Evaluation of Torrefied Bamboo for Sustainable Bioenergy Production

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Abstract

Bamboo is a potential sustainable biomass source for renewable heat and power production. Bamboo presents common fuel characteristics with other biomass feedstocks regarding heating value and chemical composition. Up to date, there are no studies on fuel properties of the bamboo specie *Guadua angustifolia*.

Bamboo is a difficult fuel and most thermal conversion processes have stringent fuel specifications, which are challenging to fulfil with biomass streams. Bamboo is tenacious and fibrous which makes it difficult and expensive to grind. Furthermore, the characteristics with regard to handling, storage and degradability are not favourable for biomass in general. The thermal pre-treatment torrefaction is a promising upgrading technology that can enhance the fuel quality by addressing these issues. During torrefaction, biomass is heated to 250-320°C in the absence of oxygen. At the end of the process the material is milled and compressed into pellets. In this way, the biomass becomes easy to grind, more hydrophobic and has a high energy density. Alternatively, wet torrefaction (Torwash) allows for combined torrefaction and washing of the feedstock. Wet torrefaction, a form of hydro-thermal treatment, in addition to dry torrefaction removes salts and minerals from biomass, improving even more the quality of the product. This is in particular interesting for feedstock containing significant amounts of undesirable alkali components for combustion or gasification, as is the case of bamboo.

This paper presents an evaluation of the use of *Guadua angustifolia* as a fuel for heat and power applications. The results of biomass fuel properties and characteristics and quality improvement via dry and wet torrefaction are assessed. Torrefaction clearly shows the improvement of fuel properties and grindability of biomass. Wet-torrefied *Guadua angustifolia* is chemically an attractive fuel, with favourable fuel properties, e.g. the results showed a 98% of alkali removal, and the production of a grindable solid fuel.

Keywords

Bamboo, *Guadua angustifolia*, biomass pre-treatment, torrefaction, bioenergy, biomass/coal-cofiring, sustainable biomass.

1. Introduction

Bamboo is a potential sustainable biomass source for renewable heat and power production. 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, gasification). The biomass used will be a combination of biomass residues, mixtures of biomass, waste and specially cultivated materials.

With view to maximizing the biomass share in the energy sector, biomass trade will become important, and regulations must be agreed upon so that the various biomass streams are produced in a sustainable way with positive social, economic and environmental impacts. Moreover, in order to simplify biomass trade and supply, the associated logistics and technology need to be optimized. Bamboo has the potential to be a sustainable biomass chain worldwide. The alternative production of bamboo as a bioenergy crop would generate local jobs and income for the poorest sectors in a rapid and continuous way. 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 their areas of influence (Riaño et al. 2001).

Bamboo presents common fuel characteristics with many other biomass feedstocks regarding heating value and chemical composition (proximate/ultimate analysis). The quality and properties of biomass as energy source differ according to the specie, maturity stage, cultivation practices, (e.g. fertilizers application), etc.

The physical and chemical properties of unprocessed bamboo as a fuel alternative to coal do not meet in general with the stringent fuel specifications of most thermal conversion processes, as is also the case with most biomass streams. For blending biomass in coal-fired power plants and entrained flow gasifiers, very small particle size is required. 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 the introduction of biomass on a large scale. Further, its characteristics with regard to handling, storage, degradability and energy density are not favourable when compared with coal. These problems can be addressed by pre-treating the biomass in order to increase energy density, grindability and storability. As a thermal pre-treatment option, torrefaction is a promising upgrading technology that can enhance the fuel quality by addressing these issues. Furthermore, wet torrefaction (Torwash), a form of hydro-thermal treatment, allows for combined torrefaction and washing of the feedstock and removes salts and minerals from biomass, improving even more the quality of the product. This is in particular interesting for (high moisture) biomass feedstocks containing significant amounts of undesirable alkali components for combustion or gasification, as is the case of bamboo.

Up to date, there are no studies on fuel properties of the bamboo specie *Guadua angustifolia*, as the reported studies on bamboo as energy source mainly refer to other species. *G.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. *G. angustifolia* is considered to be one the three largest species of bamboo and one of the 20most used worldwide (Londono 1998). 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. (Camargo et al. 2010). 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.

We have evaluated the properties of *G. angustifolia* as a fuel for heat and power applications. We carried out experiments using Guadua samples of 5 years age. The fuel was first subjected to ultimate and proximate analysis, and samples were subjected to dry and wet torrefaction. The results were evaluated comparatively to data available for other biomass species.

The paper presents the preliminary results and some early conclusions of the ongoing technical evaluation of the use of bamboo fuel in the power industry. 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 bamboo specie *Guadua angustifolia* as a biomass supply chain for bioenergy production. The technical issues related to the final fuel application are of high importance in the assessment of the complete supply chain.

2. Bamboo as an alternative energy source

Recently bamboo has received increasing attention because of its easy propagation, vigorous regeneration, fast growth, high productivity and quick maturity. Bamboo is an efficient user of land and produces more biomass per unit area than most tree species. (Kumar, 2002).

The quality and properties of bamboo as a potential biomass source differ according to the bamboo specie, maturity stage, cultivation practices, (e.g. fertilizers application) production site, which will affect the final application or conversion method, that depends on the specific properties of the material.

Bamboo's proximate analysis and heating value is comparable to most woody biomass feedstock as well as most agricultural residues, grasses and straws as can be seen on Table 1. Bamboo data was collected from different sources (Chen et al. 2011; Kwong et al. 2007; Scurlock, 2000; Stanislav et al. 2010) and refer to bamboo species other than *G. angustifolia*. Other biomass data is from Verhoeff et al. 2011.

Table 1. Proximate analysis, O/C ratio and LHV values for typical biomass streams (on dry basis except for lower heating value)

Material	Ash (%)	C (%)	H (%)	N (%)	O (%)	LHV (MJ/kg $_{daf}$)
Bamboo	0.8-3.5	44-51	5.1-6.1	0.07-0.78	40.9-46.5	17.1-18.7
Bagasse	3.1	46.6	5.7	0.2	44.5	18.2
Grass seed hay	10.6	42.4	5.8	1.6	39.6	18.1
Road side grass	23.2	38.4	5.3	2.0	31.1	19.2
Straw	10.6	42.2	5.7	0.4	41.0	17.3
Beech	0.3	45.9	6.2	0.4	47.3	17.7
Poplar	1.1	47.2	6.0	0.0	45.7	17.7
Willow	1.7	47.7	6.0	0.4	44.3	17.4
Larch	0.1	47.4	6.1	0.6	45.9	18.2
Pine	0.5	48.7	6.3	0.1	44.4	18.5
Spruce	0.3	50.4	6.4	0.0	42.9	19.7

The ash content of bamboo lies in between clean wood and herbaceous material. An example of ash composition is shown in Table 2. Bamboo composition presents critical fuel properties such as high alkali metal content which requires special attention for processing and combustion equipment.

Table 2. Chemical ash composition of bamboo based on high-temperature ash analyses (normalized to 100% ash), wt.%

	SiO_2	CaO	K_2O	P_2O_5	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	TiO_2	Sum
Bamboo	9.92	4.46	53.4	20.33	0.67	6.57	0.67	3.68	0.31	0.01	100

a. Thermal conversions options and relevant fuel properties

Bamboo, like any biomass, can be converted to heat and power, to liquid, solid or gaseous fuels and other chemical products through a variety of conversion processes. The available processing routes range from conventional uses of biomass such as firing for cooking and heating, to modern production processes like converting sugars into ethanol, to combusting and co-combusting biomass with coal for power production, to further advanced technologies such as gasification and transport fuel production. The use of bamboo replacing coal and charcoal for heating is a common practice. However the use of bamboo for power generation is negligible or even inexistent. The use of biomass in the power generation industry today primarily refers to wood, energy crops (e.g. miscanthus and willow) and agriculture waste (e.g. straw).

The evaluation of any alternative feedstock for bioenergy applications requires careful consideration of the effects that feedstock characteristics and composition have on the conversion process.

The fuel properties are directly linked to its storage, transport and pre-treatment options, and can lead to significant logistical and cost components of the bioelectricity production chain. The physical properties (particle size, density and moisture content) as well as the chemical composition (elemental, ash and volatile matter) and energy content of a fuel affect its use in a thermal system. Properties such as moisture, density and volatile matter can well be influenced and controlled by established pre-treating biomass options. By drying, (partial) devolatilisation and subsequent compression and pelletisation, biomass renders more energy dense with properties similar to pulverized coal and an increased heating value.

In addition, the ash composition of the solid fuel determines its thermal conversion behavior; certain ash properties such as 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 them, such as K/Na and Cl cause operational problems such as slagging and fouling to the power plant units. In particular the high potassium (K) content of bamboo increases the risk of slagging, fouling, corrosion and in fluidized bed systems also agglomeration.

b. Thermal conversions options and relevant fuel properties

Biomass supply chains consist of the following elements: production and harvesting, transportation, handling, storage, sizing, pre-processing (drying and/or other pre-treatment), and feeding. Furthermore advanced pre-treatment options include torrefacion (dry and wet).

Torrefaction is a mild temperature treatment at a temperature level of 250 to 320 °C in the absence of oxygen. The occurring decomposition reactions at this temperature level cause the biomass to become completely dried and to lose its tenacious and fibrous structure. In addition, torrefaction increases the calorific value and the biomass hygroscopic nature can be destructed to yield a hydrophobic material. In combination with pelletisation, it enables energy-efficient and cost-effective production of pellets with superior properties in terms of higher energy density, excellent grindability and more hydrophobic nature (eliminating/reducing biological degradation and spontaneous heating, enabling outdoor storage). For the large-scale biomass import, which is relevant to areas with low biomass resources, transportation costs can be dramatically reduced.

Dry torrefaction does not affect the inorganic (ash) composition of biomass. Alternatively, wet torrefaction is a pre-treatment of biomass in presence of water at a high pressure and temperature. This process called Torwash allows for combined torrefaction and washing of the feedstock and therefore removes soluble salts and minerals from biomass, improving further the quality of the product. This is in particular interesting for feedstocks like bamboo that contain significant amounts of undesirable alkali and/or chlorine components that affect combustion or gasification. With alkali and chlorine removal, corrosion and bed agglomeration caused by high salt content during the combustion process are substantially diminished.

3. Torrefaction of Biomass at ECN

The available torrefaction facilities at ECN, allow for both the research investigating the most important aspects of torrefaction, as well as further development of the concept to a pilot-plant incorporating ECN's torrefaction concept.

At ECN several feedstocks were tested in the past, and included various herbaceous and woody (both coniferous and deciduous) biomass streams (*i.e.* bagasse, grass seed hay, road side grass, straw, pine, willow, poplar, larch and spruce) in order to get insights into the torrefaction characteristics of these feedstocks and the properties of the torrefied material produced. The milling behaviour was determined by grinding the different materials to various particle sizes in a lab-scale cutter mill, while investigating the power consumption during grinding. **Figure 1** shows some of the results of these size reduction experiments carried out on dried and torrefied grass seed hay (GS), road side grass (RG), straw (ST), beech (BE), willow (WI), pine (PI) and spruce (SP) as well as coal.

From a technical point of view, torrefaction has a similar impact for all relatively dry lignocellulosic biomass feedstock and it may be attractive for the upgrading of certain mixed waste streams as well. It can be concluded that for all the materials tested, it is very beneficial to torrefy the material before grinding. In all cases the power consumption is reduced drastically when the material is torrefied.

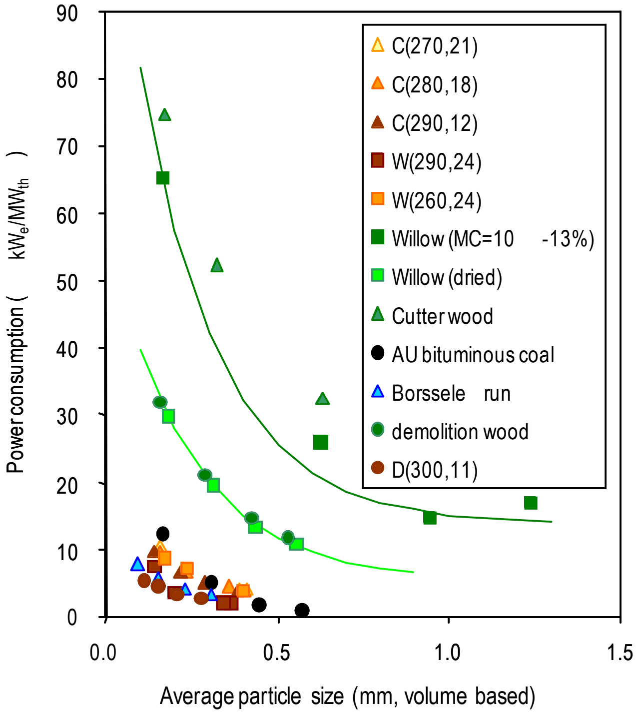

Figure 1: Power consumption as a function of final particle size (torrefaction conditions in brackets, temperature in °C, residence time in minutes) (Verhoeff, 2011)

4. Evaluation of bamboo as an alternative biomass fuel

Exploratory and conclusive experimental work is required to tackle technical aspects using any novel biomass fuel in the heat and especially the power industry. Biomass characterization and pretreatment tests were performed at preliminary stage.

Samples of *Guadua angustifolia* were received from a plantation in Colombia. The harvested Guadua was 5 years old. The material was sun dried in the harvesting location. The feedstock had a moisture content of 10-16 wt%, with particle sizes of 40x40x15 mm.

4.1 Chemical composition

The samples of *G. angustifolia* were analyzed for proximate, ultimate and ash composition. The results are shown in Table 3 and are compared to other solid fuels analyzed at ECN.

Table 3. Comparison of the ash composition of several biomass samples with *G. angustifolia* based on ICP ash analyses carried out at ECN

Fuel	**Russian Coal**	**Lignite**	**Wood**	**Olive kernel**	**Cynara carduncului**	**Shea meal**	***Guadua angustifolia***
Moisture	10.4	48	7.1	5.78	11	11.13	16.4
Proximate analysis (% mass, dry fuel basis)							
Ash	8	27	1.44	6.29	5.1	5.41	6.3
Volatile matter	32	45	80	72	75	61.9	70
HHV (KJ/kg)	27800	15000	20093	20000	19000		18750
Ultimate analysis (% mass, dry fuel basis)							
C	68	41	50.25	48	42	49.4	47.1
H	4	2.4	6.13	5.75	5.5	5.35	6.05
N	0.87	1.1	0.37	1.1	0.55	2.61	1
S	0.35	0.67	0.026	-	0.15	-	0.125
O by diff.	11.6	31	44.2	38	43	40.05	44
Ash composition (mg/kg fuel, dry basis)							
Na (± 7)	405	775	191	1300	4100	179	111
Mg (± 1)	1277	6850	404	1800	1500	1937	405
Al (± 4)	16583	9000	474	1200	160	772	339
Si (± 90)	34841	20000	1331	6200	650	1861	12143
P (± 15)	386	250	122	620	910	1684	770
K (± 20)	2390	1600	984	8900	12000	20789	23029
Ca (± 20)	2750	110000	1919	13000	12000	2145	344
Ti (± 8)	622	395	96	76	8,6	47	12.5
Mn (± 6)	89	130	66	35	17	24	6.5
Fe (± 4)	6077	9700	301	1800	110	1095	140
Zn (± 1)	21	9.3	25	12	13	3.6	10.7
Pb (± 20)	10	~5	8	25	3,5	1.9	0
Sr (± 5)	183	170	11	15	59	18.3	6.9
Ba (± 5)	260	78	29	11	26	22.4	8
S	3500	6700	260	860	1500	2704	1284
Cl (± 20)	100	76	253	2000	2800	797	568

From the *G. angustifolia* analysis performed at ECN it is clear that the chlorine (Cl) content (568 mg/kg) is higher than average wood (253 mg/kg), and less than the average herbaceous crops (as cynara). The potassium (K) concentration in *G. angustifolia* (23029 mg/kg) is much more than in wood. Most other ash forming components are lower than in herbaceous crops and more comparable to wood with a noted exception of silicon (Si) and phosphor (P).

From the above information it is obvious that Guadua's physical and chemical composition may place it well among the grass and woody biomass. This renders it attractive as a fuel, but the high K and Si content must be kept in mind.

4.2. Torwash results of *G. angustifolia*

The samples were subjected to Torwash experiments in a 20 l autoclave under elevated pressure and 200^{o}C. The produced material was mechanically dewatered. Table 4 shows the results from the Torwashed product characterization compared to the untreated or raw *G. angustifolia*.

Table 4. Comparison of raw and wet-torrefied *Guadua angustifolia.*

Proximate &ultimate (% mass, dry fuel)			Ash composition (mg/kg fuel, dry fuel)		
	Raw	**Torwashed**		**Raw**	**Torwashed**
			Na	111	29
Ash	6,3	4,5	**Mg**	405	16
			Al	339	210
HHV (KJ/kg)	18750	20286	**Si**	12143	20586
			P	770	50
C	47,1	50	**K**	23029	510
H	6.05	5,8	**Ca**	344	440
N	1	2,7	**Ti**	12.5	0.74
S	0.125	0.026	**Mn**	6.5	2,1
			Fe	140	26
			Zn	10.7	2.7
			Sr	6.9	1.2
			Ba	8	1.3
			S	1284	260
			Cl	568	120

The heating value of the torwashed *G. angustifolia* was 11% higher than of the raw material. The pre-treated material contains lower concentrations of all its inorganic components, except for Si and Ca. The removal of K is 98% and of Cl is 78% while the removal of Na was 73%. This is a dramatic improvement of the inorganic elements critical for utilization as a fuel. Typically, 500 mg/kg alkalis (K and Na) can be interpreted as a limit for fuels that will not cause any problem in co-firing.

Additional to alkali removal, the Torwash treatment gave very good and promising results:

- Torwash breaks down the fibrous structure of the material and makes milling possible.
- A series of single test pellets was made with a material density of 1200-1300 kg/m3, which indicates that a somewhat higher density than regular torrefied pellets is possible, exceeding the material density and energy density of regular wood pellets.
- As a result of the Torwash treatment, mechanical dewatering is easy. On lab-scale, the resulting cake had a moisture content of only about 30 wt%.

Note that these results are preliminary and need confirmation in larger scale tests.

5. Conclusions and outlook

Bamboo presents common fuel characteristics with other biomass feedstocks regarding heating value and chemical composition. Bamboo is tenacious and fibrous which makes it difficult and expensive to grind. Furthermore, the characteristics with regard to handling, storage and degradability are not favourable for bamboo as is the case of biomass in general.

The hydrothermal treatment (wet torrefaction of Torwash), removes salts and minerals from biomass, improving also other qualities of the product, such as grindability and moisture content. This is in particular interesting for feedstock containing significant amounts of undesirable alkali components for combustion or gasification, as is the case of bamboo.

Samples of *Guadua angustifolia* were received from a plantation in Colombia. The harvested Guadua was 5 years old. Biomass fuel analysis and pretreatment tests were performed.

From the fuel characterisation results we conclude that *G. angustifolia* is a potential solid fuel due to its elemental composition and high heating capacity. Properties are similar to those of clean wood rather than other herbaceous feedstocks, except for alkali content, which in bamboo is quite high.

When the material is hydrothermally pre-treated with wet torrefaction (Torwash), it is possible to eliminate two of the main characteristics that may prevent bamboo from being co-fired: first, the high alkali content as it removes 98% of alkali (K and Na) and second it breaks down its fibrous structure, making milling possible. It is also expected to be easy to pelletize Torwashed bamboo.

The preliminary results form the basis for the complete technical assessment of using *G. angustifolia* as an alternative energy source. Further research in this project includes specific conversion and combustion tests.

The ultimate goal of the technical assessment is to address the suitability and options to adapt this promising fuel to the existing power industry. This requires in-depth knowledge of the fuel behavior in thermal conversion systems as well as optimum pretreatment conditions and techniques. ECN expertise on torrefaction and combustion are of key importance in successful integration of bamboo in the bioenergy market in Europe.

The technical issues related to the final fuel application will be part of the techno-economic and sustainability assessment of the complete supply chain. The techno-economic and sustainability analyses of this testing biomass chain will allow for innovation and technology development, while promoting the marketing of sustainable biomass.

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