.

The feedstock falls into the milling chamber and is circulated by the hammers. In one rotation, the feedstock passes the four cutting bars. It then either gets blocked between the hammers and the bars and is cut, or it is pressed backwards in the open space between a bar and the hammers. - The resulting particle size of the milled feedstock is regulated by the bottom sieve of the mill, which allows to determine the energy consumption as function of the obtained average particle size (Figure 49).

Figure 49: Relation between power consumption and average particle size after grinding (Bamboo guadua vs. other biomass fuels and coal)



The energy consumption for grinding is presented in Figure 49 for bituminous coal, willow and 5 year old *G. angustifolia* bamboo. Tests were also performed with 3 year old bamboo, though the grindability did not differ significantly. The results for coal and willow were obtained from previous tests (Verhoeff, 2011) in which willow was torrefied at 260 °C after which the grindability was comparable with coal.

As expected the untreated bamboo is more difficult to grind than willow, and as such higher torrefaction temperatures (270 °C or even higher) are needed in order to obtain a similar grindability compared with the bituminous coal and the torrefied willow (260 °C). However, these higher temperatures may also lead to lower efficiencies (section 4.1) and as such higher production costs. Hence, when co-firing torrefied bamboo, the selection of the ideal torrefaction conditions will involve a trade-off between the torrefaction efficiency and the operating costs associated with grinding.

5.2 Technical evaluation of *Guadua* torrefied pellets for thermal power plants

Bamboo presents common fuel characteristics with other biomass feedstocks regarding heating value and chemical composition. At present, there are no studies on fuel properties of the bamboo species *G. angustifolia* for use in the heat and power sector. The scope of this section is the technical evaluation of *G. angustifolia* as a fuel feedstock, both untreated as well as pre-treated (torrefied), and to address the suitability and options to adapt this fast growing crop as an alternative fuel for existing power plants. This requires in-depth knowledge of the crop cultivation, knowledge on the optimum pre-treatment conditions and techniques to introduce this novel fuel into thermal conversion systems, and finally experimental work to evaluate the fuel behaviour in thermal conversion systems. The fuel pre-treatment and the combustion experiments were carried out at dedicated installations at ECN, with the help of specially designed probes for gas and solids sampling. The results on firing and co-firing of the bamboo species *G. angustifolia* are presented, non-pre-treated or torrefied, pure or in a blend with coal, providing predictive data on its combustion and deposition behaviour. The results were evaluated comparatively to data available for other biomass species.

5.2.1 Scope of the work

Combustion is a well-established commercial technology with applications in most industrialized and developing countries. Further development is focused on resolving environmental problems, improving the overall performance with multi-fuel operation and increasing the efficiency of the power and heat cycles. Co-firing is the combustion of more than one fuel in a power plant, a common practice to feed biomass in currently operating power station infrastructures at mass fractions up to 20% and in some cases reaching 50% of the total fuel mass fed. This represents a substantial volume of avoided CO₂ emissions. Co-firing coal with biomass is a proven technology and involves a relatively low capital cost means of increasing renewable energy generating capacity even in harsh economic. Co-firing in fossil fired power stations exceeding 100 MW electric power output takes advantage of their high electrical efficiencies; however dedicated biomass combustion at such scales can still be limited due to the local biomass availability.

The fuels tested at lab-scale were samples of a 5 year old bamboo *G. angustifolia*, virgin as well as thermally pre-treated (torrefied), and El Cerrejon coal from Colombia. The co-firing tests were performed in blends with a biomass mass fraction of 20%, as this fraction represents the common practise in co-firing power plants currently. The heat transfer behaviour was monitored on-line and ash samples were collected and subjected to elemental analyses. The results were evaluated comparatively to combustion data available for woody and herbaceous biomass species.

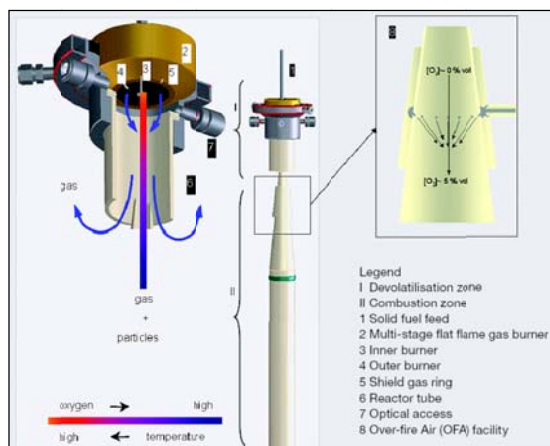
5.2.2 Experimental facility and test procedure

This section describes the test facility and presents lab-scale results on combustion and co-combustion of *Guadua a. bamboo*, either non-pre-treated or torrefied (dry and wet), pure or in a blend with coal (80 wt% coal in blend) and provides insight into the combustion and deposition behaviour and the ash characteristics for these selected coal and biomass blends aiming to suggest technical solutions and/or improvement in the operation of the full scale power plants. The testing includes:

- (1) Deposition and heat exchange monitoring tests
- (2) Ash sampling from the sensor and the fine ash filter

The Laboratory Scale Combustor Simulator (LCS) is schematically shown in **Figure 50**. It has been designed to simulate pulverised fuel combustion and dry-fed, oxygen-blown entrained flow gasification conditions in terms of particle heating rates, reaction atmosphere, and temperature–time history.

Figure 50: Schematic of the ECN's Lab-scale Combustion Simulator (LCS).



Legend: I Devolatilisation zone, II Combustion/Gasification zone, 1 Solid fuel feed, 2 Multi-stage flat flame gas burner, 3 Inner burner, 4 Outer burner, 5 Shield gas ring, 6 Reactor tube, 7 Optical access

The reactor is equipped with a conical inlet, which decelerates the flue gas and char/ash particles, enabling long residence times in spite of a relative short length. The length of the furnace is 1.2 m. The burner consists of two concentric sub burners, a primary inner burner of 0.011 m internal diameter (i.d.) and a secondary outer burner of 0.061 m i.d. The resulting gas particle flow is then drawn into the 0.076 m i.d. alumina reactor tube for complete oxidation of the fuel. The ring-shaped, concentric, staged gas burner through which solid fuels are fed is used to simulate the high initial heating rate, resulting in a very rapid pyrolysis and devolatilisation of particles. The outer burner is a flat flame burner that serves as a source for the appropriate reaction atmosphere and pilots the inner burner through which the particles enter the reactor traveling through a premixed Bunsen-like flame. This provides adequate heating rates (10^5 K/s) to the high

temperature level of e.g. a solid fuel oxidation front (1400-1600 °C), well in range with full-scale pulverised fuel boilers. The staged gas burner provides the possibility to simulate air staging as in low-NO_x burners and also the monitoring of specific combustion products such as SO₂.

Typically low particle feed rates of 0.5 – 1 milligram per second are used in order to control the gaseous environment of each particle by means of the imposed gas burner conditions. The influence of either a certain percentage of replacement of the solid fuel (coal) by biomass or the pure biomass combustion on the total heat release fluctuation and oxygen demand is insignificant.

Since the fuel particles are combusted in a premixed gas flame, the flue gas stream is not generated by the combusting fuel but mainly by the combusting gas (CH₄ and CO). The flue gas composition therefore cannot be directly interpreted but gives a trend and can be evaluated comparatively with other tests carried out under the same conditions.

The flame temperature is controlled by the flat flame gas burner, and external heaters control the temperature profile in the reactor. The calculated average gas velocity is 1.1 m/s in the vicinity of the conical burner, and reduces to 0.2 m/s when the gas enters the main reactor cylinder. Velocity calculations are based on the gas inlet volume flows, assuming laminar flow and taking into account the reactor geometry and the axial gas temperature profile. A suction pump that operates at a constant volume flow rate assures for homogeneous velocities and therefore isokinetic conditions in the reactor.

Boiler tube fouling studies are carried out by applying a horizontal probe placed at 0.850 m from the burner. This probe, with a diameter of 0.015 m, simulates the gas/particles flow around a single boiler tube in the convective section of a boiler. It is provided with a ring shaped heat-flux sensor installed on the horizontal tube as well as with a detachable tubular deposition substrate. The surface temperature of the probe is controlled by an air-cooling system.

Deposition samples can be collected in either the sensor area or the detachable probe surface. When the sensor is used, on-line data on the influence of the deposit on the effective heat flux through the tube wall are collected allowing calculating the fouling factor, which is defined as the inverse of the overall heat transfer coefficient. The ash collected on the sensor is subjected to analyses. It is also possible to collect ash on a detachable substrate and then fix the ash sample with epoxy for further electronic microscope analyses. The carbon-in-ash was determined in all ash samples.

Fuels, test conditions and test plan

Proximate (ash, volatile matter (VM) and moisture content (wt%) – oven / gravimetric) and ultimate analyses (C, H, N, O, S), as well as inorganic elemental composition using ICP/AES (29 elements) were performed on the selected fuels; the results are shown in Table 14. For the elements chlorine, sulphur, potassium and sodium their oxide equivalents SO₃, Na₂O and K₂O were calculated and presented as mass fraction in the ash, in order to facilitate the results discussion in section 5.2.5 concerning the limit values of EN 450 on fly ash utilisation in the cement industry. The fuels were ground to particles smaller than 500 µm to minimise feeding problems. In order to be able to compare the *G. angustifolia* bamboo composition with other biomass species, a representative wood composition is shown, as well as the composition of a herbaceous fuel, an energy crop grown exclusively for fuel production, *Cynara Cardunculus*. Finally, the proposed limit values for the industrial wood pellets are shown, as a relevant reference concerning biomass fuels. These pellet specifications do not include all elements. Table 14 presents comparatively the industrial pellets specifications set by the Initiative Wood Pellets Buyers (IWPB), but these values are not binding for the

users. Power plant operators decide for every fuel separately whether they accept to use it.

Table 14: Chemical analysis of tested fuels

Fuel	El Cerrejon Coal	Bamboo G. angustifolia (5 years)	Dry torrefied bamboo G. angustifolia (5 years) 255°C	Wet torrefied bamboo G. angustifolia (5 years)	Herbaceous crop (Cynara)	Wood	IWPB Industrial wood pellets specifications
Moisture %	4.5	12.0	0.3	0.1	11.0	7.1	< 10
Proximate analysis (% mass, dry fuel basis)							
Ash @ 850°C	10.5	5.1	7.6	4.5	6.2	1.4	
Ash @ 550°C	-	5.7	7.6	4.9	6.2	2.2	1 – 3
Volatiles	33.5	75	65	76	75	80	
HHV (MJ/kg)	26.68	18.81	20.88	20.28	19.00	20.10	>16.50
Ultimate analysis (mass fraction (%), dry fuel basis)							
C	69	47	51	50	42	50	
H	4.6	5.9	5.5	5.8	5.5	6.1	
N	1.11	0.30	0.34	0.27	0.55	0.37	0.5 – 1.5
S	0.802	0.084	0.068	0.026	0.015	0.026	0.15 – 0.4
O	12	43	35	44	43	44	
Ash composition (mg kg ⁻¹ , dry fuel basis)							
Na (± 7)	319	3	3.5	29.4	4100	191	
Mg (± 1)	916	218	169	15.9	1500	404	
Al (± 4)	9210	10	9.5	20.61	160	474	
Si (± 90)	25712	12731	25906	20121	650	1331	
P (± 15)	54	482	513	50.7	910	122	
K (± 20)	1588	9902	9271	510	12000	984	
Ca (± 20)	1695	252	242	396	12000	1919	
Ti (± 8)	470	0.5	0.5	0.75	8,6	96	
Mn (± 6)	42	2	2	2.1	17	66	
Fe (± 4)	5347	14	11.5	26.14	110	301	
Zn (± 1)	20	6.3	4	2.7	13	25	<200
Pb (± 20)	2	0	0	0.33	3,5	8	<20
Sr (± 5)	28	2.2	2.9	1.2	59	11	
Ba (± 5)	85	2.5	3.5	1.34	26	29	
Cl (± 20)	236	1395	949	253	2800	153	0.03 – 0.1%
mass % in ash							
** ⁷ SO ₃	2.02	0.21	0.17	0.065	0.037	0.075	
**Na ₂ O	0.043	0.0004	0.0005	0.0041	0.5535	0.026	
**K ₂ O	0.19	1.2	1.1	0.061	1.44	0.12	
**Cl	0.024	0.14	0.095	0.025	0.28	0.015	0.03 – 0.1%

⁷ ** S, K, Na and Cl expressed as SO₃, Na₂O, K₂O and Cl mass fraction % in ash

From the *G. angustifolia* analyses performed at ECN it is clear that the chlorine content is higher than for wood (100 mg/kg on average), but lower than for the average herbaceous crops. The potassium concentration in *G. angustifolia* with a value of 9200 mg/kg is much higher than in wood. Most other ash forming components are lower than in herbaceous crops and more comparable to wood with a noted exception for silicon. It appears that *Guadua*'s physical and chemical composition may place it in between the herbaceous and woody biomass. This renders it attractive as a fuel, but the high potassium and silicon content must be kept in mind concerning their potential to form ash deposits and reduce heat transfer on the boiler surfaces. As previously shown (section 4.2), the hydrothermal pre-treatment torwash allowed for the removal of 95% of potassium and the 78% of chlorine, which is a relevant improvement of the fuel composition.

Test conditions and test plan

All tests were carried out under the same LCS configuration concerning the gas burner operation, with an air stoichiometry lambda (λ) 20%, and a constant fuel feed rate of 1.1 mg/s to secure proper fuel conversion. Milled biomass and coal was used in the size range of 90-125 μm . One test series was carried out with a torrefied fuel fraction of 180-250 μm in order to monitor the effect of particle size on combustion and burnout properties. The test plan shown in **Table 15** was set up to address the objective of evaluating the bamboo pellets as a coal substitute in power plants.

Table 15: Overview of the tests

Fuels	Blend mass fraction %	Particle Size (μm)
<i>G. angustifolia</i> (untreated)	100	90 – 125
<i>G. angustifolia</i> (torrefied)	100	90–125 & 180-250
<i>G. angustifolia</i> (wet torrefied)	100	90 – 125
Cerrejón coal	100	90 – 125
Cerrejón coal / <i>G. angustifolia</i> (torrefied)	80 / 20	90 – 125

5.2.3 Indicators for the combustion behaviour of fuels

The behaviour of fuels can be evaluated based on various indicators, namely:

- (a) Deposition propensity based on the ash captured on the probe, which is linked to the ash composition but also depends on the reactor dynamics
- (b) Fouling factor, which is directly linked to the thermal conductivity of the deposit.
- (c) Indices based only on fuel composition and not on tests, e.g. fouling index.

Item (c) will be discussed in section 5.2.6.

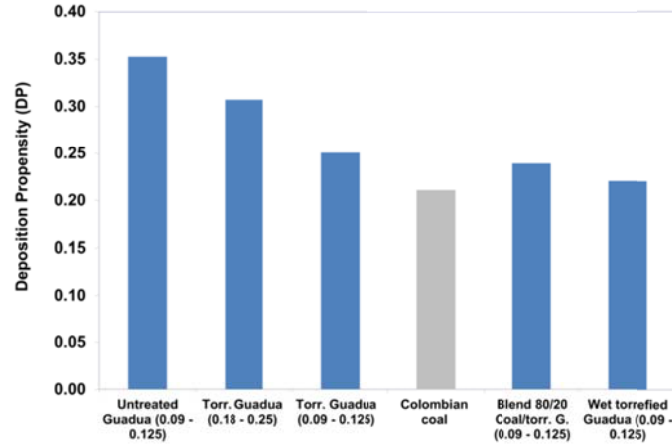
a) Deposition propensity

The ash samples collected in the horizontal probe during the experiments were weighed. In order to assess the deposition behaviour of the fuel, the deposition propensity DP is introduced, defined as the percentage of the ash collected on the deposit probe, m_{dep} , divided by the total ash content in the fuel fed, m_{ash} , as given by the proximate analysis of the fuel.

$$DP = \frac{m_{dep}}{m_{ash}} (\%) \quad (1)$$

The ash mass m_{dep} is the ash deposited on the horizontal probe that was collected after the end of the experiment. The deposition propensity provides insight into the inherent deposition characteristics of the different fuels, as it normalizes the ash deposition in relation with the fuel ash content. The deposition propensity takes into account the fuel ash content, but relies on experimental data as well, rather than only the ash composition. The deposition propensities as calculated from the equation (1) are shown in **Figure 51**.

Figure 51: Deposition tendencies for the tested fuels and blends



It seems that the deposition propensity of the untreated biomass (**Figure 51**) is higher compared to the torrefied biomass, however conclusions cannot be drawn at this point. One could notice that even when subjected to torrefaction, at temperatures well below the combustion temperature, the chemical composition of the fuel ash can change, with respect to volatile species like potassium and chlorine, as shown from the composition in **Table 14**. The potassium and chlorine content are lower in dry torrefied material than in raw material, despite the fact that a mass loss has occurred during torrefaction. In contrast, the content of silicon, an element known to be less volatile, is increased after torrefaction but this tendency is not confirmed for calcium or iron, which are also known to be not volatile. The increase in total ash content in the case of dry torrefaction, appears to be only due to Si, which may indicate that the inhomogeneity of the material is of the same order (or higher) than the effect of torrefaction. Finally, the behaviour of the blend seems to be corresponding to the blend percentage, in other words proportional to the behaviour of the individual fuels that this blend consists of.

Figure 51 also gives some information on the effect of particle size on deposition behaviour, for the size range 180-250 µm vs. 90-125 µm of torrefied bamboo. A higher deposition propensity can therefore stem from larger char particles, which increase the mass of deposit by adding char particles (rather than ash particles). In addition to this, one may notice that the carbon in ash was slightly increased in the sampled deposited ash of this higher particle size, while its ash composition was slightly closer to the original fuel. Both facts indicate that the increased deposition in the case of larger particle sizes could be due to char deposited rather than larger ash particles. It has to be noted however that it could simply be the fact that smaller particles will better follow the flue gas flow whereas the momentum of larger particles cause more particles to bounce onto the sensor tube.

b) Fouling behaviour

Based on the heat flux data measured on-line by the sensor probes, the fouling factor R_f of the tested fuels can be estimated, which corresponds to the heat transfer resistance of each tested fuel:

$$R_f = \left(\frac{1}{U_1} - \frac{1}{U_0} \right) = \frac{T_g - T_c^1}{HF_1} - \frac{T_g - T_c^0}{HF_0} \quad \text{Equation 1}$$

R_f – fouling factor, $K \cdot m^2 \cdot W^{-1}$ (heat transfer resistance)

U_1 – ash deposits heat transfer coefficient after time $t=t_1$, $W \cdot K^{-1} \cdot m^{-2}$

U_0 – initial heat transfer coefficient after $t=t_0=0$, $W \cdot K^{-1} \cdot m^{-2}$

T_g – flue gas temperature, K,

T_c – coolant medium temperature in the deposition probe, K,

HF_1 – heat flux to the sensor after time $t=t_1$, $W \cdot m^{-2}$

HF_0 – initial heat flux to the sensor $t=t_0=0$, $W \cdot m^{-2}$

Sub index 1 refers to the conditions after elapsed time $t=t_1$, while sub index 0 refers to the initial conditions $t=t_0=0$.

The fouling factors of the fuels are depicted in **Figure 52** as function of the ash accumulated on the deposition probe. The moment at which fuel feeding started was considered as the start of the heat flux measurement. In all cases the heat flux, surface temperatures, cooling airflow rate and furnace temperatures were at steady state during measurement. In order to compare the fuel behaviour of *G. angustifolia* (untreated or pre-treated) with other previously used biomass types, the fouling behaviour of an average woody biomass and *Cynara Cardunculus* are shown in the same graph. The wood represents a commonly used woody biomass, and the herbaceous biomass a novel proposed feedstock (DEBCO project, 2008).

Figure 52: Fouling factors versus accumulated feed rate for the tested fuels under air combustion conditions.

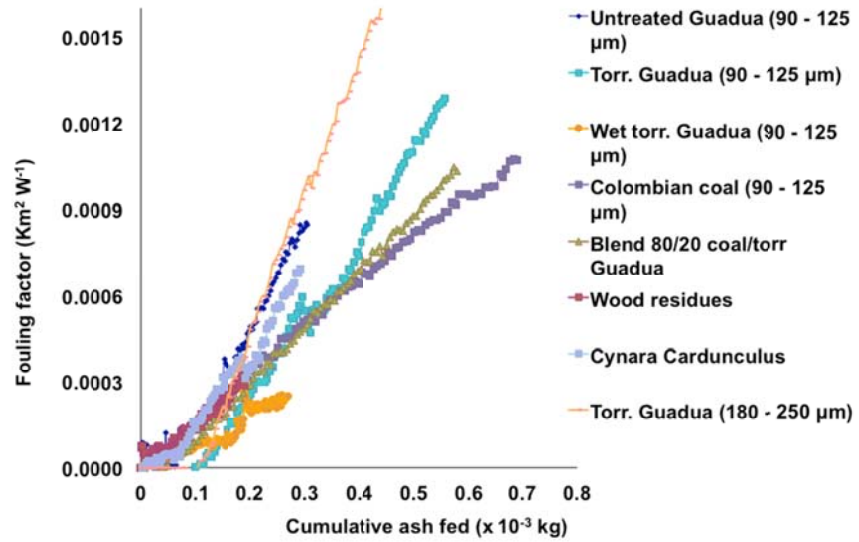


Figure 52 indicates that the untreated bamboo *G. angustifolia* shows more severe fouling behaviour than the dry torrefied Guadua, in accordance with the deposition tendency results. In relation with an average herbaceous fuel, it seems that untreated *G. angustifolia* behaves similar since the fouling factor lines are close, however the wet torrefied *G. angustifolia* shows fouling behaviour comparable to representative clean wood. The coarser sample of dry torrefied *G. angustifolia* displays the highest fouling behaviour, probably due to deposited unburnt char particles or larger ash particles. It must be noted that the absolute values depicted in this graph do not have a practical value, however their relative position to each other gives a comparative evaluation of the fouling behaviour of these fuels.

A final remark is that the slope of the fouling factor lines in **Figure 52** are called *Specific fouling factor* and are described in Equation 2, simply as the ratio between the fouling factor value and the corresponding accumulated ash value.

$$\text{Specific f.f.} = \frac{\text{Fouling factor value}}{\text{Cumulative ash fed (gr)}} \quad \text{Equation 2}$$

This value can be used to give a fast numerical comparison of the fouling behaviour amongst different fuels, rather than graphically and will be used in section 5.2.6.

5.2.4 Fuel conversion and emission behaviour

The results on the carbon in ash in the samples analysed are shown in **Table 16**. The CO, CO₂, and O₂ concentration in the flue gas were monitored continuously. The CO levels were always low, slightly higher than the levels of CO emissions when the reactor is operated on the methane (pilot) flame without fuel, indicating a high fuel conversion. Although the carbon levels were low in all ash samples, a small difference was found between two size fractions of torrefied bamboo, namely the carbon-in-ash was a bit higher in the larger particle fraction, which also may explain the higher deposition propensity and justifying the existence of more char in the deposit.

Table 16: Carbon in ash and flue gas composition

Fuel / Blend	C in ash (mass fraction %, dry) Deposited ash / Filter ash	Flue gas at the exit (CO ₂ %/O ₂ volume %, CO $\mu\text{L}\cdot\text{L}^{-1}$)	NO _x ($\mu\text{L}\cdot\text{L}^{-1}$)
G. angustifolia (torrefied, 180-250 μm)	1.9/2.7	10.7% / 3.5% / 2	90
G. angustifolia (untreated, 90-125 μm)	1.4/1.3	10.5% / 3.5% / 3	85
Coal (fine powder)	1.2/2.2	10.2% / 3.5% / 3	140
Coal biomass blend 80% coal /20% biomass	1.3/3.7	10.7% / 2.9% / 1	137
G. angustifolia (torrefied, 0.09-0.125 mm)	1.4/1.3	10.3% / 3.1% / 4	85
G. angustifolia (torwashed, 0.09-0.125 mm)	1.4/1.5	8.8% / 3.5% / -	80

5.2.5 Chemical composition analysis:

Element enrichment – ash analyses of deposited and fly ash

The behaviour and distribution of the inorganic ash elements was defined and quantified by performing a mass balance including the mass and the composition of the

fuels and the ash samples obtained from: (1) the deposited ash and (2) the fly ash obtained from the filter, which represents the ash that was not deposited on the probe. The element concentrations in the sampled ash are presented as their ratio to the element concentration in the original fuel; this ratio is called elements enrichment or enrichment factor (EF). Therefore, the original fuels are normalised to EF=1 for each of their elements (reference value).

In the paragraphs below, main conclusions are discussed based on the results presented in **Figure 53** and **Figure 54**.

Figure 53: a & b Element enrichment (enrichment factor) of refractory oxides of the filter ash (fine ash) and the sensor ash (deposited ash)

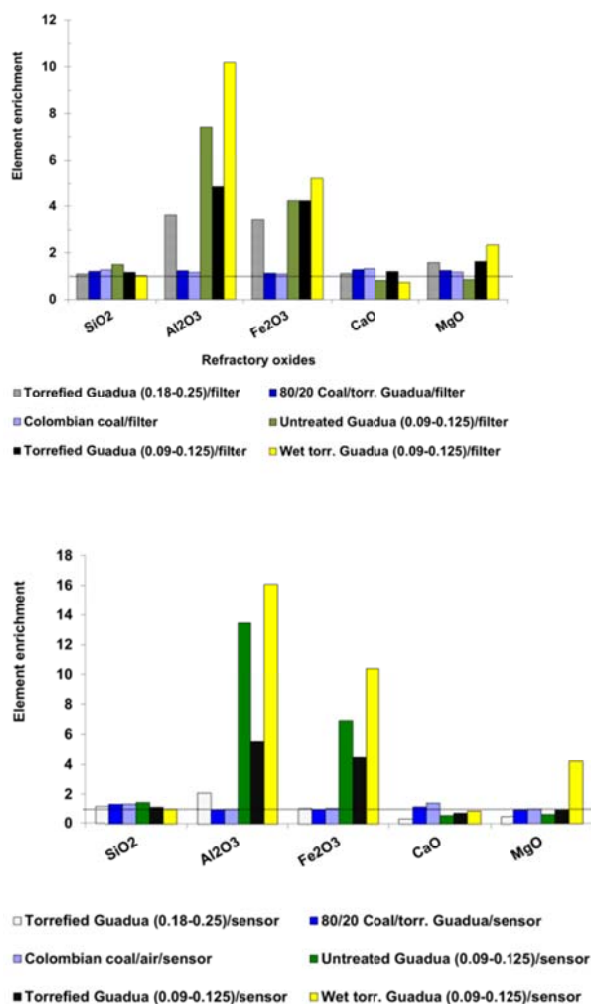
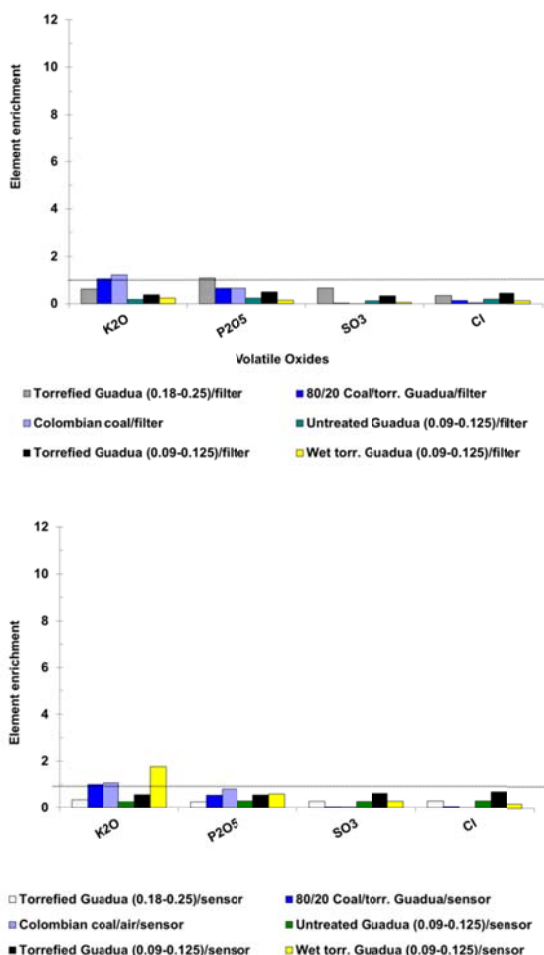


Figure 54: a & b: Element enrichment (enrichment factor) of volatile oxides in the filter (fine ash) and the sensor (deposited ash)



Coal and coal blend: Sulphur and chlorine were depleted in the ash, indicating their release in the gas phase, possibly due to alkali sulphation. The relatively small sulphur concentration and the high silicon content of the fuel ash may indicate that most of the potassium and sodium in the deposit is expected to form alkali silicates rather than bind with sulphur, which is rather released in the gas phase. Alkalis seem to remain in the ash instead of entering the gas phase but not to a level that they enrich the ash compared to the original fuel ash.

Untreated & torrefied biomass: No enrichment for potassium and chlorine is observed, while only negligible amounts of sulphur were detected in the ash of untreated and torrefied biomass. Potassium enters the gas phase probably due to the chlorine that is present, which facilitates the volatilization of elements that would otherwise deposit. From the refractory elements aluminium and iron are present in the ash; the rest of the main oxides are detected at the same levels as in the original fuels before combustion (no element enrichment).

According to EN 450 for use of pulverised fly ash in cement, the relevant limits are chlorine < 0.1 % mass fraction, sulphur as SO_3 < 3.0 % mass fraction and alkali as Na_2O equivalent ($\text{Na}_2\text{O} + 0.658 \text{ K}_2\text{O}$) < 5 % mass fraction. **Figure 54** shows that their concentration in the filter ash is less than it was in the fuel. By comparing the above mentioned EN 450 thresholds with the SO_3 , chlorine and alkali oxide mass fractions (%) shown in Table 2 it can be concluded that the fly ash from the combustion of this particular bamboo species could be considered in the cement industry, however a full evaluation of the fly ash conforming to the EN 450 standard was not carried out.

The depletion of volatile elements in both the filter and the sensor ash in case of dry torrefied material indicates these are entering the flue gas phase, possibly ending up on the economiser tubes, the FGD unit or exiting in the flue gas stream. Gas cleaning measures may have to be taken in case of using *G. angustifolia*, dry torrefied or virgin, using dry electrostatic precipitators (ESP), wet electrostatic precipitators for gaseous acid pollutant control and fabric filters (FF) for high removal efficiency. Removal of HCl from flue gas may be necessary, using hydrated lime injected into the boiler (Ogden, 2010). Concerning the torwashed biomass, it has already undergone serious depletion of potassium and chlorine in the pre-treatment phase, therefore very low concentrations are expected in the flue gas leading to minor or no issues.

5.2.6 Evaluation of alternative bamboo species based on fuel composition

Additional to *G. angustifolia*, four additional bamboo species (*Guadua amplexifolia*, *Bambusa vulgaris*, *Dendrocalamus strictus*, and *Chusquea subulata*) were subjected to proximate, ultimate and ash element analyses in order to carry out a preliminary evaluation based on their compositions. The characterization results are shown in **Table 17**.

Table 17: Fuel composition of alternative bamboo species

Fuel	<i>Guadua amplexifolia</i>	<i>Dendrocalamus strictus</i>	<i>Bambusa vulgaris</i>	<i>Chusquea subulata</i>
Moisture %	11	9.6	9.3	11
Proximate analysis (mass fraction %, dry fuel basis)				
Ash @ 815 °C	3.8	5.6	2.7	6.9
Ash @ 550 °C	4.9	6.5	2.9	7.1
Volatile matter	74	75	76	74
HHV (MJ/kg)	18.78	18.73	19.05	18.56
Ultimate analysis (mass fraction %, dry fuel basis)				
C	47	47	48	46
H	6.0	5.9	6.1	5.4
N	0.8	1.2	0.6	0.8
S	0.2	0.2	0.1	0.1
O	43	41	43	42
Ash composition (mg kg⁻¹, dry fuel basis)				
Na (± 7)	12	14	5	13
Mg (± 1)	290	1617	225	482
Al (± 4)	13	5	6	21
Si (± 90)	6209	21105	7570	20260
P (± 15)	1283	1786	892	2766
K (± 20)	16402	3656	6907	7158
Ca (± 20)	380	346	215	379
Ti (± 8)	1	0	0	1
Mn (± 6)	7	7	4	9
Fe (± 4)	20	22	17	54
Zn (± 1)	22	33	8	32
Pb (± 20)	< 0.6	< 0.6	< 0.6	2
Sr (± 5)	2	1	1	5
Ba (± 5)	1	1	1	3
Cl (± 20)	859	438	213	1205

The fouling behaviour of fuels in a combustion facility can be evaluated based on indicators that conclude experimental findings and on fuel composition indicators. It is mainly the experimental results that can be extrapolated in the larger scale while the indicators based only on fuel composition give rather an overall or general estimation of the expected fouling behaviour. In sections above, there were presented and discussed the Deposition Propensity and the Fouling Factor for the tested fuels and blends based on lab-scale tests. In this paragraph an attempt to evaluate the combustion behaviour is presented based on the fuel ash composition of the bamboo species presented in **Table 17** that were not tested at lab-scale.

The Base to Acid (RB/A) ratio has been introduced for a first assessment of the fouling behaviour of fuels (Ogden, 2010), defined as the ratio between basic to acid oxides in the fuel ash:

$$R_{B/A} = \frac{Fe_2O + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

Equation 3

Where

B = $Fe_2O_3 + CaO + MgO + K_2O + Na_2O$, and

A = $SiO_2 + TiO_2 + Al_2O_3$, the sum of these oxides in weight percentage.

The RB/A provides the base for a first assessment of the potential for slagging and fouling. The fouling index (Fi), referenced in (Ogden, 2010) (Bryers, 1996) is calculated as the product of the base-to-acid ratio RB/A and Na_2O (expressed as mass % in the ash)

$$Fi = RB/A \times Na_2O \text{ (\%, mass fraction in ash)}$$

Equation 4

The classification of fouling potential was determined by (Bryers, 1996):

$Fi < 0.2$ Low Fouling

$0.2 < Fi < 0.5$ Medium Fouling

$0.5 < Fi < 1.0$ High Fouling

$Fi > 1.0$ Severe Fouling

This index is considered to not be easily applicable to biomass fuels, because their ash compositions form different chemical systems compared to the coal ash. The majority of the potassium in coal ashes is present as a constituent of the clay minerals, and is not considered to be available for release by volatilisation in the flame to the same extent as in most biomass materials. In biomass, typically potassium is the dominant alkali metal and present in a form available for release by volatilisation. Therefore, it was

chosen to not base our evaluation on the fouling index, as it would lead to misleading results.

A more useful number is the alkali index (Jenkins, Baxter & Miles, 1998), which has become popular in recent years as a threshold indicator for fouling and slagging for biomass fuels. Even though all biomass fuels exhibit fouling behaviour, the rate and extend differs depending on their quite variable ash composition and ash content. The alkali index, in this paper described as A_i , expresses the quantity of alkali oxide in the fuel per unit of fuel energy (kg/GJ):

$$A_i = (HHV)^{-1} \cdot w_a \cdot (w_{K_2O} + w_{Na_2O}) \quad \text{Equation 5}$$

HHV is the higher heating value in GJ/kg of the fuel (the value obtained from a bomb calorimeter, the higher heating value at constant volume, dry basis), w_a is the mass fraction (dimensionless) of ash in the fuel, w_{K_2O} and w_{Na_2O} are the mass fractions (dimensionless) of the alkali oxides K_2O and Na_2O in the ash. (Jenkins, Baxter & Miles, 1998) have suggested that for alkali index values above 170 g/GJ fouling is probable, and for values above 340 g/GJ fouling is virtually certain to occur. The threshold levels are determined principally on the basis of experience.

Other indicators proposed in literature are the so-called critical molar ratios of the fuels: Ca/S, S/Cl, Al/Cl (Aho, 2013).

The above presented indicators for all tested fuels and novel bamboo species are shown in **Table 18**. Knowing the fouling behaviour (see **Figure 52**) of the tested fuels in the experimental set-up allows for a first evaluation of the effectiveness of the proposed indicators. Based on this evaluation, some comments for the novel bamboo species can be given as to their expected fouling behaviour. **Table 18** shows the deposition propensity (DP) values as obtained from **Figure 51**, the specific fouling factors as obtained from **Figure 52**, and finally the proposed indicators shown in this paragraph. The Specific fouling factor is defined simply as the ratio of the fouling factor value to the accumulated ash value, both values read from the graph shown in **Figure 52** described and explained in Equation 2.

Based on the values of the specific fouling factor obtained from **Figure 52** and shown in **Table 18** it can be stated that the alkali index A_i is in line with the fouling behaviour of the tested fuels. The highest values of Specific f.f and A_i refer to the untreated bamboo, the values are lower for the torrefied bamboo, and even more for the torwashed bamboo. Therefore it can be assumed that a first, preliminary evaluation of the non-tested fuels is possible based on their fuel composition. From the untested fuels, *G. amplexifolia* seems to be the worst candidate based on its A_i values. Given the fact that values A_i within the range 170 – 340 g/GJ indicate low to medium fouling, the species *D. strictus* may prove better than the rest. However, even though *B. vulgaris* shows A_i values that are not very favourable, it is a promising fuel in terms of ash composition as it conforms to the IWPB specifications especially concerning Cl and ash concentration (**Table 14** and **Table 17**).

Table 18: Alkali index, critical molar ratios and specific fouling factors of tested fuels and alternative bamboo species

	A_i	Ca/S	S/Cl	Al/Cl	Specific f. f. $Km^2/(Wgr_{ash})$
Tested fuels					
<i>G. angustifolia</i>	0.67	0.24	0.68	0.01	$2.9 \cdot 10^{-3}$
Dry torrefied <i>G. angustifolia</i> .	0.52	0.28	0.81	0.01	$2.4 \cdot 10^{-3}$
Coal El Cerrejon	0.09	0.17	37.2	50.6	$1.5 \cdot 10^{-3}$
Blend Coal/ Dry Torr. <i>G. angustifolia</i> 80/20	0.17	0.19	29.9	40.5	$1.8 \cdot 10^{-3}$
Wet torrefied <i>G. angustifolia</i>	0.03	1.20	1.18	0.11	$8.9 \cdot 10^{-4}$
Wood	0.09	5.9	1.86	4.02	$9.1 \cdot 10^{-4}$
<i>C. cardunculus</i>	0.88	6.4	0.59	0.07	$3.1 \cdot 10^{-3}$
Other bamboo species					
<i>G. amplexifolia</i>	0.94	0.16	2.47	0.02	-
<i>B. vulgaris</i>	0.41	0.32	2.75	0.04	-
<i>D. strictus</i>	0.21	0.18	3.77	0.01	-
<i>Ch. subulata</i>	0.49	0.17	1.16	0.02	-

Concerning the other three indicators Ca/S , S/Cl , Al/Cl (Aho, 2013), a high Ca/S ratio (>3) indicates effective SO_2 autocapture, which is the case in wood and *C. cardunculus*, probably due to the very low sulphur concentrations, but not in the bamboo species under consideration. The surplus of sulphur is available for other reactions and potentially emitted as SO_2 . In the case of the S/Cl ratio, values <4 indicate corrosion risk, while values >4 indicate effective sulphation of alkalis, releasing chlorine in the gas phase. This the case only for the coal and coal blend, hence chlorine is not expected in the deposits, reducing therefore the corrosion risk. A high Al/Cl ratio indicates low fouling problems because of enough alumina silicates that bind (neutralise) alkalis towards effective alkali aluminium silicate formation; this is the case only in the coal and coal blend, thus implying, risk of fouling for the other blends.

The analysis above forecasts that some species of bamboo can be suitable fuels, while others are not advisable. In any case, bamboo in general seems to be a good replacement for clean wood when alkalis and chlorine are removed by the torwash process. However, further detailed analysis based on fuel composition need to be carried out as a follow-up research step, such as for example, chemical fractionation for the ash composition, in order to define more precisely which elements and to what extend they are available for reactions, or whether they are inert and despite the high concentrations these do not affect the melting behaviour of ash. Alkalis and chlorine are mobile elements and are expected to be present in variable concentrations in bamboo

feedstock. Especially biomass alkalis are highly mobile in contrast to coal alkalis; therefore the above-mentioned indices need to be evaluated carefully.

It must be noted that no absolute conclusions based on these indicators can be drawn because fouling (ash deposition) behaviour also depends on boiler lay-out and dynamics (Tortosa Masia, 2007), on the actual combustion conditions and the particle size distribution of the fuels. These factors were not taken into account in these indicators and that may affect the final ash release and behaviour. Finally, it is important to compare the fuel values with pellet specifications, which is a decisive factor whether a fuel would be considered for use during co-firing. In that case, *B. vulgaris* seems a good candidate due to low chlorine and low ash content, even if the fuel indicators at this stage seem not that favourable. However, the IWPB criteria were developed for wood pellets; other biomass types may need to comply with other sets of criteria. A comparison with the IWPB criteria is only indicative.

5.2.7 Conclusions from the technical evaluation of bamboo as a co-firing fuel

This chapter presents the results of the fuel characterisation, pre-treatment (dry torrefaction and torwash) and combustion of the five year old bamboo species *G. angustifolia*, in blends with coal. In comparison with woody and herbaceous biomass fuels, *G. angustifolia* presents comparable fuel characteristics with other woody and herbaceous biomass feedstocks, regarding heating value and chemical composition, however the alkali content in the virgin material is quite high. It is tenacious and fibrous which makes it difficult and expensive to grind, handle and store. Dry torrefaction improves the physical qualities of the fuel, such as grindability and moisture content. Wet torrefaction removes salts and minerals from the biomass. From the fuel characterisation results it was concluded that wet torrefied *G. angustifolia* is a high quality solid fuel concerning its elemental composition and heating value, which are then similar to clean wood.

Concerning the combustion simulation trials, the virgin bamboo species show fouling potential similar to herbaceous biomass; dry torrefaction improves the fouling behaviour somewhat, as shown in the fouling factors and deposition propensity results, and torwash renders a product of high quality that minimises risk of fouling and deposition. Therefore, despite the lower alkali and chlorine content compared to other herbaceous fuels, the combustion of 100 % virgin but also dry torrefied *G. angustifolia* bamboo is still not recommended before extensive and dedicated assessment of the fouling and slagging risk during pilot-scale tests or with additional detailed lab-scale tests, mainly due to the increased alkali content of the fuel compared to clean wood. In any case, the material needs to be grinded very fine, which is possible after torrefaction. Co-firing at relatively small percentage though is an option as is the standard practice nowadays, due to the counteracting effects of coal ash, minimising the risks of slagging and fouling.

Finally, four other bamboo species were identified as potential candidates for coal substitutes as well, but they were not pre-treated and tested in the laboratory scale combustion facility. Instead, a brief evaluation of their fouling tendency was carried out based on their ash elemental composition using the alkali index and other fuel indicators suggested in literature. The calculated values suggest that some bamboo species such as *Bambusa vulgaris* and *Dendrocalamus strictus* should be further assessed to be included in the fuel portfolio of modern pulverized fuel power plants.

5.3 Gasification

Apart from biomass (co-)firing in coal-based systems another important application of biomass is the production of syngas through entrained flow (EF) gasification. Syngas is a key intermediate product for a wide range of energy carriers and products, e.g., power, fuels, chemical products, substitute natural gas, and hydrogen. One of the early markets for biomass-based syngas production is power production. It is expected that clean woody biomass, extensively used today as the main biomass source, will be phased out from the power industry and used as the feedstock for second- and third-generation biofuels because this is a product with a higher value than heat and power. Therefore, there is a growing interest in the application of alternative feedstocks, for both power generation and the production of transportation fuels. Biomass materials such as straw, a range of palm oil residues and corn residues, as well as some bamboo species have physical and chemical properties that are widely different from those of the widely used wood, such as higher ash content which is also rich in alkaline and chlorine, which is prone to cause operating problems when used at higher shares for co-firing in existing coal-fired power stations, especially with respect to slagging, fouling, and corrosion, as explained in previous sections. However, exactly this drawback (the low melting temperatures of the ash) make these fuels potentially well-suited for slagging thermal conversion systems in which slag formation on the gasifier walls is essential for safe operation. For the production of syngas from bamboo it is thus of key importance to know what the effects are of ashes on the slagging and fouling behaviour.

A series of tests were carried out under entrained flow gasification conditions in order to complete the evaluation of *G. angustifolia* bamboo as a fuel in the current energy sector installations and in specific to assess its suitability for entrained flow gasification. The LCS installation (see section 5.2.2) was again used, albeit at different operating conditions that are described below.

5.3.1 Reactor set up and conditions

In the gasification mode the open reactor system is replaced by a double-walled sealed one. This allows to perform the tests under syngas conditions. The achievable residence times are similar to those under regular combustion conditions, while at the same time much higher flame temperatures can be obtained (>2250 °C). This paragraph presents lab scale results on gasification and co-gasification of torrefied *G. angustifolia* bamboo,

pure or in a blend with El Cerrejon coal (80 wt% coal blend). It provides information on the conversion efficiency, the slagging behaviour and ash partitioning of the selected fuels. The aim was to suggest technical solutions and/or improvement in the operation of the full scale power plants. The testing includes:

(1) Slag formation (Near burner slagging tests)

(2) Conversion efficiency (End-point kinetic tests)

(3) Particulate matter (PM) emission study

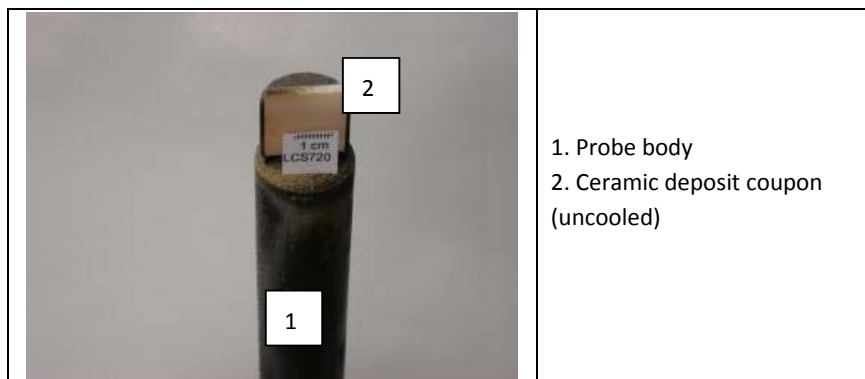
Various ash/char samples have been collected and further analysed by means of the SEM/EDX technique for the morphology of ash/char particles and the elemental composition. The ash formation dynamics (endpoint kinetics) were determined by the amount of carbon in the ash, performing slow ashing of the filter residue under controlled oven conditions.

The gas composition was monitored in order to control the conditions (CO , CO_2 , O_2 , and H_2). The fuels tested were the 5 year old torrefied bamboo *G. angustifolia*, El Cerrejon coal from Colombia and the blends of 20% biomass and 80% Cerrejon coal with and without a flux material.

Slag formation - Near burner slagging tests

Near burner slagging tests have been performed using the vertical deposition probe, which is displayed in **Figure 55**. The alumina deposition substrates have been used during the near-burner slagging tests. The distance of the probe with the alumina substrate was fixed at 410 mm from the burner.

Figure 55: Vertical Deposition Probe (VDP) for near-burner slagging studies



Conversion efficiency test

For this set of tests, only the ash/char was applied at the reactor exit, and the vertical probe for collecting slag samples. The particulate matter has been collected at a fixed height from the burner, corresponding to a residence time of approximately 2 seconds. The temperature of the probe cooling medium was kept at 110 °C. The rest of the sampling train was kept at 105 °C, to prevent water condensation. The carbon conversion was determined by applying Weight Loss and Loss on Ignition (LOI).

Particulate matter (PM) emission study

For these tests, particle samples of ash were taken at the same location as the samples obtained for conversion determination using a Pilat Mark 5 cascade impactor. The impactor stages were weighted and analysed for particle morphology and chemical composition by means of scanning electron microscopy coupled with energy-dispersive X-ray (SEM-EDX).

All three sets of tests were performed under the same high-temperature gasification conditions. The furnace settings applied for gasification study were 1500/1500/1500 °C for the top, middle and the bottom section respectively.

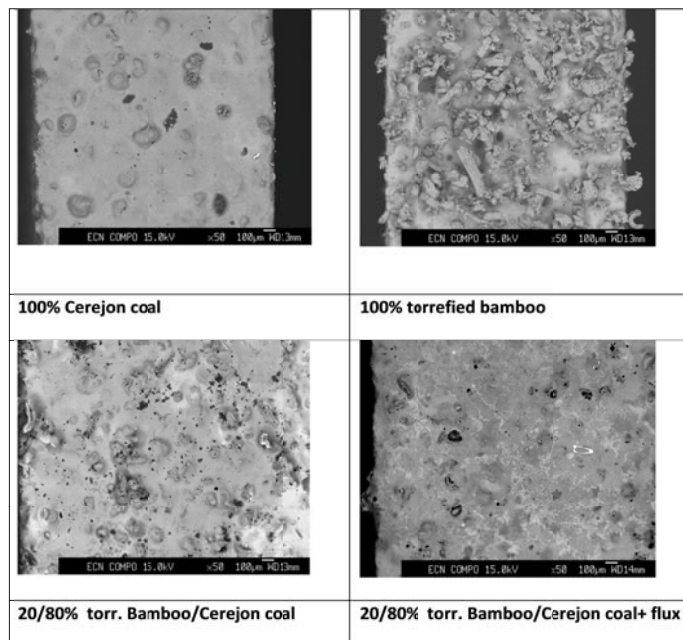
5.3.2 Gasification tests results and discussion

Slag formation

Slagging refers to the deposition that takes place in the high temperature refractory sections of boilers (close to the burner area) where radiant heat transfer is dominant and occurs due to the presence of molten ashes.

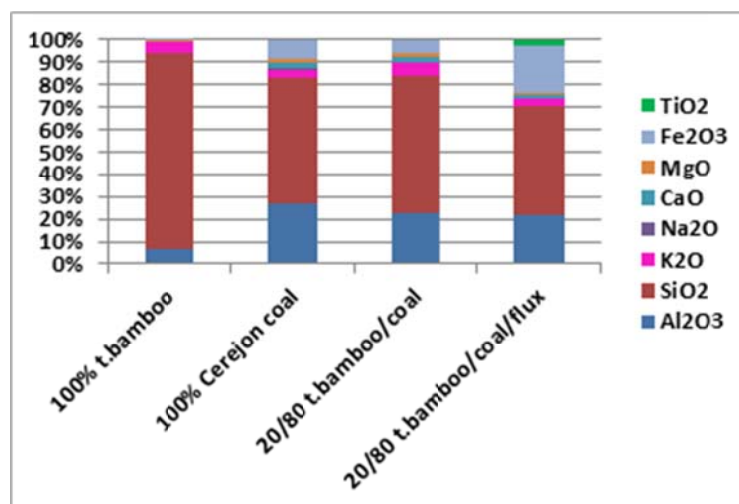
The slagging propensities of the studied fuels and blends were assessed using the vertical deposition probe in the LCS. The duration of the each slag formation experiment was approximately 2 hours. The alumina substrate with the ash deposit have been subjected to SEM/EDX analysis. **Figure 56** display the backscatter SEM images of all four slag deposit samples from the gasification experiments. It should be noted that a brighter scale indicates the presence of elements with a higher atomic number.

Figure 56: Slag formation at 1550 °C; distance 410mm from the burner; different fuels



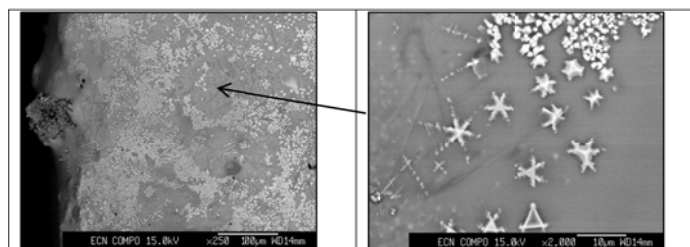
The SEM image in **Figure 56** exhibits slag deposition of Cerrejon coal 100% and its blends with 20% torrefied bamboo with and without flux also under gasification conditions. The molten slag layer with some partially converted particles can be observed with different proportions of melting. All samples demonstrate rather non homogeneous slag compositions. In spite of the relatively long sampling time the slag still contains partially converted particles. As a consequence of the presence of these large particles the composition across the sample varies significantly. Especially the 100% torrefied bamboo slag sample displayed some fly ash particles that are not entirely dissolved in the slag (see **Figure 56**). Nevertheless the particles are softened and they stick together and form bigger agglomerates. The torrefied bamboo fuel contains a significant amount of silica oxide (see **Figure 57**), a compound known for its high ash fusion temperature. This is an indication of a low slagging potential.

Figure 57: Slag deposit compositions during LCS gasification experiments with torrefied *G. angustifolia* bamboo fuel and their blend



Representative results of the chemical composition of all slag deposit are given in **Figure 57** where the direct effect of mixing biomass can be observed. The potassium from bamboo, iron from the coal and flux material together with titanium, decrease ash melting temperature in sample 20/80 torrefied bamboo/coal. No chlorine, sulphur and phosphorus were detected in the slag deposit.

Figure 58: Slag formation at 1550°C; distance 410mm from the burner; 20/80 torrefied *G. angustifolia* bamboo /Cerrejon coal+ flux; detail with iron rich crystalline structure



Furthermore the crystalline structure has been detected all around the sample. Detailed SEM/EDX analysis showed that the bright crystalline structure (see **Figure 58**, detail) is composed of iron, aluminium and silica. Those crystals are most probably formed in the molten slag during the cooling.

Conversion efficiency

Generally, the conversion process can be subdivided into three steps: particle heat-up and drying, devolatilisation and char burnout. During gasification the fuel is subjected to pyrolysis, oxidation and reduction. Reactions with oxygen are highly exothermic and result in a sharp rise of the temperature up to 1200 - 1500 °C. The reaction products of the oxidation (hot gases and glowing charcoal) are converted as much as possible into chemical energy of the producer gas during the reduction.

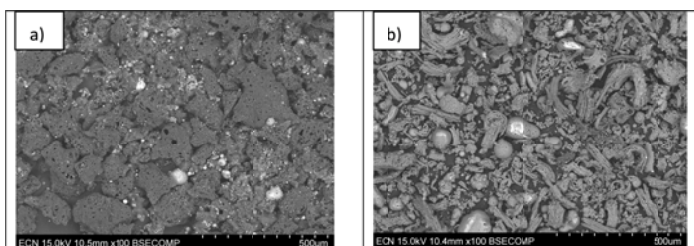
All fuels have been milled to sizes below 500 micron. The typical particle size distribution of the biofuels is bimodal, where coarser particles and a fine fraction can be observed. The PSD of the coal sample is more homogeneous, containing a fine fraction. The coarse torrefied bamboo particles (500 micron) have been found in the fly ash and were not completely converted after the gasification experiments. **Table 19** shows the results from the conversion tests. Despite the representative residence time of the particles, the conversion of the coal blends during the gasification is lower (74-84%).

Table 19: Results of the fuel conversion during gasification and combustion experiments

EF gasification	Fuel	Conversion [%]	ash% in fuel
	100% Cerrejon coal	74.5	30.3
	100% torrefied bamboo	99.5	93.0
	20/80% Cerrejon/torrefied bamboo	84.8	36.4

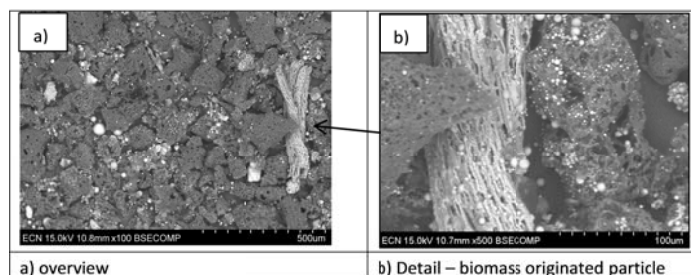
The reactivity of the biomass is somewhat higher than the reactivity of Cerrejon coal. Nevertheless the conversion values under gasification conditions are in the range of the previously studied biomass or biomass/coal blended samples at ECN. The fly ash deposits collected during 100% coal and 100% torrefied bamboo gasification are depicted in **Figure 59**.

Figure 59: The ash deposit: a) 100% coal and a) 100% torrefied bamboo



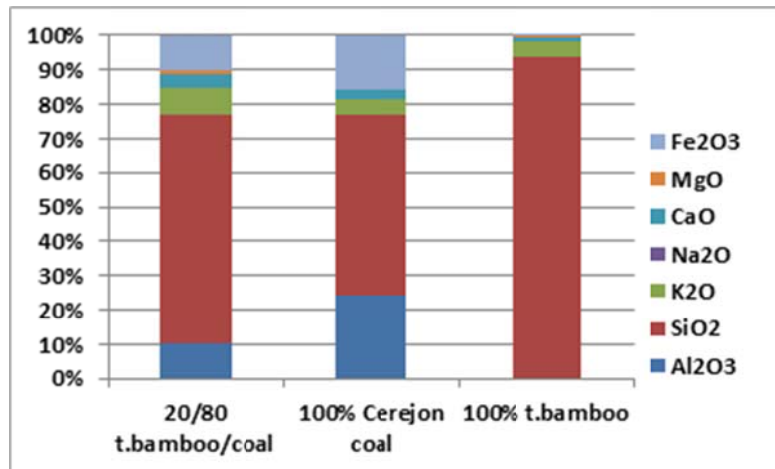
The difference between the ash sample after the gasification test with 100% coal or 100% torrefied biomass is significant. The SEM/EDX analyses revealed that the 100% coal ash contains 82% of carbon while the ash deposit from 100% torrefied bamboo gasification contains mainly silica oxide. This observation supports the earlier presented reactivity data.

Figure 60: The ash deposit: blend 20/80 torrefied bamboo/coal, a) overview; b) detail



As can be seen in **Figure 60** the ash after the gasification of the blend 20/80 torrefied bamboo/coal is composed of mineralised biomass particles as well as unconverted carbon particles originating from the coal. The main elements detected in the particle of the biomass origin (see **Figure 60 b**) are silica oxide with trace amounts of potassium. The mineral part of the ash deposit contains mostly granular spherical deposits. The sphere-shaped ash particles are composed mainly of silica oxides and alumina silicates. Besides these alumina silicate cenospheres, similar particles were identified that were enriched in iron. These most probably stem from mineral pyrite, commonly found in coal. Compared to the 100% biomass gasification scenario, less potassium in the deposit has been detected. The chemical composition of filter ash deposit samples analysed by means of SEM/EDX technique is given in following **Figure 61**. The results are normalised and expressed on carbon free basis.

Figure 61: Filter ash deposit compositions during EF gasification experiments – conversion test



Particulate matter (PM) emission study

The ash samples for the PM study were obtained by sampling the (partly) converted fuel in the LCS by means of an 11 stage Pilat MARK V cascade impactor at 2000 ms residence time. This allows for the separation of the coarse ash (composed of the unconverted organic matrix and the non-volatile, ash-forming elements) from the volatile (alkali oxides and salts) and near- and sub-micron-sized aerosols upon the thermal conversion process. Each stage was inspected at three different magnifications,

depending on the loading of the substrate in order to determine the particle size of the deposit. After taking the measurement, the surface of each stack was analysed by means of EDX at three points. The final results were calculated by averaging the results per stack and per deposition stage.

During this test the influence of the flux addition to the 20/80 torrefied bamboo/coal blend was investigated. The following results are related to two fly ash samples collected by using the cascade impactor. Fly ash particles consist of coarse particulates, which represent the largest fraction by weight in cascade impactor samples. The comparison of the averaged, normalised chemical compositions of the single cascade impactor ash fractions is shown in **Figure 62**.

The addition of the flux had a beneficial effect on alkali capturing and decreased the submicron particulates formation. The submicron fraction forms 1% of the total ash in the sample from the test with the blend (20/80 torrefied bamboo/coal). While the concentration of submicron fraction (PM1) amounted 0.3% when the flux was added to the blend. Apart from the carbonaceous fine fraction, also alkali alumina silicates, chlorine and sulphur have been found in the last stages of the impactor. The chlorine and sulphur are most likely in the form of alkali salts. Furthermore from the molecular ratios the alkalis are also present in form of hydroxides. All these compounds are known for an increasing probability to form sticky deposits followed by fouling on the heat exchanging areas. The SEM micrographs of the coarsest and finest fractions of the PM samples of the cascade impactor are shown in **Figure 63**.

Figure 62: Chemical composition of the single stages of the cascade impactor at 20/80 torrefied bamboo/coal fuel a) fly ash blend; b) fly ash blend with flux

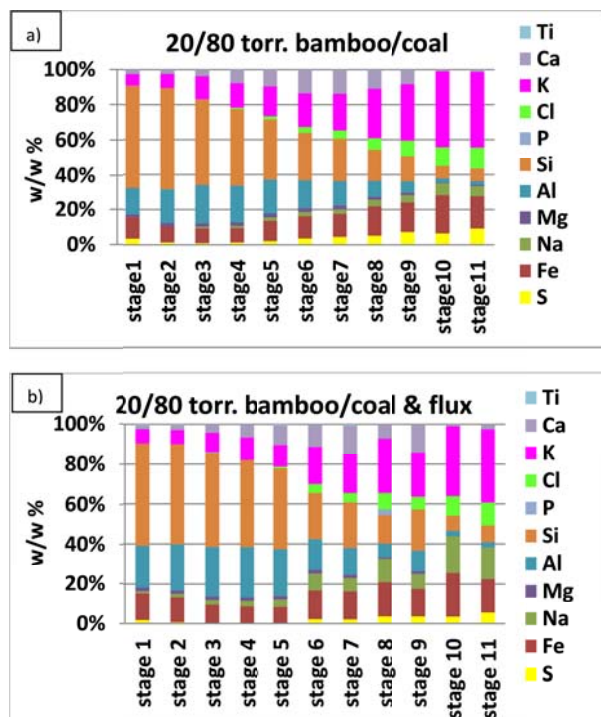
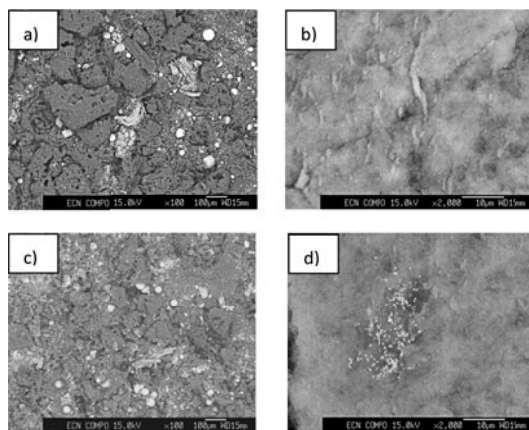


Figure 63: SEM micrographs of the first (coarse) and last stage of the cascade impactor; a) and b) 20/80 torrefied bamboo/coal fuel; c) and d) 20/80 torrefied bamboo/coal fuel & flux



5.3.3 Conclusions related to EF gasification

Lab-scale results on the gasification and co-gasification of torrefied bamboo, pure or in a blend with El Cerrejon coal (80% weight coal blend) have been presented. Tests provided insight on the conversion efficiency, the slagging behaviour and the ash partitioning of the selected fuels. Several aspects have been studied and therefore the following conclusions can be driven.

The selected coal, Cerrejon C exhibited low conversion rates during the EF gasification conditions, while the torrefied bamboo was almost completely converted under the same conditions.

The particulate matter emissions has been studied for a blended sample (20/80 torr. bamboo/coal) with and without the influence of the flux material. The results suggest a positive effect on alkali capturing and decreased submicron particulates formation when a flux is added. Even though that submicron fraction forms less than 1% of the total fly ash, further attention shall be paid to its chemical composition. Alkali salts and hydroxides can cause issues downstream on heat exchanging areas.

EF gasification of 100% biomass exhibits a low slagging potential due to the high silica oxide content in the fuel. It could present a drawback in an entrained flow gasifier, while it could be beneficial in other thermal conversion technologies (down draft gasifier; PF combustion). Nevertheless the addition of the torrefied bamboo to a low rank coal (alkali, iron or ash-rich) can be advantageous in an entrained flow gasification process.

6

Techno-economic evaluation

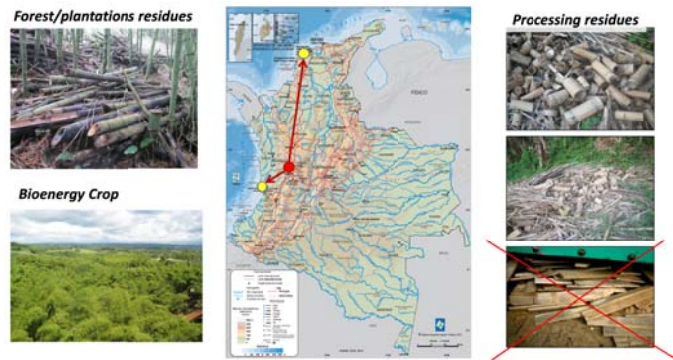
This chapter presents the overall cost estimation of imported torrefied *G. angustifolia* bamboo pellets from Colombia to the port of Rotterdam. Section 6.1 presents the main figures and assumptions used for the estimation of the overall cost of delivering bamboo to a torrefaction plant, while section 6.2 deals with the estimation of torrefaction cost and the resulting pellets price at the port of Rotterdam.

6.1 Bamboo production costs

The cost of bamboo production are mainly dependent on: the cultivated species, the plant section which will be further processed, the scale of production and location. The assumed distance from the production site to the processing site is of 50 km. The cost estimation takes into account literature data (e.g. (Cruz, 2009)) and field collected data for the production of the species *Guadua angustifolia* in the coffee region of Colombia . **Figure 64** illustrates the location with respect to the export ports of Buenaventura and Cartagena as well as the two bamboo sources considered:

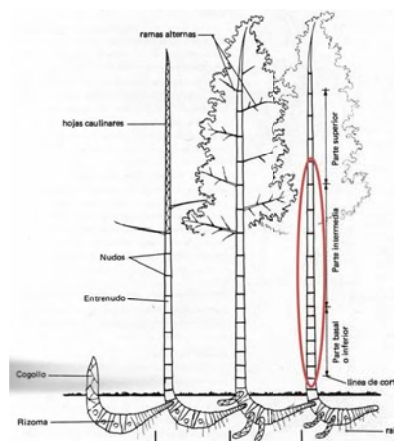
- Bamboo residues resulting from forest and plantation management
- Bamboo from a dedicated energy crop

Figure 64: Base case study bamboo sources and location (red) with relative distance to sea ports (yellow).



The plant section which is most suitable as solid fuel is the culm, due to its physical and chemical properties (See **Figure 65**).

Figure 65: . Bamboo plant sections. Picture source: (Hidalgo, 1981)



The residues scenarios excludes the sourcing of material from processing sites of bamboo poles for furniture and construction material production, as this material is mostly chemically pre-treated, which is not suitable for pellets production.

The main assumptions and biomass cost at the production site and central collection point are presented in **Table 20**. These are estimated based on price cost for commercial plantations of about 2000 €/Ha-year (Cruz, 2009). From these about 50% are related to estimated manual labour cost. The assumed production cost at the harvesting site are 20 €/ton_{dry} and 70 €/ton_{dry} for the residues and energy crop cases respectively. The price difference accounts for the total cost allocation to the main product, which for the residues case is assumed to be the bamboo poles for the construction/furniture market which corresponds to about 70% of mature culms.

Table 20: Feedstock production cost parameters

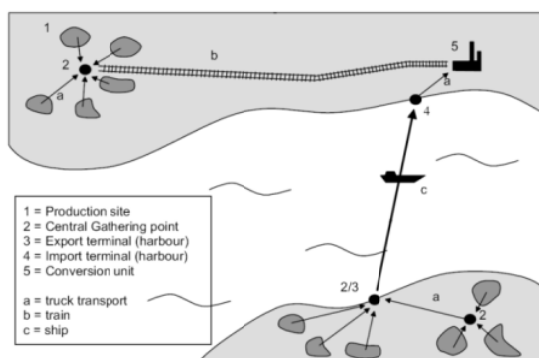
Parameter	Unit	Residues	Energy Crop
Annual productivity	Ton _{dry} /Ha-year	15	30
Production cost at harvesting	€/Ton	20	70
Average transport cost to central point (50 km)	€/Ton	5	5

6.2 Torrefied bamboo pellets in Rotterdam Port

Considering the whole route of conversion of overseas bamboo to bio-product (being electricity, fuels or chemicals) in the Netherlands, numerous processing steps at different locations along the route can be defined. If the large-scale end-use is located in the Netherlands, the bamboo can be imported as original feedstock (bamboo stems, flattened culms (see esterilla in section 3.4.1) or chunks) or as biomass intermediate (torrefied pellets). Other intermediates like pyrolysis oil or conventional pellets are not taken into account in this study.

An overview of an overall system for products from imported bamboo is presented in Figure 66 (Hamelinck, 2005). The bamboo is collected at a number of production locations (e.g. forests or plantations) and transported to collection facilities, from where it will be transported to and stored at a central port. From the central port, the bamboo is transported (i.e. by ship or train) to a large-scale end-user, in this specific case a power plant located in the Netherlands.

Figure 66 Overview of an overall system for products from imported biomass Source (Hamelinck, 2005)



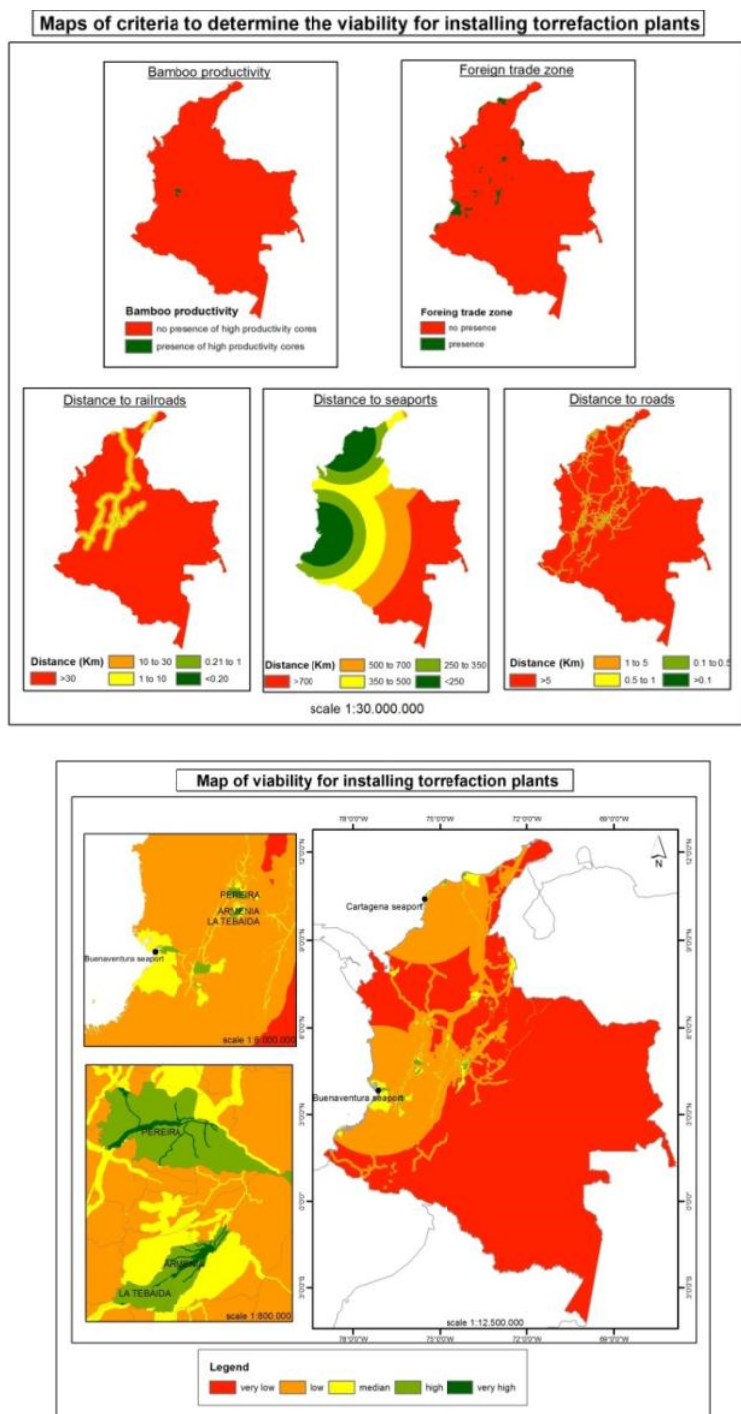
The bamboo torrefaction facility might be located at the central gathering point (2) or the export terminal (3). As all bamboo, however, has to be transported by land to this facility and land transport is relatively expensive the distances between production site and central gathering point, as well as between central gathering point and export terminal should be kept small.

As a result, the maximum scale of the conversion facility is restricted by the biomass supply (e.g. roughly 50-100 kton/yr for the central gathering point and several hundred kton/yr for the export terminal) and, hence, the facility might, depending on the scale-up potential of that facility, become relatively more expensive (Calis, 2002b; Calis, 2002a).

Figure 67 illustrates the potential areas where torrefaction plants could be installed for the processing of guadua from specifically the coffee region in Colombia. The selection criteria for the estimation of potential areas include:

- Areas with high productivity potential for the production of guadua in the coffee region (see section 3.4.1, **Figure 20**)
- Free handle zones proximity
- Distance to sea ports (Cartagena and Buenaventura)
- Distance to rail roads
- Distance to roads

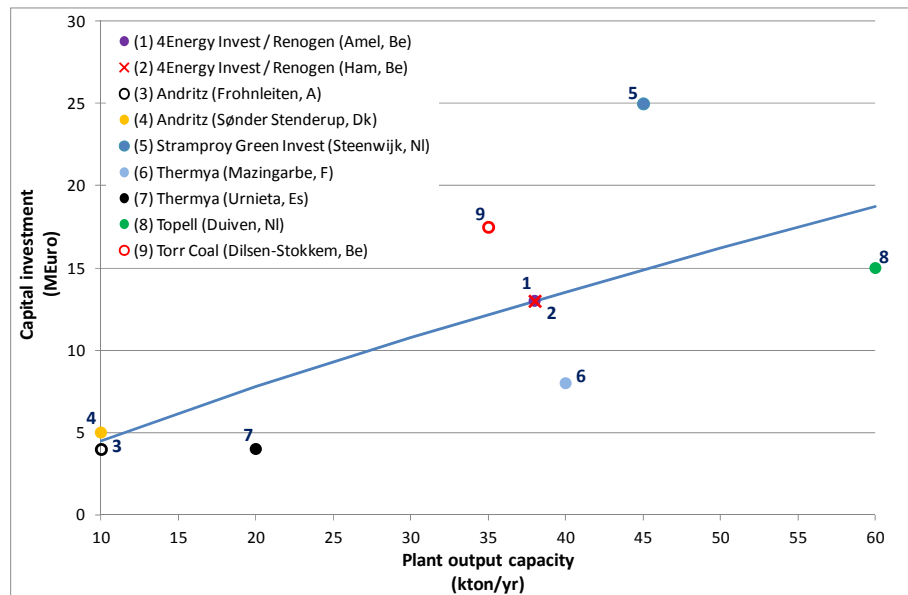
Figure 67: a & b . Selection criteria and potential location for the installation of torrefaction plants based on the processing of guadua from the coffee region in Colombia.



Most torrefaction plants are limited in scale and therefore constructed modular, with typical sizes foreseen on commercial scale of 50-100 kton/yr. As such, bamboo can be pre-treated in the export terminal or even in the central gathering point without being burdened by the economy-of-scale effect.

On this foreseen commercial scale, however, only a small amount of torrefaction plants exist as can be seen in Figure 68. This figure represents the reported capital investment costs of different semi-industrial torrefaction plants in Europe. Please note that at the time of reference the Andritz plant in Austria, as well as the Torr-Coal plant, was not (yet) equipped with a densification step. The investment figure also contains a scaling line having the 4Energy Invest plants as a reference and using standard scaling rules to determine costs for plants with different capacities. The large deviation for in particular the torrefaction plant in Steenwijk and to smaller extend the Torr Coal and Thermya plants shows the large uncertainty that still exists in expected costs for torrefaction.

Figure 68 Investment costs of different semi-industrial torrefaction plants (Data from: (Hilgers, 2012))



The estimation of the import of *G. angustifolia* as a solid fuel to the Rotterdam harbour from overseas central biomass gathering points transported via harbours is based on the model applied by (Zwart, Boerrigter & van der Drift, 2006).

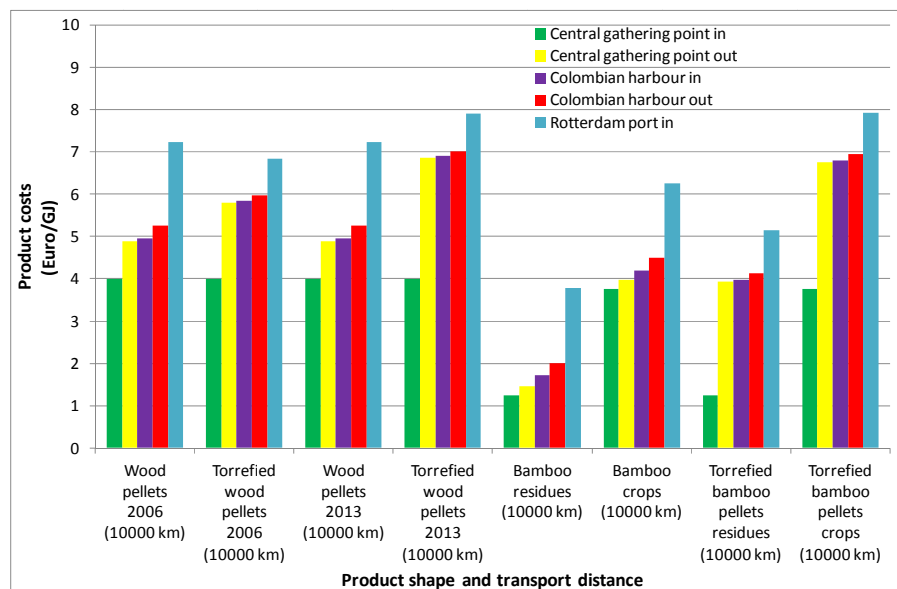
Specific data on torrefaction efficiencies, torrefaction investments and fuel costs are updated based on the results however different. The following data has been used in the evaluation of the bamboo chain:

- Torrefaction related data
- Investment based on reported costs of semi-commercial plants
- Torrefaction efficiency as achieved for bamboo at a temperature of 270°C
- Bamboo and product properties as achieved at a temperature of 270°C
- Transport distances of 10,000 km from Colombian harbour to Rotterdam port
- Bamboo costs 0-50 (residues) and 50-100 (energy crops) €/ ton_{dry}

- g. Bamboo production of 15 (residues) and 30 (energy crops) ton_{dry} per ha per yr
- h. Average internal transport cost to export port (150-300 km) of 15 €/ ton_{dry}
- i. International maritime transport cost 35 €/ ton_{dry}

In Figure 69, the results are summarized based on the updated data. As a reference, the 2006 data for wood chips and torrefied wood pellets, have been included though also have been updated for the updated 2013 estimates of the capital costs of torrefaction.

Figure 69: Bamboo costs at different locations of the transport chain



For wood the torrefied wood pellets now are slightly more expensive in the Rotterdam port than conventional wood pellets, due to the change assumed capital investment required for torrefaction. The difference however is still limited and the choice of traded product will still depend strongly on other properties, e.g. hydrophobicity, grindability and durability.

For bamboo, the costs of non-torrefied bamboo in the Rotterdam port are considerably lower than for the torrefied bamboo. This is mainly caused by the already relatively low moisture content of bamboo, as well as the high bulk density of bamboo. Although bamboo stems can have a lower bulk density, the density of bamboo chips (or crushed bamboo stems) is significantly higher than of wood chips. The difference is that significant that the choice of traded product will less depend on other properties.

The advantage of using bamboo residues for energy purposes is also clear. Due to the lower costs in Colombia, the residues can land in the Rotterdam port for 4 to 5 €/GJ, which is significantly lower than the current wood pellet price. If bamboo is specifically produced as energy crops, the costs of untreated bamboo in Rotterdam are still low (5 €/GJ), whereas the costs for torrefied bamboo pellets become comparable with the costs for torrefied wood pellets (8 €/GJ). Even if the estimated cost of use of residual streams appear to be the lowest, the development of the bamboo to fuel chain would

depend on other factors such as: availability, logistics and sustainability, among others. Some of this issues are briefly discussed in sections 6.1 and 6.2.

6.1 Quantities of biomass

The estimation of available and potential residues from *G. angustifolia* forest and plantations is based on an average biomass yield of 15 ton_{dry}/ha-year . The leaves and branches are not taken into account on this estimation. However, the yield can vary between 7 ton/ha-year to 35 ton/ha-year, depending on: site characteristics, age of the plantation and management practices.

For the base case region-coffee axis, and based on the inventory data of *G. angustifolia* stands (28,000 Ha) (Kleinn, Morales-Hidalgo, 2006) the estimated potential production is about 420 kton/year (see **Table 21**).

Figure 70 illustrates the distribution of natural guadua stands in 5 departments of the coffee area, and a distinction is made between managed and unmanaged stands. If conditions and incentives are created for the management of natural stands, the fuel potential on residual *G. angustifolia* streams of the region could be about 260 MW_{th}. At national level according to last inventory (51,000 Ha), the potential is about 765 kton/year.

Figure 70: Natural *Guadua angustifolia* forest in the coffee region. Managed vs. Unmanaged stands

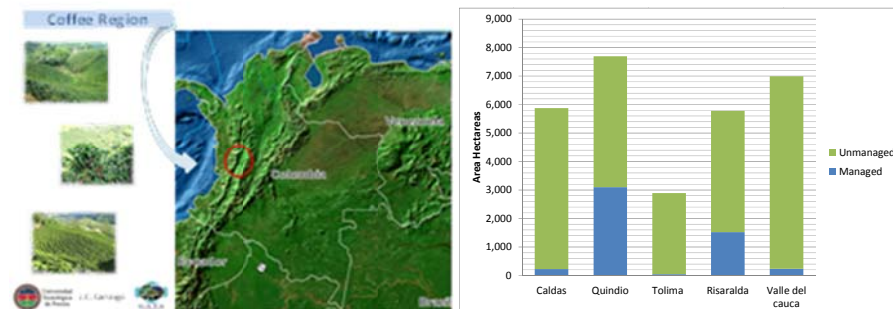


Table 21: Residual guadua-biomass potential

Natural stands	Hectares	kton/year	MWth
National	51,000	765	480
Coffee axis	28,000	420	260

Apart from the exploitation of *G. angustifolia* stands, an alternative scenario is the establishment of bamboo plantations as dedicated bioenergy crops. As for the coffee axis, when the total area with potential for high productivity is considered (125,000 Ha)

(Camargo, 2007b) the production can be as high as 1,800 kTon/year, equivalent to 1,100 MW_{th} of fuel.

Table 22: *G. angustifolia* biomass potential as bioenergy crop

Potential suitable area	Hectares	kton/year
Coffee axis	125,000	1,800
Other regions	Unknown	-
Reforestation crop in 2% of national degraded land	400,000	6,000

Please note this figures are an estimation. The potential at national level requires detailed studies and zoning as it has been done by (Camargo, 2007b) for the coffee axis region. When considering the hypothetical scenario of reforestation 2% of the country degraded land, there would be enough potential for producing millions of tons annually.

The national potential would extend to most of geographical zones in the country if other bamboo species alternative to *G. angustifolia* are considered See section 3.4, **Table 3**. Including alternative species would considerable increase the biomass availability either for the national or international market, .

6.2 Residue or bioenergy crop?

As reported by (Brinkmann, 2012), the bamboo resources may either be classified as a residue, or as a crop, depending on what material is used. When the market opportunities for bamboo poles for the construction and furniture market is favourable, then the good quality culms shall be considered the main product (crop) from the plantation, and cannot be classified as residue. On the other hand, leftovers from the harvest of good quality culms (dry culms, branches) as well as from the processing of good quality culms can be classified as residues. For the category 'in between', i.e. culms which may or may not be suitable for certain material applications, it is somewhat vague whether these materials can be classified as residues or not. Depending on market circumstances, both material which is classified as residues, and material which is clearly not residues may be considered for pellets production. Effectively, this means that certification against the full set of sustainability criteria (in NTA 8080 or alike) is required, and certification against a more limited set of criteria only (applicable for residues), is not an option. This increases the overall costs of certification, and besides also the specific certification costs per tonne of pellets (because material use of part of the biomass will also still happen, depending on market conditions) (Brinkmann, 2012).

The development of the chain based either on residuals streams or on dedicated bioenergy crops have both potential benefits and limitations. **Table 23** presents a qualitative comparison of some aspects between the different alternatives.

Table 23: Qualitative comparison. Residues vs. Bioenergy crop

Parameter	Residues from forest	Residues from plantations	Bioenergy crop/plantations	Comments
Yield per ha	+	++	+++	Forest exploitation is controlled and needs permit in Colombia (See section 3.4.2) A bioenergy crop/plantation could have higher productivities as it is not required a permit and there are no limits for exploitation, part from of those of proper stand management.
Current potential	++	+	--	Existing area covered/ Species
Future Potential	++	++	+++	Suitable area
Cost	++	++	+	Main production/management cost are allocated to main product
Small holders	++	+	+	Forestry Management Units FMU (see section 3.4.3)
GHG emissions reduction	+	+	+++	Use of residues account for emissions from the collection point → Does not include carbon stock (see section 7.1)

7

Sustainability assessment

The increased use of biomass for biofuels and bio products may produce conflicts as well as synergies between socio-economic and environmental impacts, especially in developing countries. The need for standards, as regards sustainability concerns, has become more evident. This means that it needs to be ensured that any particular production system is environmentally, socially and economically sustainable. It should furthermore contribute to the reduction of greenhouse gases (GHG), not create negative environmental and socio-economic impacts and contribute to positive social impacts.

In Europe the Renewable Energy Directive on the promotion of the use of energy from renewable sources sets targets for GHG reduction. The Directive includes sustainability requirements for biofuels (transport) and bio-liquids (electricity, heating and cooling) (Art 17-19). In Art 17(9), the European Commission announced a report and proposals on requirements for a sustainability scheme for energy uses of biomass, other than biofuels and bioliquids.

In February 2010, the European Commission adopted a report on requirements for a sustainability scheme for solid and gaseous biomass used for generating electricity, heating and cooling (COM(2010)11). At that stage, no binding criteria were suggested on European level. Nevertheless, the Commission formulated recommendations to Member States developing sustainability schemes, mainly for imports. The Commission wishes to ensure that national legislation concerning these biomass types is in almost all respects compliant with the rules laid down in the Renewable Energy Directive (for liquid biofuels), to ensure greater consistency and to avoid unwarranted discrimination in the use of raw materials (Biobench, nd). To date there has not been further communication from the Commission regarding obligatory criteria on this matter. Nevertheless, 12 different voluntary schemes have been accepted by the EC to ensure sustainability compliance with the RED. Some of these schemes are applicable not only to liquid liquid biofuels but also to solid biomass.

This chapter on sustainability will focus on the requirements of the Dutch Sustainability Standard NTA 8080 accepted by the EC in 2012. The NTA 8080 Standard is framed in 9 principles containing criteria and indicators. The EC also accepted the NTA 8081 which

includes the 'rules' to enable certification against the requirements of the NTA 8080. It is important to note that other certification schemes can also be applied as explained in section 7.11.

The chapter presents the information on a top to bottom form considering first the International (where applicable), National and then the local level of the base case study. There is a reference to the NTA8080 standard at the beginning of each section. An Annex containing all applicable legislation in Colombia is also presented.

The base case study area is within the Autonomous Regional Corporations of Risaralda (CARDER); Tolima (CORTOLIMA) and Quindío (CRQ) in the coffee region in Colombia. As such, the corporations regulate environmental issues including forestry, forest management and regulation (see section 3.4.2). The base case study is the Corporative for the sustainable management of guadua (bamboo) (CORGUADUA) which has 5 members (or units) which have been certified by the Forest Stewardship Council (FSC). The FSC audit report (GFA Consulting Group, 2005) which certified CORGUADUA with an area of 96 ha is used as reference document along this section.

Additionally, section 7.2 presents the results of an screening Life Cycle Assessment (LCA) of the complete bamboo supply chain as a solid fuel for electricity production. Besides greenhouse gases emissions, additional potential environmental impacts on air, water and soil are assessed and compared with those of coal-based electricity production. The input data is based on literature and results obtained in this project. This includes the agronomic inputs and outputs for which default emissions factors were used.

7.1 Greenhouse gas emissions

Principle 1: The greenhouse gas balance of the production chain and application of the biomass shall be positive

Criterion 1.1: In the application of biomass a net emission reduction of greenhouse gases shall take place along the whole chain. The reduction is calculated in relation to a reference situation with fossil fuels.

Principle 2: Biomass production shall not be at the expense of important carbon sinks in the vegetation and in the soil

Criterion 2.1: Conservation of above-ground (vegetation) carbon sinks when biomass units are installed.

Criterion 2.2: The conservation of underground (soil) carbon sinks when biomass units are installed.

The evaluation covers the complete biomass to chain for the production of electricity and its relationship to the goals in reducing greenhouse gas (GHG) emissions according to the EC recommendations for solid biomass (EC, 2010) and the certification system NTA8080/8081. The specific reductions should to be at least 70% as compared to the

fossil-based reference, coal. The specific case is the supply chain from the bamboo species *G.angustifolia* from a bio-energy crop. The base case scenario is a plantation with a productivity (extraction) of 30 ton/dry-ha-year. The GHG balance accounts with the emissions as listed in **Table 24** .

Table 24: Accounted GHG emissions for the biomass chain (EC, 2010)

Ep=	Total emissions from the production of the fuel before energy conversion
Ep=	$e_{ec}+e_l+e_p+e_{td}+e_u-e_{sca}-e_{ccs}-e_{ccr}$
e_{ec}=	emissions from the extraction or cultivation of raw materials
e_l=	annualized emissions from carbon stock changes caused by land use change
e_p=	emissions from processing
e_{td}=	emissions from transport and distribution
e_u=	emissions from the fuel in use, that is GHG emitted during the combustion of solid and gaseous biomass
e_{sca}=	emissions savings from soil carbon accumulation via improved agricultural management
e_{ccs}=	emissions saving from carbon capture and geological storage
e_{ccr}=	emissions savings from carbon capture and replacement

Greenhouse gas emissions from the use of the solid fuel in installations delivering only electricity are calculated as follows:

$$EC_{el} = Ep/n_{el}$$

Where,

EC_{el} is the total GHG emissions from the final energy commodity (gCO₂eq/MJ) that is electricity.

n_{el} is the electrical efficiency, defined as the annual electricity produced divided by the fuel input. The assumed value is 0.4, which is the average value for a power plant.

The GHG emissions savings are calculated as:

$$SAVING = (EC_f - EC_{el})/EC_f$$

Where

EC_f is total emissions from the fossil fuel comparator, coal based electricity. The reference GHG emissions for coal-based electricity according to the EC (COM 2010) is **198 g CO₂eq/ MJ**.

The paragraphs below explain the assumptions for the calculation of the accounted emissions..

Cultivation

Available data on agronomic inputs varies considerably depending on type of system (forest, plantation) and soil types. As an example, the interviewed bamboo producers (CORGUADUA) do not use any fertilizers, as the current productivity of their forest is enough for their market. However, fertilizers use might be necessary when new

plantations are established depending on the soil quality. In order to assess the potential impact of fertilizers application, literature data from (Bonilla, 2010) was used. The reference fertilizers input per hectare per year is: 60 kg of N fertilizer, 15 kg of P fertilizer and 60 kg of K fertilizer.

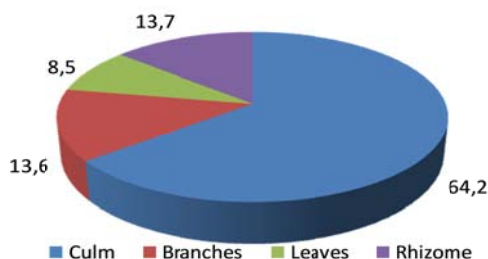
In terms of field emissions, there is not available information on GHG emission levels from bamboo forest and plantations. Therefore the default emissions factors used are those concluded in the harmonisation of greenhouse gas (GHG) emission calculations of biofuels throughout the European Union (see (Biograce, 2013).

Carbon Stock

The carbon content on bamboo systems, has been studied by different authors. The International Network of bamboo and Rattan (INBAR) has evidenced some advantages of bamboo species for carbon sequestration with regards to trees, because of the growth pattern, see (Yiping, 2010). However, it must be remarked that more than 1000 bamboo species are identified, which have in fact different growth patterns and specific characteristics, therefore values of carbon stock can vary considerable among species .

The carbon content and biomass distribution per plant section are relevant variables for the estimation of the carbon stock and potential GHG emissions reductions along the complete biomass to energy chain. **Figure 71** presents the biomass content distribution per plant section of the bamboo species *G. angustifolia*.

Figure 71: Biomass content distribution on *G. angustifolia*

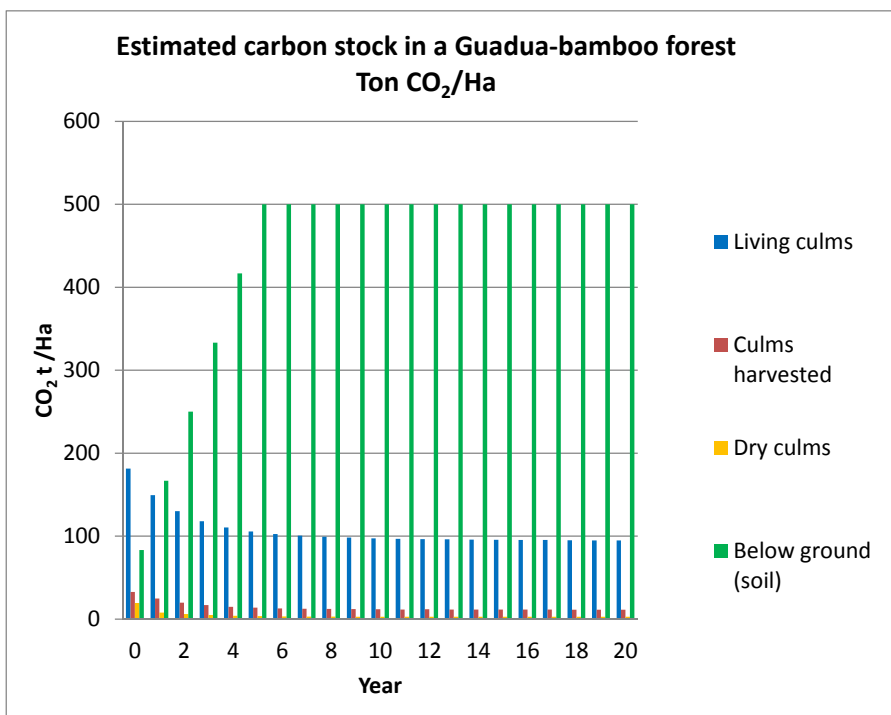


In order to provide information on carbon stored in *G. angustifolia* (culms, information from an inventory was used for simulation. Information on guadua culms was gathered in Yarima farm located in Pereira, Colombia. About 26 ha of natural guadua forest were assessed in terms of dendrometric and stands variables. Bamboo forest were located under the following ecological conditions: an elevation of 1,150 masl, 2,500 mm/ year of precipitation on average, 24°C on average and soils ultisols slightly acids.

Considering guadua stands with 5,200 culms per ha on average the scenario was defined according to the applied harvesting regime. The total number of living culms, the harvested culms and dry culms were simulated under an annual harvesting of 25% of mature culms (average 10 ton_{dry}/ha-year). The scenario is modelled for a period of 20 years. Data on below ground biomass and soil carbon is used to estimate the total carbon stock. According to (Camargo, 2012), for 7 year old *G. angustifolia* soil carbon at a depth of 0.5 mt has been measured as 500 ton CO₂/ha. This value of carbon stock is superior than most biomass systems.

Figure 72 presents the total CO₂ values considering the regime of harvesting above mentioned. The values are shown in terms of living culms, culms harvested, dry culms and below ground (and soil) carbon.

Figure 72: Carbon stock in a Guadua-bamboo forest/plantation

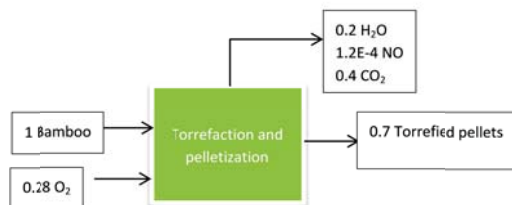


When establishing bamboo plantations the carbon stock change will result in a positive contribution in most of cases. However data is scarce and methodologies for accounting and monitoring are still under agreement..

Processing and transport

The emissions related to the biomass processing via torrefaction, are estimated based on the experimental results obtained within this project and the resulting overall mass balances as presented in **Figure 73**.

Figure 73 Torrefaction mass balance



The emissions related to transport are estimated based on the standard values as presented in the harmonisation of greenhouse gas (GHG) emission calculations of biofuels throughout the European Union (see (Biograce, 2013)) .

- Electricity supply in Colombia is mainly hydropower
- Transport from plantation to the processing site (50 km by diesel powered truck)
- Transport from processing site to export port in Colombia (300 km by diesel powered truck)
- interoceanic transport from export to Rotterdam port (10,000 km by ship)

7.1.1 GHG emissions reduction

From the input data stated above, the resulting GHG emissions of electricity produced from torrefied bamboo from a dedicated plantation are calculated as 26 g CO₂eq/MJ. Therefore the GHG emissions reductions are above the 70% suggested by the EC (2010). The calculation excludes the potential carbon storage and bonus (29 gr CO₂/MJ) which could be added when the establishment of plantations contribute to restoring of degraded land, see EC (2010). When these are included, the GHG emissions reduction would result in negative emissions, therefore being an opportunity for carbon capture and storage. A summary of GHG emissions reductions data for different scenarios is listed in **Table 25**. Please note that the estimated values are highly dependent on the cultivation and harvesting strategy.

Table 25: Summary of estimated potential GHG emission reductions of 1 MJ of bamboo-based electricity as compared to fossil reference.

Reference fuel comparison source		EC (2010)	NTA 8080	SimaPro
Coal-based electricity	g CO ₂ eq/MJ	198	199	194
Bamboo-based electricity. Bamboo source:		% GHG emissions reduction		
Bioenergy crop/plantation	26	87%	87%	87%
Residues from forest management ⁸	19.5	90%	90%	90%
Bioenergy crop/plantation from restoring degraded land	-3.0	102%	102%	102%
Bioenergy crop/plantation including carbon stock	-320	262%	261%	265%

The no yet clarity on definitions of degraded land does not allow yet to include additional bonus for restoring of degraded land. Additionally, the lack of standard data (values) for specific crop emissions and savings pose a challenge as data must be

⁸ The residues scenario is based in a yield of 15 ton dw/ha-year. For residues scenarios the accounting methodology starts at the collection of residues, therefore agronomic inputs and carbon stock are not included.

demonstrated, therefore emissions and carbon stock figures should be measured and monitored.

Bamboo can be an excellent reforestation crop with a carbon stock superior than most biomass systems. This can be an opportunity for a country like Colombia with a considerable record of land degradation (see section 7.4).



7.2 Environmental impacts assessment. An LCA approach

The Life Cycle Assessment (LCA) aims to quantify the environmental impacts on air, soil, and water of the complete biomass chain and to compare these impacts with those of coal-based electricity production. Additional to greenhouse gases emissions, other potential environmental impacts are assessed, such as: abiotic depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. The input data is based on literature data and the results obtained in this project.

The characterization step is carried out using the CML method developed by the Centre of Environmental Science from Leiden University version CML 2 baseline 2000 V2.05 in SimaPro7. The reference data used is from the Ecoinvent database. The impact categories definitions and indicators are listed in **Table 26**.

Table 26: CML method impact categories and indicators

Impact category	Definition	Unit
Abiotic depletion	Depletion of non-living natural resources, including energy resources	kg Sb ⁹ eq.
Global warming	Contribution of a substance to the greenhouse effect	kg CO ₂ eq.
Ozone layer depletion	Thinning of the stratospheric ozone layer as a result of anthropogenic emissions	kg CFC ¹⁰ -11 eq.
Human toxicity	Impacts of toxic substances present in the environment on human health	kg 1,4-DCB ¹¹ eq.
Fresh water aquatic ecotoxicity	Impacts of toxic substances on freshwater aquatic ecosystems	kg 1,4-DCB eq.
Marine aquatic ecotoxicity	Impacts of toxic substances on marine aquatic ecosystems	kg 1,4-DCB eq.
Terrestrial ecotoxicity	Impacts of toxic substances on terrestrial ecosystems	kg 1,4-DCB eq.
Photochemical oxidation	Capacity of volatile organic compounds and carbon monoxide to produce photo-oxidants such as ozone	kg C ₂ H ₄ eq.
Acidification	Impacts of acidifying pollutants (mainly SO ₂ , NO _x and NH _x), through emissions to the air, on the natural and man-made environment, human health and natural resources	kg SO ₂ eq.
Eutrophication	Impacts of eutrofying substances (nutrients), through emissions to air, water and soil, on the natural and man-made environment, and natural resources	kg PO ₄ ³⁻ eq.

The input data for *G. angustifolia* bamboo production is based on overall estimates for well-established stands with a productivity of 30 ton_{dry}/ha-year. The inputs data is as presented in section 7.1.

⁹ Sb: Antimony

¹⁰ CFC: Chlorofluorocarbons

¹¹ DCB: Diclorobenzene

Figure 74: Relative comparison of environmental impacts of the production of 1 MJ of electricity Coal vs. *G. angustifolia* bamboo

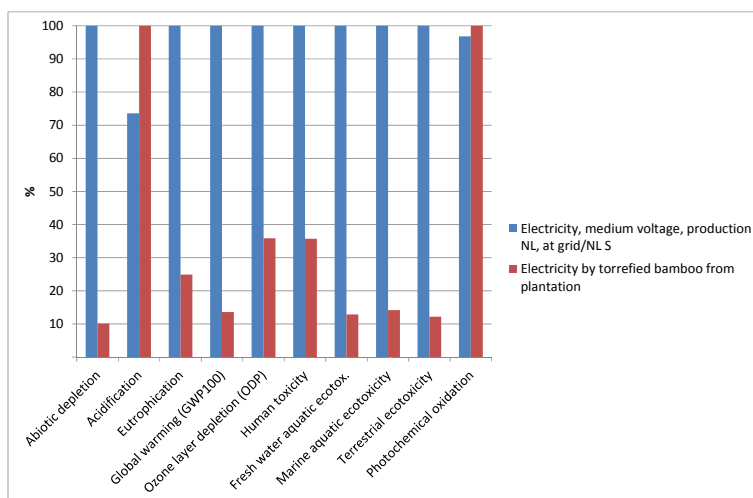
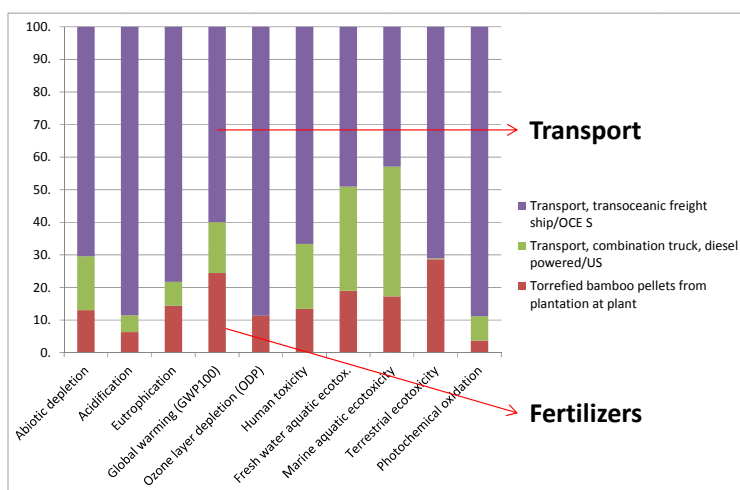


Figure 75: Bamboo chain process steps contribution to impact categories



When compared to coal-based electricity, the use of torrefied *G. angustifolia* bamboo as solid fuel in NL results in a reduction of greenhouse gases emissions above the 70% recommended by the EC (2010) and by the NTA8080 System. When including emissions saving from carbon accumulation and potential bonus for restoring of degraded land, the GHG emissions reduction would increase substantially leading to C storage opportunities. The results are dependent on the cultivation and harvesting strategy (see section 7.1).

The LCA results (see **Figure 74**) indicate the superior environmental performance of the bamboo chain compared to the coal-based reference. This applies for all impacts categories with the exception of acidification and photochemical oxidation. Both exceptions mainly stem from emissions related to interoceanic transport fuel usage and the potential use of fertilizers (**Figure 75**). These potential negative impacts are common to biomass chains. However, transport related impacts are lower for bamboo than for other biomass feedstocks (for the equivalent transport distances), due to its high density. Reduction of transport related impacts could be achieved by reducing the use of fossil fuels in interoceanic transport, (e.g. by replacing them with sustainable biofuels). Reduction of potential impacts related to fertilizers use could be accomplished by an integrated system with:

- Biofertilizers use which are produced from the bamboo leaves as well as from other sources available in the region.
- Recycling of minerals resulting from the processing steps, in particular if hydrothermal (Torwash) pre-treatment is applied where a stream rich in minerals is produced.
- Soil properties improvement via alternatives such as biochar production and use in the plantations could be explored.

Additional issues related to impacts on water and soil are discussed in detail in sections 7.4 and 7.5.

7.3 Biodiversity

Principle 4: Biomass production shall not affect protected or vulnerable biodiversity and will, where possible, have to strengthen biodiversity

4a. National regulations and laws biomass production and production area

4b. Protected areas

4c. Areas with HCV

4d. Maintenance and recovery of biodiversity

4e. Strengthening of biodiversity.

Colombia is listed as one of the world's "megadiverse" countries, hosting close to 14% of the planet's biodiversity (CBD, 2013). According to WWF (2013), the main pressures affecting land biodiversity in Colombia include growing population, infrastructure development, inadequate use of resources, over-harvesting, illegal logging in coastal tropical rainforest, erosion and social and cultural conflicts. In addition, other activities such as the projected expansion of industrial-scale agriculture such as oil palm and rice cultivation, and extensive cattle ranching have also been identified as other problems threatening regions such as the Orinoco Basin.

Some impacts related to biofuel production are considered within the Renewable Energy Directive (RED) (EC, 2009) with the sustainability requirements for biomass used for biofuels. For instance, it includes the consideration to respect the Cartagena Protocol on Biosafety and the Convention on International Trade in Endangered Species of Wild Fauna and Flora.

Colombia has signed the following International Conventions and Agreements (**Table 27**). These conventions are the most recognized internationally dealing with biodiversity and protection of ecosystems.

Table 27: International Conventions related to biodiversity signed by Colombia

Acronym	Convention	Date of signature	Date of ratification
CBD	Convention on Biological Diversity	1992	1994
CITES	Convention on International Trade in Endangered Species of Wild Flora and Fauna	1973	1981
ITTO	Convention of the International Tropical Timber Organisation	2006	2011
OTCA	Amazon Cooperation Treaty	1978	1979
CMS	Convention on Migratory Species	Not signed but memory of understanding	
RAMSAR	Convention on wetlands	1981	1997

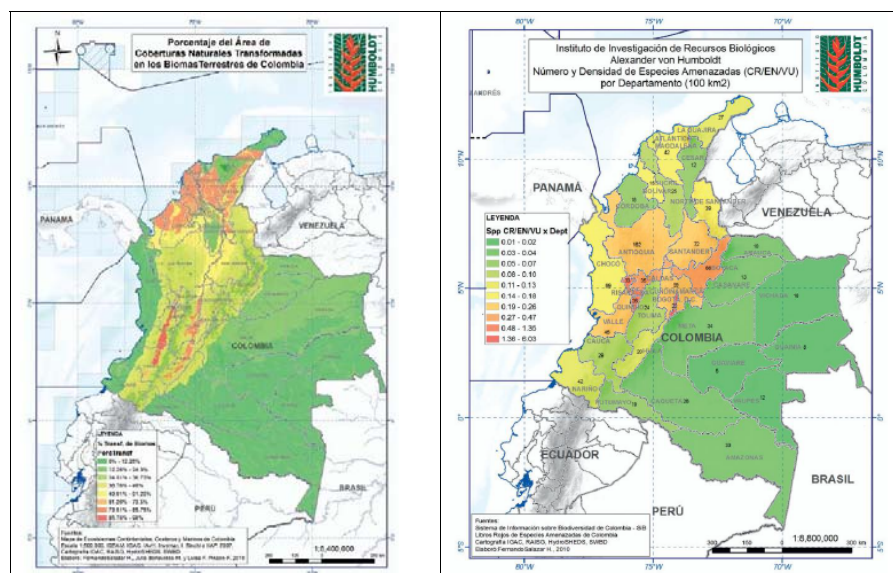
At National level the laws and decrees related to biodiversity and conservation areas include:

- Law 99 of 1993 of Environment and National Environmental System
- Decree Law 2811 of 1974 jV National Code of Natural Renewable Resources and Environmental Protection
- Decree 1791 of 1996 jV Forestry Management
- Other decrees and regulations are included in the Laws annex.

Colombia has a National Nature Parks System that has consolidated the conservation of more than 10 million acres, corresponding to 10% of the national territory. All ecosystems are represented within this protected area network, where dry forests and savannahs are the least abundant (CBD, 2013).

The Humboldt Institute in Colombia has developed maps related to biodiversity at National level. Figure 76 shows the percentage of area transformed in Colombia Natural Biomass (Ecosystems) and the number of endangered species per department.

Figure 76. Changes in natural ecosystems and number of endangered species in Colombia



It can be observed from the national level that the area of the base case is in between 35 to 45% of transformed ecosystems mainly due to agricultural activities and urban density. The density of number of endangered species in the area of the project is in the medium-low range (yellow area).

In the case study region, the management of the *guaduales* is recommended to be done in forest nucleos (nucleos forestales). These are areas where the productive activities are carried out around a local forest area including the biomass production, silvicultural activities, forest management and feedstock transformation (Cruz, 2009). The purpose of these *nucleos* is to concentrate the activities to guarantee the availability of the products at long term and to aid the development of co-products and new markets (Cruz, 2009).

The FSC audit report (GFA Consulting Group, 2005) certified CORGUADUA with an area of 96 ha. The report declared the farms with forested areas are not in protected areas. In the Forest Management Units (FMU) several species were identified as threatened, critically threatened and vulnerable:

- Cane fox (Zorro canero) (*Cerdocyon thous*); Annex II CITES
- Mountain dog (Perro de monte) (*Potos flavus*), Annex III CITES
- Coati (*Cusumbo solo*) (*Nasua nasua*), Anexo III CITES
- Anteater (Oso Hormiguero) (*Tamandua mexicana*); Annex III CITES
- Weasel (Comadreja) (*Mustela sp*) Z}Annex II CITES

Other *guaduales* (bamboo forests) in the region have been researched by the Universidad Tecnológica de Pereira reporting biodiversity lists.

It is noted in the FSC audit report (GFA, 2005) that personnel from the farms observe that there are no hunting or extracting activities in the farms and forests.

The NTA8080 request information on High Value Conservation areas (HVC). The FSC audit conducted in the area considered this assessment was not necessary. There is no definition or reference in the Colombian legislation on this issue.

Since 2001 the regional environmental authority or Corporación Autónoma Regional (CARs) from the coffee region states (Caldas, Quindío, Risaralda, Tolima and Valle del Cauca) started activities in the framework of a project called “Sustainable Management of Forests in Colombia” (Manejo Sostenible de Bosques en Colombia) to improve the forest management of guadua stands. One of the outcomes from this project was a Norm (Unified Norm for the management of natural guadua forests or Norma Unificada para el manejo de guaduales naturales in spanish), which defined the guidelines for an adequate management in the framework of legislation.

The planning for bamboo forests in Colombia included the land use planning which considers five attributes: topography, climate, soils, landscape ecology and socioeconomics. Biodiversity is included within the landscape ecology variable. These allowed establishing forest management units (UFM) which consider productivity (low, medium and high). According to the FSC audit report there are farms that favour the natural regeneration of the guadua (bamboo forest) using corridors along streams.

In this form along with the national and regional regulations it is possible to have productive units without damaging other types of vegetation or the local production areas dedicated for other crops such as coffee and fruits.

7.4 Soil quality

Principle 5: In the production and processing of biomass, the soil, and soil quality must be retained or even improved

Criterion 5.1: No violation of national laws and regulations those are applicable to soil management.

Criterion 5.2: In the production and processing of biomass best practices must be applied to retain or improve the soil and soil quality.

Criterion 5.3: The use of residual products must not be at variance with other local functions for the conservation of the soil

According to (Vera, 2006), Colombia can be divided into four geographic regions: the Andean highlands, consisting of the three Andean ranges and intervening valley lowlands; the Caribbean lowlands coastal region; the Pacific lowlands coastal region, separated from the Caribbean lowlands by swamps at the base of the Isthmus of Panama; and eastern Colombia, the great plain that lies to the east of the Andes and that includes the Amazon portion of the country. The majority of the population is concentrated in the Andean highlands and valleys, followed by the Caribbean lowlands.

The density of population along the Pacific coast and in the Eastern Plains and Amazon regions is extremely low. The extremely varied soils reflect the climatic, topographic, and geologic conditions. The Quindío department (part of the coffee region), west of Bogotá, is renowned for its rich soils. On the other hand, soils East of the Andes are typically highly leached, low pH, ultisols and oxisols (Vera, 2006).

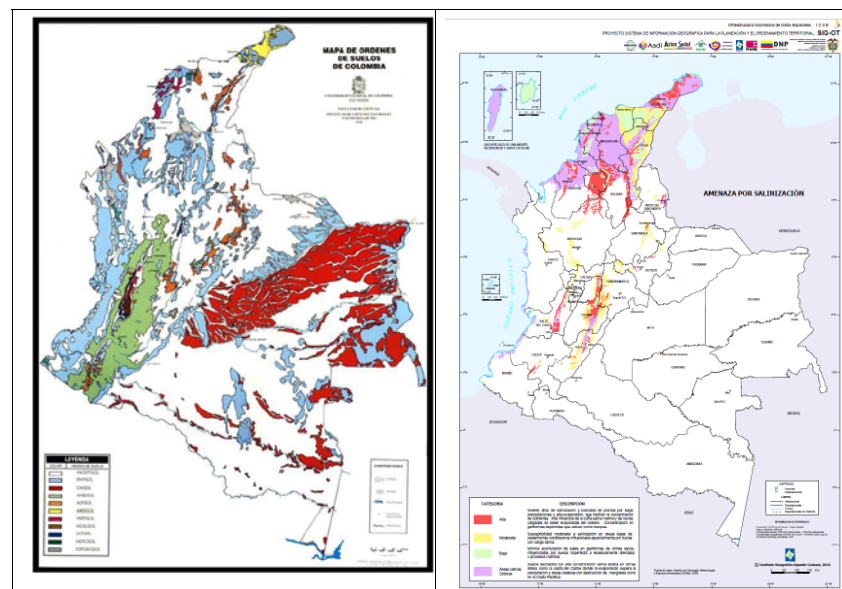
At International level, Colombia has signed and ratified the United Nations Convention to Combat Desertification (signed in 1992 and ratified in 1994), to improve the living conditions for people in drylands, to maintain and restore land and soil productivity, and to mitigate the effects of drought.

At National level laws and decrees related to conservation and protection of soils include:

- Law 99 of 1993 of Environment and National Environmental System
- Decree Law 2811 of 1974 IV National Code of Natural Renewable Resources and Environmental Protection
- Decree 1791 of 1996 IV Forestry Management

Colombia's main environmental problems are soil erosion, deforestation, and the preservation of its wildlife. Soil erosion has resulted from the loss of vegetation and heavy rainfall, and the soil has also been damaged by overuse of fertilizers and pesticides. **Figure 74** shows the classification of soils in Colombia and the risk of salinization.

Figure 77: Classification of soils in Colombia and the risk of salinization (IGAC, 2012)



The area of the base case assessment (coffee region) is not in the area of risk of salinization or on risk of erosion (see **Figure 78**) . Nevertheless, soil erosion could be of concern in the area.

Figure 78: Soil erosion in Colombia Source: IGAC, (2012)



The UTP conducted soil analysis including loss of soil and nutrients assessment (Rodriguez, 2009) regarding the areas of production of guadua. The bamboo forest of guadua (guadual) is reported to be in small patches and it is quite homogenous in plant species because the main species is guadua. Those guaduales where adequate forest management has been taken have high plant diversity. The management implies three main stages: pre-harvest, harvest and postharvest. Environmental impact parameters are reviewed in each one of these stages. These parameters include soil, water, air, flora, fauna and landscape. Assessment of the organic matter in the guadual was conducted by the University.

The guadua forests forms rhizomes which contribute to soil recuperation and conservation. Guadua forms great networks which turns them into efficient biological “walls” diminishing lateral undercutting and deeply anchors them in the soil. This helps to counteract erosion and avoids deterioration. Furthermore, the rapid growth of guadua contributes to biomass production and its incorporation into the soil, which enriches and improves soil texture and structure (Villota, 2010). Therefore, the benefits of conserving and managing the guadua areas is important for soil and water protection.



The FSC audit report (GFA, 2005) states that for the harvest, residues are chopped into small pieces in the site to allow a faster degradation and recycle in the soil. The extraction of the cut material is done by hand to avoid the use of animals and therefore

damage to the soil. The FSC audit report also mentioned that the farms with forest management for bamboo have environmental guides which include measures against erosion. The report does not mention any non-compliance related to soil protection in the farms with forest management.

7.5 Water availability and quality

Principle 7: In the production and processing of biomass ground and surface water must not be depleted and the water quality must be maintained or improved.

- 7a. National regulations and laws for water management
- 7b. Preservation and improvement of water quality
- 7c. Renewable sources

According to (Blackman, 2005), Colombia is a relatively humid country with highly varied topography. Despite the abundance of water resources, in 11 municipalities with 1.2 million of inhabitants, some areas in water availability can be scarce. These municipalities are mainly located in parts of the Magdalena and Cauca watershed basins and along the Caribbean coast. It was projected that 19% of all municipalities, containing 38% of the urban population, will face significant water scarcity problems by 2016 (Blackman, 2005). **Figure 85** shows the main hydrological (rivers) system in Colombia.

Regarding water quality, Colombia also faces problems related to the high population size and the industrial density mainly in the Andean region. The Cauca and Magdalena rivers have high levels of pollution, and the Bogotá River is reputed to be one of the most polluted rivers in the world (Blackman et al 2005). In addition large cities (e.g. Cali, Bogotá, Medellín, Barranquilla, Cartagena, and Bucaramanga) contribute to the high biological oxygen demand (BOD) levels. The industrial sector also contributes to the high pollution levels in water as majority of industrial wastewater is not treated. Furthermore, agriculture is also a leading contributor to water pollution through the high use of agrochemicals.

Colombia's government has different plans to remediate the problem and therefore is signatory of different international Conventions and Agreements related to water which are listed in **Table 28**:

Table 28: International Conventions and Agreements signed by Colombia's government

Acronym	Convention	Date of signature	Date of ratification
OTCA	Amazon Cooperation Treaty	1978	1979
RAMSAR	Convention on wetlands	1981	1997
UNFCC	United Nations Framework on Climate Change		2001
UNCDD	United Nations Convention to Combat Desertification		1999

At National level the laws and decrees related to water resources include:

- Law 99 of 1993 of Environment and National Environmental System
- Decree Law 2811 of 1974 iV National Code of Natural Renewable Resources and Environmental Protection
- Decree 1791 of 1996 iV Forestry Management

In the study area, the Autonomous Regional Corporations of Risaralda (CARDER); Tolima (Cortolima) and Quindío (CRQ) within the coffee region in Colombia, the corporations (local environmental authorities) regulate environmental issues including:

- Forestry: forest management and regulation
- Water: concessions and governance
- Management and control of the use of rivers and ravines
- Control of pollution in aqueducts

The FSC audit reports state that impact evaluation conducted for water as for other environmental issues. Nevertheless, it was not stated which indicators were measured. It is assumed that physical and chemical indicators for water were assessed. The physical and chemical indicators for water are more related to the treatment for immunisation of the bamboo previous to be exported (post-harvest). This processing step is not part of the assessment of the biomass chain as for torrefied pellets production the material used cannot be chemically treated.

Guadua is a water table preserver; therefore no water depletion in biomass production sites is expected. In respect to the regulation of the water cycle, rhizomes and leaves in the soil which are in the process of decomposition, form a type of sponge that avoids that water can flow at rapid and continuous speed. As a result, water is stored during raining season in: root structures, the soil and guadua stems. During dry season, the stored water is released again.



The audit report of the FSC stated that in the certified farms it is avoided to dispose residues in the streams (permanent and temporal) as this may cause the blockage of the flow (GFA, 2005). This practice is also part of the harvest and post-harvest management.

Regarding the possibility of installing a torrefaction plant in the study region, the industrial Tax free zones in the area do have facilities for water use, water treatment and sewage system. Nevertheless, a proper environmental impact assessment needs to be conducted for each specific location and region.

7.6 Air quality

Principle 7: In the production and processing of biomass the air quality shall be maintained or improved

Criterion 7.1: No violation of national laws and regulations that are applicable to emissions and air quality.

Criterion 7.2: In the production and processing of biomass best practices shall be applied to reduce emissions and air pollution.

Criterion 7.3: No burning as part of the installation or management of biomass production units (BPUs).

At national level, following regulations would apply for air emissions related to local transport as well as for the operation of a torrefaction plant.

- Decree 948 of 1995 with relates to the prevention and control of atmospheric contamination and to the protection of air quality.
- Decree 2107 of 1995 – Regulates the protection and control of air quality.
- Resolution 005 of 1996, Resolution 619 of 1997, Resolution 0610 of 2010 and R

- Resolution 0760 of 2010. These regulate the allowed emissions levels produced from terrestrial mobile sources (gasoline and diesel). Establish the partial factors from which a permit is required for the fixed sources emissions. Normative for air quality in the national territory under reference conditions.

An estimation of the potential impacts due to air emissions along the complete chain are assessed by the LCA as presented in section 7.2. It must be noted that when demonstration projects are to be developed, the specific impacts related to the installation and operation of processing facilities need to be assessed in each specific case.

7.7 Land rights

Principle 9: The production of biomass shall contribute towards the social well-being of the employees and the local population

Criterion 9.3: The use of land shall not lead to the violation of official property and use, and customary law without the free and prior consent of the sufficiently informed local population.

Land rights have been one of the main concerns regarding social sustainability in the production of bioenergy crops, particularly in developing countries where communal land is available. According to GRAIN (2012) there have been until 2012 6 land deals that can be considered “grabbed” (**Table 29**). This means that there are claims that the land acquisition was not done in a transparent form and/or there was displacement of local population.

Although the land grabs have not occurred directly in the case study area and the purpose of the acquisition of land is by no means directly related with the bamboo or guadua sector, the issue is important because it shows the lack of transparency for the acquisition of land.

For the base case assessed, the FSC audit report (GFA, 2005) confirmed that all farms have documents of ownership or leasing updated and legal tenure. The FSC audit report stated that there are not indigenous area, land of communal use within the certified area or in the State (Department).

One of the international conventions from the International Organisation on Labour is C169 - Indigenous and Tribal Peoples Convention, 1989 (No. 169) where rights of indigenous people have to be kept. The area of the case study does not include indigenous population.

Table 29: Land grabs in Colombia (GRAIN, 2012)

Landgrabber	Base	Sector	Hectares	Production	Projected investment	Status of deal	Summary
Black River Asset Management	US	Finance	90,000	Cereals	US\$55 million	Done	Black River, a hedge fund owned by US agribusiness giant Cargill, is targeting farmland acquisitions, mainly in South America and Asia. In June 2011, Colombian Senator Wilson Arias reported that Black River, through its recently created Colombian subsidiary, Colombia Agro SAS, had acquired 6 farms covering 25,000 ha in Altillanura, a region targeted for the expansion of soybean production, for US\$6.2 million. In January 2012, the newspaper El Tiempo reported that Cargill had spent US\$ 55 million to acquire 90,000 ha.
China	China	Government	400,000	Cereals		Proposed	In 2010, Portafolio reported that the Chinese Ambassador, accompanied by Chinese business representatives, made a request to the Government of Colombia on behalf of the Chinese government for 400,000 ha in Orinoquía to produce cereals for export to China using Chinese labour. Lands were not identified, however, and later reports indicate that the project has yet to move beyond the initial proposal.
Grupo Poligrow	Spain	Finance	60,000	Oil palm	US\$7 million	Done	In 2008 Spain's Grupo Poligrow, through its subsidiary Poligrow Colombia Ltda, established a 2,500-ha oil-palm plantation on lands it acquired in Meta, Colombia. Colombian Senator Wilson Arias reports that the company has acquired a total of over 60,000 ha in Meta for around US\$7 million.
Ingacot Group	Argentina	Agribusiness	1,000	Maize, soybeans		Done	The Ingacot Group, which produces soybeans and maize on large areas of land that it rents in Argentina, began operations in Colombia in 2009. It rents farmlands in the Magdalena Central area of Colombia, where it reproduces its soybean-maize rotation model of large-scale farming.
Merhav Group	Israel	Construction, finance	10,000	Sugar cane	US\$300 million	Done	Israeli tycoon Yosef Maiman is the sole owner of the Merhav Group, which also controls 61.5% of Ampal-American Israel Corporation, a holding and investment company incorporated in New York and traded on Nasdaq and the Tel Aviv Stock Exchange. A joint venture between these companies, Merhav-Ampal Group, established a large-scale sugar-cane and ethanol project in Colombia in 2010 on 10,000 ha of lands that the company purchased and leased in Pivajay, Magdalena.

Landgrabber	Base	Sector	Hectares	Production	Projected investment	Status of deal	Summary
Monica Semillas	Brazil	Agribusiness	13,000	Crops	US\$6.2 million	Done	In 2008, Mónica, a company owned by Brazil's Marchett and Cambruzzi families that controls 160,000 ha of farmland in Brazil and Bolivia and is one of Latin America's largest producers of soybeans, established a number of subsidiaries in Colombia, under the control of their Bolivian subsidiary Mónica Semillas de Bolivia. By way of these subsidiaries, the company acquired 13,000 ha of farmland in Puerto Gaitan, Colombia, and was able to access subsidies and credit from the state programme Agro Ingreso Seguro

Nevertheless, the following regional and national laws were reviewed for other areas to be considered:

National:

- Law 70 of 1993 or Law of Black communities
- Law 21 of 1991, for the ratification of the Convention 169 of the International Labour Organisation on Indigenous and Tribal communities
- Law 141 of 1961 (and modifications in Law 50 of 1990 and Law 584 of 2000) – on the Labour Code
- Law 80 of 1993 – General Regulation on Contracts in Public Administration
- Law 100 of 1993 – Integral Social Security System
- Resolution 02400 of 1979 – Industrial Security Regulation
- Law 1448 de 2011- Law of victims-Land/ Policy of land restitution.

For the case of Colombia there have been reports on the problem of forced displacement of rural communities especially for the cases of palm oil.¹²¹³ The new Law for Victims of Displacement seeks the restitution of land to those displaced by conflict and support the legal use and tenure of land. Some of this areas require the implementation of agricultural projects where small holders can participate.

The development of the bamboo chain, not only for the energy but also for the materials sector, could be an opportunity for the establishment and exploitation of bamboo plantations. Hence providing alternatives for development for those returning to their land. It requires low capital investments and could also be an alternative to other crops which are not economically viable. Additionally, the ample products related to bamboo processing could offer opportunities for knowledge, skills and technological development.

¹² http://www.javeriana.edu.co/Facultades/C_Juridicas/pub_rev/documents/03-LAPROTECCIONDELAPROPIEDAD_000.pdf

¹³ ww2.unhabitat.org/programmes/landtenure/documents/ColumbiaFinal.doc · DOC file

7.8 Impact on local economy

Principle 8: The production of biomass shall contribute towards local prosperity

Criterion 8.1: Positive contribution of private company activities towards the local economy and activities

The current population in Colombia is about 46 million. The distribution in the different natural regions and departments is presented in **Figure 79** and **Figure 80**. It can be seen that the Andes region is the most populated region in Colombia and the rural populations is the highest in most of departments of the country.

Figure 79: Population distribution by region

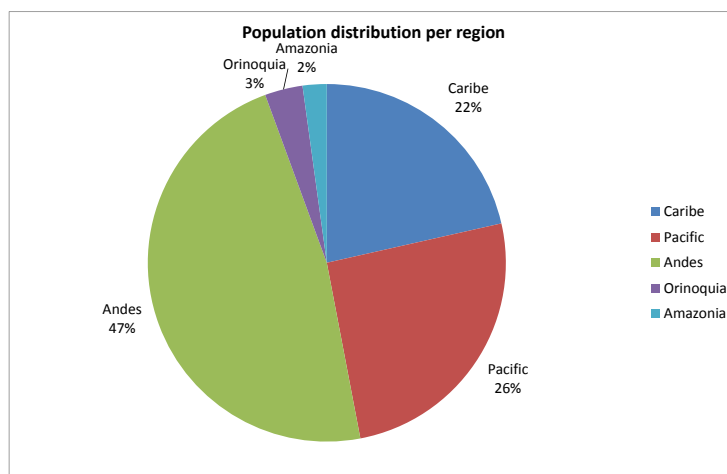
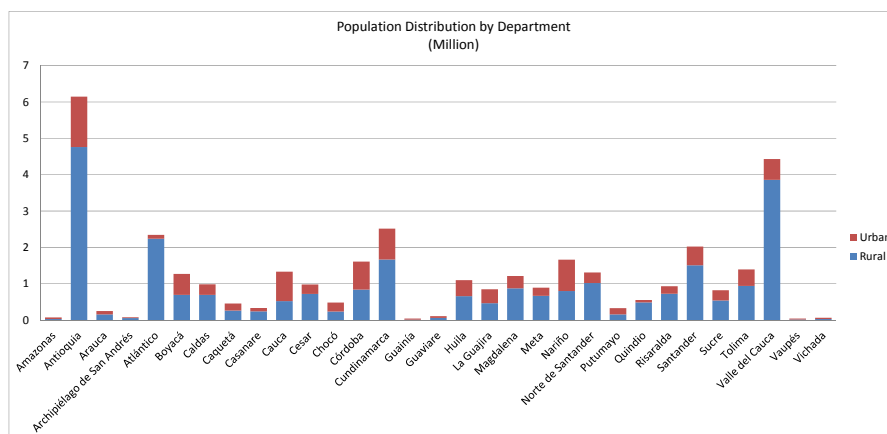
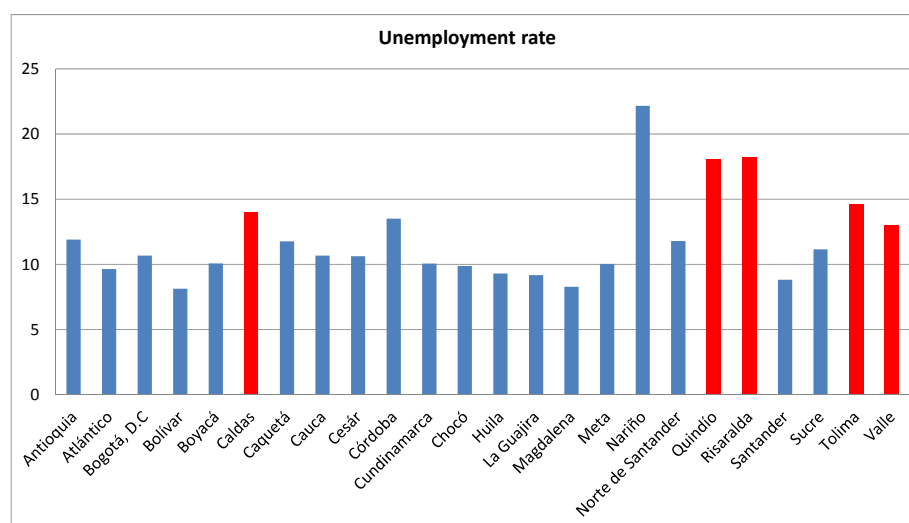


Figure 80: Population distribution by Department (DANE, 2010)



According to the National Department Administration in Colombia (DANE, 2010), the unemployment rate by Department is shown in **Figure 81**. It can be observed that the five Departments of the Coffee Axis (red) have a high rate of unemployment compared to other departments in Colombia, only surpassed by the Nariño Department.

Figure 81: Unemployment rate by Department (DANE, 2010)



The implementation of a supply chain of bamboo may contribute for the job creation in the area. According to the report by (Villota, 2010) the commercialisation of guadua as raw material is a process consisting of production and sale of cylindrical guadua with little aggregated value. The selection of the bamboo is based on the quality demanded and are derived from external characteristics (colour, diameter, length). Currently, the supply of raw material for the guadua industry (concentrated mainly in construction, furniture, craftwork, and a small but growing industry of guadua laminate), comes from natural guadua forests.

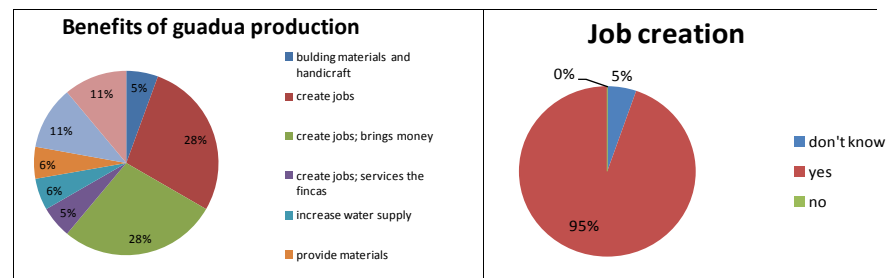
“The market has a small group of producers that offers raw material (cylindrical guadua and “esterilla”, used for flooring) according to high quality standards. This guadua undergoes a rigorous selection process starting with classification and selection of stems prior to harvest, following specific maturity and morphological criteria (diameter and erectness). Subsequently, harvest is conducted following particular timely conditions (at night between 9 p.m. and 4 a.m.) and with respect to the lunar phase (waning moon). Finally, the post-harvest treatment of the material includes hardening, followed by an immunisation through immersion into borax, and finally the drying and storing of the product” ((Villota, 2010), page 18).

The majority of enterprises in the sector buy raw material from “guadueros” (guadua harvesters) according to specific negotiation conditions. This shall guarantee that guadua is continuously supplied according to the established requirements. The actors involved know the characteristics of guadua in respect to the quality of raw material used in the different steps of processing. The main market segment that applies here is the construction sector in which guadua is used as a permanent structural element.

The above activities and market were verified during the field trip in 2011. It is expected that the market of guadua residues and guadua (and/or other bamboo species) for bioenergy market will improve the supply chains in the area and therefore enlarging the bamboo market.

A small survey (19 respondents) was applied to find out the opinion of the local community regarding the activities of the guadua production in the region. In terms of the benefits of the guadua production, majority of the respondents consider it contributes to job creation (95%). The benefits of the guadua production were also related to job creation and economic improvement in the region (**Figure 82**).

Figure 82: Benefits of the production of Guadua according to community's survey (Diaz-Chavez).



In Colombia and particularly in the coffee region, *G. angustifolia* represents an important natural resource traditionally used by farmers to build long-lived products such as houses, furniture, handicrafts, veneers and flooring. A significant amount of it is not suitable for manufacturing products and is available from processing sites and from forest resource management. These residues could be used for bioenergy production, providing a potential economic use for this material.

7.9 Well-being of the local population and of employees

Principle 9: The production of biomass shall contribute towards the social well-being of the employees and the local population

Criterion 9.1: No negative effects on the working conditions of employees.

Criterion 9.2: No negative effects on human rights.

Criterion 9.4: Positive contribution to the well-being of local population.

Criterion 9.5: Insight into possible violations of the integrity of the company.

Working conditions have been included in most sustainability schemes for biofuels and biomass accepted by the EC (EC, 2010). For working conditions legal issues at international level, **Table 30** shows, following the requirements of the RED (2009), the ILO conventions that Colombia has ratified (ILO 2013).

Table 30: ILO conventions and ratification in Colombia

ILO Convention	Ratified	In force
Convention concerning Forced or Compulsory Labour (No 29)	1969	✓
Convention concerning Freedom of Association and Protection of the Right to Organise (No 87)	1976	✓
Convention concerning the Application of the Principles of the Right to Organise and to Bargain Collectively (No 98)	1976	✓
Convention concerning Equal Remuneration of Men and Women Workers for Work of Equal Value (No 100)	1963	✓
Convention concerning the Abolition of Forced Labour (No 105)	1963	✓
Convention concerning Discrimination in Respect of Employment and Occupation (No 111)	1969	✓
Convention concerning Minimum Age for Admission to Employment (No 138)	2001	✓
Convention concerning the Prohibition and Immediate Action for the Elimination of the Worst Forms of Child Labour (No 182).	2005	✓

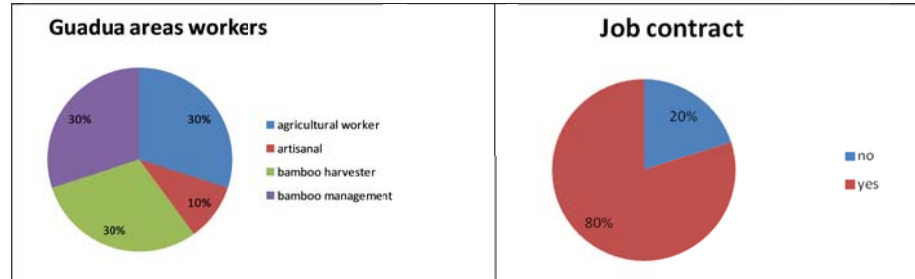
At the local level, the FSC audit report (GFA, 2005) demonstrated that the case study farms have capacity building in place for the workers. They also assist universities receiving students. Besides, the farms association (Corguadua) offer technical training for the members.

The FSC report (GFA, 2005) stated that all health and safety measures were in place in the farms audited. This was also witnessed during the field trip in 2011 where measures were observed for the cut of the bamboo (e.g. personnel equipment such as lens, boots, gloves, helmets) and also for the chemical treatment of the bamboo poles (pools with chemical).

Gender issues have been considered. Four out of five audited farms have legal representatives or owners of the farms are women (e.g. YARIMA GUADUA E.U; Núcleo Forestal de Guadua la Esmeralda – NFGLE – de la Sociedad Colombiana Del Bambú; Hacienda Santa Barbara; COMFAMILIAR RISARALDA). The work in the gradual requires physical endure and although it does discriminate women working there, it was not observed during the field trip.

A small survey (11 respondents) was applied to local workers to gain some knowledge regarding their perceptions on working conditions and the sector of the supply chain where they work. **Figure 83** shows two of the findings. The classification of agricultural worker was deemed as general conducting other activities apart from harvesting, such as cleaning the gradual.

Figure 83: Results from survey applied to workers



Despite the majority of the 11 workers interviewed do have a contract, majority of workers in the agricultural sector in Colombia do not have job contracts.

Small holders have no or barely personnel employed besides members or their own family. They have generally local background and the expectations are that they obtain products and services from local suppliers as well. In that way small-holders contribute sufficiently to the local prosperity and social well-being and do not need to demonstrate this according to the requirements of NTA8080 (NEN, 2009).

7.10 Stakeholder consultation

Surveys and interviews were conducted in the area. A total of 19 questionnaires were conducted with residents of local communities of the coffee region. A total of 11 questionnaires were applied to workers in the region working in areas related to *G. angustifolia* bamboo production.

Interviews in 2012 were conducted with several stakeholders related with the *G. angustifolia* activities in the Coffee region as well as in Cundinamarca department. The meetings were held in Pereira, Cali and in Bogota. **Table 31** presents the interviewed stakeholders.

Table 31: Consulted organizations at local and national level regarding the production of guadua

Organisation
Ministry of Environmental Affairs
Ministry of Agriculture
National University (Bogota)
Free Handle Zones (Pereira and Quindío and Armenia)
WWF, Pereira
Yarima Farm (Corguadua member)
La Esmeralda Farm (nucleo) (Corduadua member)
FSC, Cali
Geoambiente, Bogota
Guadua productive chain, Cundinamarca Department
Javeriana University, Bogota

Additionally, two events were organized in April 2013 to present the project results to a broader community. The dissemination event was called “Bamboo and biomass in Colombia: bioenergy source for development”. One meeting was held at the Technological University of Pereira and a second one at the Dutch Embassy in Bogota. Stakeholders from the guadua production sector as well as NGOs research and public institutions were present.

The stakeholders interviews and the meetings attendees helped to identify some initiatives and the characteristics of the guadua supply chain in Colombia.

Most of the points that the interviewees referred to during the interviews and meetings are summarized as follows:

- The bamboo supply chain exists but not fully developed. This supply chain is based on *G. angustifolia*.
- The internal road transport cost as well as infrastructure are some of the limiting factors for the development of an economically viable chain.
- The lack of incentives and the institutional barriers for the management of natural stands also are limiting factors.
- National legislation is ambiguous regarding the management of guadua, it is not clear if it is an agricultural or a forestry product. Therefore the policy regulations remain between two different ministries, Agriculture and Environment. (See details in section 3.4.2)
- The ambiguity of the product does not allow full management and use of the forest resource at local level with the local environmental authorities (Corporaciones) as guaduales are considered for protection of water resources.
- National guidelines exist for the management of guaduales and FSC certification standard but the last one does not contribute to increase the demand of the product.
- Management of guadua is done to favour environmental issues therefore mechanization is not possible and resource management (harvest) is time demanding.

- *G. angustifolia* and other species of bamboo have not been considered as a possible source of biomass in the country. There is lack of awareness on the potential and benefits of the feedstock.
- It is recommended to improve the management of the product in the regions where it can be found.
- The promotion of bamboo production should be focused not only on the supply but also on the processing of material for the energy, the construction and the material sectors.
- Other regions apart from the coffee region are also suitable for bamboo production aiming to supply material and products for the local market as well as for the international market.
- Alternatives for valorisation would lead to the management of natural stands and the establishment of plantations.
- The current access to international markets of bamboo finished products from Colombia is very limited as the major global supplier is China; therefore the opening of new markets (local and international) and products diversification would highly benefit the bamboo sector.

The study conducted by Retz, reflected similar issues. Retz shows that actors believe that, despite the many problems the guadua sector faces in Colombia, a guadua industry is viable including smaller and larger producers of guadua forests. Indeed, to secure a continuous supply with a consistent quality, plantations must be included, especially as the full potential of all natural forests is not exploited. And it is still the question whether operators with only a relative small guadua forests, are willing to be saddled with the administrative mill to legally exploit their guadua. It is assumed that plantations will mainly be established by operators with significant financial resources, which might push smaller, often more vulnerable, producers out of the market. In this context, the equity component of FSC certification, requiring financial resources as well, might be compromised. These plantations are often established within or adjacent to natural guadua forests as form of reforestation or to expand the area under guadua for increased the supply of culms. Undergrowth is tolerated, in general, and are hence not considered as pure stands as is often associated with tree plantations (Retz, 2010).

The views of the interviewees and the stakeholders meetings address mainly to the management of the resource and the legal issues. Both of them can be solved to favour the development of the supply chain if the guadua in particular is considered as an agricultural product rather than a forestal one.

7.11 Certification

Although there is currently not a regulation or sustainability criteria in the EU for imported solid biomass for energy production, there have been several initiatives that consider them.

Other schemes related to the use of forest resources are also applicable to biomass for energy, such as the **Rain Forest Alliance Forest Stewardship Council** (FSC) and the **Pan**

European Forestry Commission (PEFC) both standards consider issues on biodiversity, soil, water, management and in the case of FSC carbon stocks.

The **Swan label** for biofuels and biofuel pellets are part of the Nordic Swan eco-label for Scandinavian countries (Denmark, Finland, Iceland, Norway, Sweden). The label covers 67 product groups of which one is wood pellets.

The **Laborelec label (LBE)** is a business to business certification system developed by the research centre Laborelec (part of RDF Suez) and SGS for the electricity company Electrabel in 2005. Focuses on woody biomass but also on agricultural residues.

Green Gold Label (GGL) is a business to business certification initiative started by the Dutch energy company Essent and Skall International (Control Union) in 2002.

Pelkman et al (2011) reviewed some of the sustainability criteria in some voluntary schemes used in Europe for solid biomass (mainly pellets) (see **Table 32**).

Table 32: Sustainability criteria in some voluntary schemes (Pelkman et al, 2011)

Criteria	System				
	NTA8080	LBE*	DRAX	GGL	Swan**
GHG savings	X	X***	X	X	X
Energy Balance		X***		X	X
Biodiversity	X		X	X	X
Carbon Stocks	X		X	X	
Land Use change					
Ecosystem services	X			X	
Soil protection	X		X	X	
Water protection	X		X	X	
Air protection	X		X		
Restoring of degraded land	X			X	
Social principles	X		X	X	X

* Laborelec does not have its own sustainability standard

** Swan label for pellets

*** no criteria, but required evaluation and approach

The voluntary verification scheme, **The Initiative Wood Pellets Buyers (IWPB)** unites utility firms that fire large quantities of wood pellets aiming to have a common sustainability approach. The goal is to enable the trading of industrial wood pellets among the partnering companies. **The IWPB brings together GDF SUEZ, RWE, E.On, Vattenfall, Drax Plc, and Dong**, as well as **certifying companies SGS, Inspectorate, and Control Union. Laborelec** participates in this work panel as a technical expert. All biomass-fired power plants rely on long-term contracts. When one of them needs to shut down unexpectedly, it is in the plant's best interest to trade its wood pellet supply. Hence, contract forms and legal conditions must be harmonized to ensure appropriate trading conditions¹⁴.

¹⁴ (<http://www.laborelec.be/ENG/services/biomass-analysis/initiative-wood-pellet-buyers-iwpb/>)

The IWPB addresses three main issues:

- 1) the layout and conditions of procurement contracts for wood pellets,
- 2) the technical specifications for wood pellets,
- 3) the sustainability principles applicable to wood pellets/woody biomass sourcing and trading.

The IWPB present a proposal of sustainability principles for the sourcing and trading of woody biomass among IWPB members. In the longer term, it is anticipated that these principles will be recognised and adopted by the wider market ¹⁵.

The Dutch Sustainability Standard **NTA 8080** was accepted by the EC in 2012. The NTA 8080 Standard is framed in 9 principles containing criteria and indicators and covers the complete chain of liquid, gaseous and solid biofuels. The EC also accepted the NTA 8081 which includes the 'rules' to enable certification against the requirements of the NTA 8080..

All actors and process steps (production, processing and end users) along the biomass chain should comply with sustainability criteria. When considering the bamboo production step, sustainable forest management of the base case study is addressed via forest certification. The forest certification has been promoted under the principles of the Forest Stewardship Council (FSC), consequently specific standards were elaborated for Guadua standard, because of particularities of these kind of forests. This standard is under review by FSC. The criteria from FSC are presented in **Table 33**.

Table 33: FSC standard's principles

Number	Principles
1.	Laws and FSC principles
2.	Rights and responsibilities of land use
3.	Indigenous groups rights
4.	Community relationships and workers' rights
5.	Forest benefits
6.	Environmental impact
7.	Management plan
8.	Monitoring and assessment
9.	Management of forests with a high conservation value
10.	Plantations

Guaduales from 5 farms and one organization were certified. At the moment, it is also possible to commercialize transformed guadua products with the stamp of FSC. From this group of certified farms, two were visited: Nucleo Forestal de Guadua La Esmeralda, and Hacienda Yarima. La Esmeralda is part of a nucleo while la Esmeralda is independent but forms part of Corguadua, the organization formed to be able to be certified.

¹⁵ http://www.laborelec.be/ENG/wp-content/uploads/2012/08/2012-06-05-IWPB-Initiative_Wood_Pellets_Buyers-Sustainability_principles_Report1_Public_draft-v2.pdf

The costs of NTA certification might be a barrier for the producers. Certification costs have been covered through an initiative from GIZ for some of the producers of Corguadua in the coffee region. It has been estimated by the producers that without this project it would be too costly to continue the certification

When bamboo producers are small-holders, they should comply with the sustainability requirements in the NTA 8080 as large companies. However, their efforts, which they have to deliver are in relation to the profits.

To offer small-holders these possibilities, small-holders are released from a number of provisions. It concerns the requirements with regard to;

- Consultation of stakeholders
- Prosperity
- Working conditions
- Contribution to social well-being of local population
- Integrity

In addition, small holders have the opportunity to certify themselves as a group (or connection with a region) (NEN, 2009).

As previously mentioned the corporation Corguadua has a FSC group certification. The experience gained by this group along their certification process, is a valuable model to learn from when other certification schemes are to be implemented specifically for the bioenergy market.

When is intended to certify the complete biomass to energy chain, It needs to be “demonstrated” that the GHG emissions reduction is of at least 50-70% of the fossil-based route (for NTA 8080). Bamboo is not yet considered within the biomass supply chains from which default data is provided by the EC. Therefore, it is required to measure, monitor and demonstrate the potential superior performance of the bamboo chain (see section 7.1.1).

7.12 Other issues

The Global Bioenergy Partnership is currently conducting a pilot for the application of indicators at national level regarding bioenergy. These indicators have been considered for the palm oil and sugar cane production and the biofuels products. **Table 34** shows the three pillars GBEP has been identifying. Nevertheless, this pilot does not consider other bioenergy feedstocks.

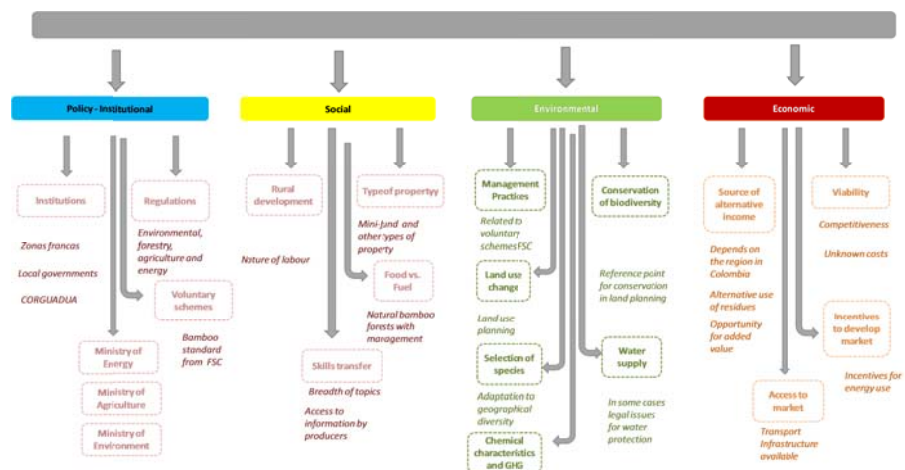
Table 34: Global Bioenergy partnership (GBEP) pillars

PILLARS		
GBEP's work on sustainability indicators was developed under the following three pillars, noting interlinkages between them:		
Environmental	Social	Economic
THEMES		
GBEP considers the following themes relevant, and these guided the development of indicators under this pillar:		
Greenhouse gas emissions, Productive capacity of the land and ecosystems, Air quality, Water availability, use efficiency and quality, Biological diversity, Land-use change, including indirect effects.	Price and supply of a national food basket, Access to land, water and other natural resources, Labour conditions, Rural and social development, Access to energy, Human health and safety.	Resource availability and use efficiencies in bioenergy production, conversion, distribution and end-use, Economic development, Economic viability and competitiveness of bioenergy, Access to technology and technological capabilities, Energy security/Diversification of sources and supply, Energy security/Infrastructure and logistics for distribution and use.

As part of the screening of sustainability issues, several issues were identified in the supply chain of guadua (**Figure 84**). According to Diaz-Chavez (2011) four pillars of sustainability need to be considered. They include the traditional pillars of sustainability environmental, social and economic but a fourth one is considered as policy and institutions should be also part of sustainability and not just a driver.

As it can be observed in **Figure 84** other issues were identified as part of the sustainability issues including transport, access to market and incentives in the economic pillar. In the environmental pillar selection of species and conservation areas are examples of some of the considerations discussed in previous sections.

Figure 84 Sustainability screening for the project of torrefied pellets from bamboo in Colombia (Diaz-Chavez, 2012).



In the social aspect, rural development was part of the screening and is an area that should be further explored in other regions in Colombia, as in the coffee region, the agricultural activities are well developed. Regarding policy institutions, other issues identified were institutions related to the supply chain of guadua and the local

government (see details in section 3.4.2 **Figure 18** and **Figure 19**) as well as the incentives such as the free trade zones which for the development of industrial areas.

8

Conclusions and recommendations

Bamboo has the potential to be a sustainable feedstock in the bio-based economy, not only for the energy but also for the chemicals and materials sectors. The techno-economic potential of the biomass chain for the bio-based economy differs according to the species, maturity stage, production site and cultivation practices (e.g. fertilizers application), harvesting alternatives (e.g. selective harvesting vs. clear cutting), etc.

From the evaluation of the complete biomass chain dealing with the technical, economic and sustainability issues following conclusions and recommendation are addressed:

Technical assessment

Samples of five year old bamboo species *G. angustifolia* were subjected to fuel analysis, pre-treatment tests (torrefaction, dry and wet) as well as combustion and gasification trials. Additional to *G. angustifolia*, four additional bamboo species (*Guadua amplexifolia*, *Bambusa vulgaris*, *Dendrocalamus strictus*, and *Chusquea subulata*) were characterized in order to carry out a preliminary evaluation based on their compositions. From the performed tests it is concluded that:

- This fuel presents comparable fuel characteristics with other biomass feedstocks regarding heating value and chemical composition. Untreated material is tenacious and fibrous which makes it difficult and expensive to grind. Its composition lies between woody and herbaceous biomass, however the alkali content in the untreated material is quite high.
- Torrefaction improves the physical qualities of the fuel, such as grindability and moisture content. Torwash removes salts and minerals from biomass. This is in particular interesting for feedstocks containing significant amounts of undesirable alkali components, as is the case of bamboo, in case of use in combustion or gasification. From the fuel characterisation results it was concluded that wet torrefied *G. angustifolia* is a high quality solid fuel concerning its elemental composition and heating value, which are similar to clean wood.

- Quantitative baseline data on the project show that bamboo behaves differently in torrefaction than other biomass species. In particular its high energy density will require some consideration on both equipment design as well as operating conditions.
- Concerning the combustion simulation trials, the non-pre-treated *G. angustifolia* bamboo shows fouling potential similar to herbaceous biomass; dry torrefaction improves the fouling behaviour somewhat, as shown in the fouling factors and deposition propensity results, and torwash renders a product of high quality that minimises risk of fouling and deposition.
- Despite the lower alkali and chlorine content compared to other herbaceous fuels, the combustion of 100 % virgin but also dry torrefied *G. angustifolia* bamboo is still not recommended before extensive and dedicated assessment of the fouling and slagging risks at pilot-scale or with additional detailed lab-scale tests. This is mainly necessary with respect to the increased alkali content of the fuel compared to clean wood. On the positive side, the material needs to be pulverised, which is straightforward after dry torrefaction. Co-firing at relatively small percentage though is an option as is the standard practice nowadays, due to the counteracting effects of coal ash, minimising the risks of slagging and fouling.
- Other bamboo species identified as potential candidates for coal substitution were not pre-treated and tested in the laboratory scale combustion facility, however a brief evaluation of their fouling tendency was carried out based on their ash elemental composition. The calculated values suggest that some bamboo species such as *Bambusa vulgaris* and *Dendrocalamus strictus* could be further assessed for use in pulverized fuel power plants.
- As for the gasification test, the entrained flow gasification of 100% guadua exhibits a low slagging potential due to high silica oxide content in the fuel. Nevertheless the addition of the torrefied bamboo to a low rank coal (alkali, iron or the ash rich) can be advantageous in entrained flow gasification process. The addition of a aluminosilicate flux material can improve the slagging behaviour, as well as significantly increase the capture of alkali and thereby reduce the downstream fouling propensity.

Economic evaluation

- Bamboo has some advantages over other lignocellulosic feedstocks such as: high land productivities (10-40 ton/ha-year) and higher biomass densities (500-600 kg/m³) which results in reduced production and transport costs.
- In the coffee region of Colombia an annual potential of 400 to 1,800 kton_{dry} could be produced from natural stands or from plantations of *G. angustifolia*. The potential of other bamboo species, and regions in the country, needs to be assessed.
- From the overall economic model applied, and based on the available local data as well as on estimates, the torrefied bamboo pellets could cost between 5-8 €/GJ (2012) at the port of Rotterdam, depending on the source and local logistics strategies. This price range is within the current price of white pellets, therefore could be a potential for the economic competitiveness of the chain. Detailed feasibility studies need to be performed for specific business cases.

Sustainability assessment

Apart from the techno-economic feasibility, the sustainability performance of the bamboo chain has been assessed based on the certification system NTA8080. Additionally an screening LCA has been performed in order to identify the potential environmental impacts of electricity production from bamboo and to compare them with those of coal-based electricity. The main finding of the sustainability assessment are:

- The bamboo chain has the potential to comply with all sustainability requirements as presented in NTA8080 and by the EC recommendations for solid biomass EC (COM 2010).
- From the case-study which considers a group of farms which are FSC certified it has been identified the barriers and opportunities with FSC certification and with other certification schemes which would apply to solid biomass such as NTA8080.
 - The costs of NTA certification might be a barrier for the producers. Up to date FSC certification costs have been covered through an initiative from GTZ for some of the producers of Corguadua in the coffee region. It has been estimated by the producers that without external funding it would be too costly to continue the certification under the current market conditions.
 - The permits required by the Colombian law for the exploitation of natural Guadua bamboo forest results in vicious circles and lack of competitiveness of the sector under the current market conditions.
 - The valorisation of residual streams from forest and plantations might represent an incentive for increasing forest management. Alternatively, established plantations do not require permits for exploitation. The establishment of plantations in unused/or degraded land as well as a reforestation crop might be a better alternative for the development of the biomass chain.
 - The production of bamboo biomass is a low capital investment and labour intensive activity which would lead to employment generation for the rural population.
 - The experience and knowledge gained by the FSC certified farms in the coffee region could be reproduced in other regions of the country with potential for bamboo production.
- When compared to coal-based electricity, the use of torrefied *G. angustifolia* bamboo as solid fuel in NL results in a reduction of greenhouse gases emissions above the 70% recommended by the EC (2010) and by the NTA8080 System. When including emissions saving from carbon accumulation and potential bonus for restoring of degraded land, the GHG emissions reduction would increase substantially leading to C storage opportunities. The results are dependent on the cultivation and harvesting strategy and whether the system is based on the use of residues or dedicated forest/plantations.
- The LCA results indicate the superior environmental performance of the bamboo chain compared to the coal-based reference. This applies for all

impacts categories with the exception of acidification and photochemical oxidation. Both exceptions mainly stem from emissions related to interoceanic transport fuel usage and the potential use of fertilizers. These potential negative impacts are common to biomass chains. However, transport related impacts are lower for bamboo than for other biomass feedstocks (for the equivalent transport distances), due to its high density. Reduction of transport related impacts could be achieved by reducing the use of fossil fuels in interoceanic transport, (e.g. by replacing them with sustainable biofuels). Reduction of potential impacts related to fertilizers use could be accomplished by an integrated system with:

- Biofertilizers use which are produced from the bamboo leaves as well as from other sources available in the region.
 - Recycling of minerals resulting from the processing steps, in particular if hydrothermal (Torwash) pre-treatment is applied where a stream rich in minerals is produced.
 - Soil properties improvement via alternatives such as biochar production and use in the plantations could be explored
- Additionally, the sustainability criteria which are not yet part of FSC standards - specifically the GHG - could become an market opportunity for bamboo producers and end users.
- Bamboo is not included in the list of the default biomass chains considered by the EC, therefore it needs to be “demonstrated” that the GHG emissions reduction is at least 50-70% of the fossil-based route. There are no default values in EU-RED for bamboo forest/plantations, the GHG emissions reductions data needs to be demonstrated, therefore monitoring activities are required.
- The macro monitoring of bamboo production issues should include: biodiversity, preservation, land use, food security, social well-being and local prosperity, and specifically for bamboo also the competition with existing utilization markets, i.e. furniture production. In certain countries competition with this existing market is not considered to be an issue since the added value for this market is much higher than for energy use. Additionally, the access to international markets of finished bamboo products from Colombia is very limited as the major global supplier is China; therefore the opening of new markets (local and international) and product diversification would highly benefit the bamboo sector.

Chain development

- The interest in bamboo as an alternative feedstock is increasing rapidly. However, the end use of the feedstock and the supply chain development requires the direct involvement of the private sector as well as the support of public institutions in both the producing countries as well as end use countries. The development of the supply chain requires an active role of all actors involved either in the international and/or national markets. The participation of end users in any follow up initiative is a must.

Additional relevant issues for the supply chain development are:

- The recognition of bamboo as a biomass source for different applications in the local and international market.

- The Colombian public institutions (ministry of environment and ministry of agriculture) should develop a regulatory framework that clearly defines bamboo either as an agricultural resource, a forestry resource or an agro-forestry resource.
- Multidisciplinary expertise on bamboo production, pre-treatment, conversion and system assessments are of key importance in the successful integration of bamboo in the bio-based market in Europe and other regions.

Colombia

A.1. Maps

Figure 85: Colombia physical map



Figure 86: Natural regions map



A.2. Colombia's environmental and socio-economic information

Location

Colombia is located in the northern tip of South America with access to the Caribbean sea, and the Atlantic and Pacific oceans (Figure 1). Its geographic coordinates are: 4° 00

N, 72° 00 W.

Geographical characteristics:

It has an area of 114175 (1000 Ha) with a land area of 110950 (1000 Ha). The agricultural land is 43785.6 (1000 Ha)

Environmental characteristics (Vera, 2006)

The Colombian rivers have historically conditioned human settlement and farming. The most important river system is the Magdalena; its basin, including that of its major tributary, the Cauca, covers 260 000 km². In this area are developed the nation's main socio-economic activities and is the area where more than three-fourths of the population is settled.

The extremely varied soils reflect the climatic, topographic, and geologic conditions and are suitable for agriculture activities.

Colombia can be divided into four geographic regions: the Andean highlands, consisting of the three Andean ranges and intervening valley lowlands; the Caribbean lowlands coastal region; the Pacific lowlands coastal region, separated from the Caribbean lowlands by swamps at the base of the Isthmus of Panama; and eastern Colombia, the great plain that lies to the east of the Andes and that includes the Amazon portion of the country. The majority of the population is concentrated in the Andean highlands and valleys, followed by the Caribbean lowlands. Because of the country's proximity to the Equator, its climate is tropical and isothermal but annual precipitation is variable. Climatic differences are related to altitude and the displacement of the inter-tropical convergence zone between the two major air masses from which the northeast and southeast trade winds originate.

Population size and characteristics

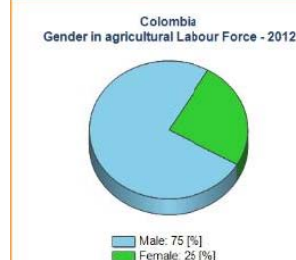
The population size is of 48165(1000).

Human Development Index 0.689

Source (FAO, 2013)

Colombia: Evolution of population and labour force composition							
	Share [%]				Annual growth rate [%]		
	1997	2002	2007	2012	1997-2002	2002-2007	2007-2012
Rural population [%]	28.81	27.33	25.82	24.33	-1.05	-1.13	-1.18
Labour force in agriculture [%]	21.58	18.54	16.04	13.95	-2.99	-2.86	-2.75
Females [% of labour force]	20.86	23.08	24.38	25	2.04	1.1	0.5

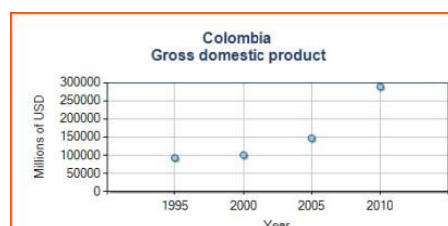
Source (FAO, 2013)



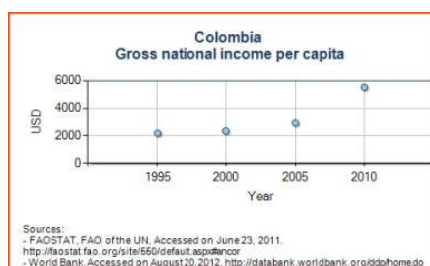
Source: FAOSTAT, FAO of the UN, Accessed on June 23, 2011.
<http://faostat.fao.org/site/550/default.aspx?lang=en>

Source (FAO, 2013)

Gross Domestic Product, 288189 (millions of US dollars) Source



Source (FAO, 2013)



Source (FAO, 2013)

Natural Resources (Vera, 2006)

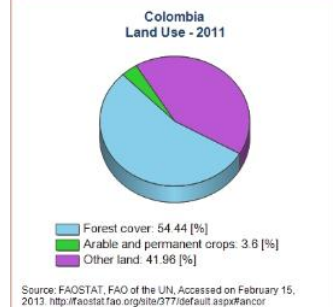
The country is extremely rich in terms of renewable and non-renewable natural resources, including oil, emeralds, gold, numerous metals, coal, and a rich vegetation and fauna. Colombia's leading exports are oil and coffee. Despite long-term, and continuing, social disturbances, the economy is strong but investments have been lagging behind.

Land tenure (Vera, 2006)

Land tenure patterns have remained remarkably unchanged since the initiation of agrarian reform efforts in the 1930s; landholding remains highly concentrated. The national agricultural census of 1971 showed an obvious imbalance in land distribution: ten percent of the farms

Colombia: Evolution of land use							
	Area [Millions of ha]				Annual growth rate [%]		
	1996	2001	2006	2011	1996-2001	2001-2006	2006-2011
Total area	110.95	110.95	110.95	110.95	0	0	0
Arable land	2.43	2.43	1.9	2.1	0	-4.8	2.02
Permanent cro	1.66	1.7	1.46	1.9	0.48	-3	5.41
Forest cover	61.91	61.41	60.9	60.4	-0.16	-0.17	-0.16

Source (FAO, 2013)



Source (FAO, 2013)

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