Bamboo

Analyzing the potential of bamboo feedstock for the biobased economy

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Index

Executive summary

Bamboos are a large group of rapidly growing woody grasses, that can be sustainably managed in short-cycled harvesting schemes in many parts of the world. Bamboo stands can be managed by individual producers and its production does not require large investments. This makes bamboo an ideal crop for rural development, especially in developing countries.

Bamboo plants are among the most versatile and widely utilized plants, with applications varying from edible shoots to soil protection and construction. Bamboo technical properties are also favorable for biobased applications, such as paper, bio-chemicals and bio-energy. The most productive species may yield over 30 t/ha dry matter biomass. On average the yield of the most common bamboo crop in well managed forests or plantations in China could reach up to 25 t/ha. In China 4.2 million ha of bamboo is reported (personal communication INBAR). In contrast to most commodity crops there are very limited statistics available for bamboos. For other countries than China the production data are most often not reliable. This can be ascribed to the fact that the internal markets for bamboo and bamboo products is still very informal and does not enter statistics. In recent years (since 2007) world trade statistics for bamboo and bamboo products are published by INBAR. From these trade data a slight decline can be observed in most recent years of the markets for bamboo and bamboo products. The total volume of bamboo exports has been ranging between 120 and 150 kT/yr, while for bamboo pulp this remains below 100 kT/yr. Bamboo charcoal exports amount 30-75 kT/yr. Despite this decline ascribed to the economic recession the growth potential is considered large.

Large scale use of bamboo for dedicated energy production for thermal conversion or second generation fuels will be difficult because harvesting cannot or hardly be mechanized; non-energy uses should have more attractive market value; plantations have to be established vegetatively, making it slow and relatively costly on a large scale; fuel quality for thermal conversion is lower than for wood but generally better than for herbaceous biomass.

The concept of whole crop biorefinery, enabling optimal use of bamboos in a variety of products, from high end uses down to combustion of residues for generation of heat and electricity should be more appropriate for bamboo. That this concept works can be observed already in China’s Linan county, where bamboo has been developed into a sustainable feedstock for the region’s biobased economy. It should be noted that the use of conservation agents (such as boron salts), when bamboo is used for building material, limits other uses such as most energy applications.

Also in other regions of the world are bamboos more and more considered key resource for development, such as in Colombia. In a country with a tradition in bamboo architecture, the unique properties of Guadua bamboo are recognized by the Colombian authorities and laid down in a national bamboo building code, of particular importance for earthquake prone areas. Other areas in the world with great bamboo potential include Ethiopia, with over a million hectares of Ethiopian Lowland bamboo. This species grows on dry land and poor soils and holds great promise as feedstock for many uses, including building materials, flooring, edible shoots and pulp and paper.

In order to realize the full potential of bamboo as feedstock for the biobased economy, more Research and Development is required focusing especially on propagation, stand management and chemical processing.

It is hoped that this publication leads to improved understanding of the potential of bamboo in the biobased economy.

English name: Bamboo

Other names for bamboo: bamboe (NL), bambou (F), bambú (S), 竹(Chinese)

Latin names: The main species of relevance include *Phyllostachys pubescens; Oxythenantera abyssinica; Guadua angustifolia;*

Plant Family: *Poaceae* (*Graminae*). Herbaceous, woody stems

Origin: China (Moso), Ethiopia (Savanna bamboo), Colombia (Guadua)

Occurrence: Tropics, sub-tropics, and Mediterranean climates of all continents (except Europe).

Current uses: Rural handicrafts, tools, building materials, paper, textiles, heat; young shoots as food

Growth habit: Natural forest and plantations

Growth cycle: Perennial plant; propagated mainly through rhizomes, (cell culture cloning possible)

Agronomic practice: Bamboo stems are not mechanically harvested, but by hand selectively from mixed stands. Propagation by vegetative methods.

Yields: widely variable, depending on variety, soil, and climate conditions up to 26 t/ha/y

Biobased applications/conversion and quality aspects: bamboos are lignocellulosic biomass. It contains more inorganic components and ash than wood and generally less than herbaceous biomass such as straw. Bamboo is a major feedstock for the biobased economy. Currently, used in textiles, paper and building applications.

Costs: Bamboo is a low cost biomass (poor man's timber). However, as most of bamboo is produced by smallholder farmers, collection costs and logistical costs may be high.

Sustainability/Impacts: Use of bamboo may increase local economies by increasing income and labor opportunities.

Outlook: Modernization of bamboo agricultural practice in many developing countries will lead to more bamboo being marketed as feedstock for the biobased economy. The outlook as bulk energy crop requires adaptations of local infrastructure and crop management that are yet insufficient in place.

1 Bamboo: an introduction

1.1 General characteristics

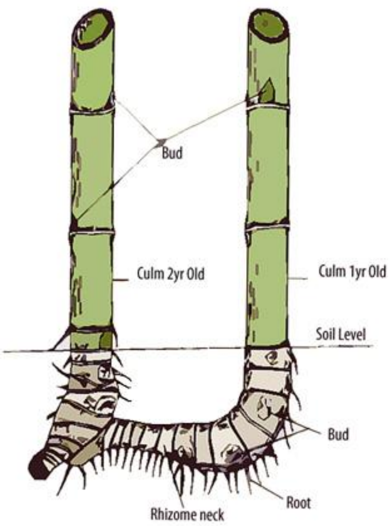
Bamboo is the common name for a group of rapidly growing tall grasses, uniting around twelve hundred species worldwide. Typical features of the bamboo plant are distinct protrusions on the culm, called "nodes" with intermediate parts called "internodes".

Bamboos belong to the family of grasses (*Poaceae*), just like rice, wheat, other cereals and sugar cane. A division is made between herbaceous and woody species. Especially woody bamboos are known for their high versatility, with many current and potential uses. Another distinction is made between "running" (monopodial) bamboos and "clumping" (sympodial) bamboos, with the latter dominating tropical regions and growing in clumps.

1.2 Growth and distribution

The growth vigor of bamboos is unmatched by any other plant in nature. Some species reach over 40 meters in height, in only a few months' time or grow faster than 1 meter per day. Bamboo is also a very hardy plant, surviving under the harshest of conditions. Bamboo plants are perennial; once established, there is no need for replanting, as harvested culms are replaced by new shoots emerging from the underground rhizome system (as illustrated in Figure 1). This aspect enables sustainable, regular harvesting of culms and thus stable income for producers, with only low investments.

Figure 1: Bamboo anatomy. source: http://www.renewbamboo.com/index.php/component/k2/item/53-bambooanatomy



Bamboo has a wide distribution, naturally occurring in a range between 40^0 southern and northern latitude on all continents, except Europe. Though bamboos occur in both tropical and temperate climates, warm and humid conditions are preferred by most species. An annual mean temperature of 20 to 30 degrees is preferred and precipitation levels of 1000 to 2000 mm. Some species, such as *Dendrocalamus strictus*, survive under drier conditions in India, with 750 to 1000 mm of annual precipitation. Most bamboos are found on sandy loam to loamy clay soils.

1.3 Natural bamboo forests and plantations

Most bamboo in the world grows in natural forest, with China being the exception. China has an estimated 4.2 million hectares of bamboo plantations, of which 60% is concentrated in four contiguous provinces: Fujian, Jianxi, Zhejiang and Hunan. An additional area of approximately 3 million hectares includes "mixed and mountain natural bamboo stands". The yields of bamboo plantations vary considerably depending on species, management and location. Very productive species may yield more than 30 t/ha /yr dry matter. A well-managed bamboo plantation yields on average 25 t/ha/ yr.

Other nations, in both tropical and temperate regions, are lesser known for their, often considerable, bamboo reserves. The internal market and trade of bamboo and bamboo products are still mostly informal and do not enter economic or trade statistics. For example, Peru's Alto Purus region has approximately 2,5 million hectares of tropical rainforest dominated by bamboo species. And Chile has around 3,5 million hectares of temperate forests with presence of bamboo species.

Africa too has large areas of natural bamboo stands. Ethiopia can boast the largest bamboo coverage in Africa, with over 1 million hectares of Savannah bamboo (*Oxythenantera abyssinica*).

2 Current uses and status as a biomass crop

2.1 Bamboo: a worldwide biobased feedstock

Especially woody bamboos are among the most versatile plants in the world. Many countries in Asia such as Bangladesh, India, Indonesia and China have traditionally depended on bamboo resources for building materials, local craft, flooring, food and as feedstock for paper and fibre board.
A number of bamboo species have been identified as priority species for research and development, for their current and potential role in rural development, industry and ecological services. Three of these species include *Phyllostachys pubescens*, *Guadua angustifolia* and *Oxythenantera abyssinica*, representing the continents of Asia, South America and Africa respectively.

2.2 Phyllostachys pubescens

This is a medium to large bamboo of the "running" type, also known as Moso bamboo. It is native to temperate regions of China where it is widely cultivated. It has been introduced in other countries, such as Japan, Korea and Vietnam. Culms are 10 to 20 meters tall, reaching diameters of up to 18 centimeters. Culms are straight, strong and suitable for construction whereas its young shoots are edible. In China alone, approximately 5 million hectares of Moso plantations have been established (photo). Economically, Moso bamboo is the most important bamboo species in the world. Applications include bamboo flooring, that is produced in China and exported to the United States and Europe. It is also widely cultivated for production of shoots, which is considered a delicacy throughout Asia. Moso bamboo is a key species for rural and industrial development, particularly in south-eastern parts of China.

Figure 2: Moso bamboo and application in laminated panel

2.3 Guadua angustifolia

This is a large tropical (clumping) bamboo with culms reaching 30 meters in height and diameters up to 20 centimeters. It is known for its superior mechanical properties and durability, earning it the nickname *acero vegetal* (vegetative steel) in its native Colombia. The species' native habitat is found in the tropical Andean regions of Colombia, Ecuador and Venezuela and it was introduced in countries such as Costa Rica, Mexico and even China. In Colombia, approximately 50.000 hectares of natural Guadua bamboo stands remain. It is included in the national building standard of Colombia and widely considered ideal building material in areas prone to earthquakes. Adoption of Guadua bamboo by the Spanish conquistadores has led to a unique architectural style reaching its peak in the 1920's that incorporates bamboo culms, called *bahareque*. And in recent times, (Guadua) bamboo architecture has been taken to new heights, among other by Colombian architect Simon Vélez who was awarded the Prince Claus Award in 2009. Recently Guadua was evaluated for thermal conversion and for production of torrefied pellets see chapter 3.6.

Figure 3: Bahareque style and modern Guadua bamboo house in Colombia (Simon Velez)

2.4 Oxythenantera abyssinica

This species has a wide distribution in Africa, including Ethiopia, Eritrea, Sudan, Tanzania. In Ethiopia alone, it covers approximately one million hectares of land, making it the most abundant bamboo resource of Africa. Other names include savannah bamboo (FAO) and Ethiopian Lowland Bamboo. It is a bamboo of the clumping type, with solid stems, contrary to most bamboos including Moso and Guadua, which are hollow. It grows approximately 7 meters high and reaches a culm diameter of 5 centimeters. It is a hardy plant, found on slopes, on open grassland and on poor, well-drained soils. The species has traditionally been used for construction of houses, fuel, feed, fodder, handicrafts, furniture and countless other products. Its importance for ecology and biodiversity is considerable, yet its full economic potential is yet to be developed. Nevertheless, recently a South African paper pulp company has invested in a bamboo fed pulp production facility in Ethiopia. Other potential bamboo based products for local use include particle boards, medium density board, charcoal and scores of other products.

Figure 4: Ethiopian Lowland Bamboo (source: website East African Bamboo Project)

3 Potential uses in the biobased economy

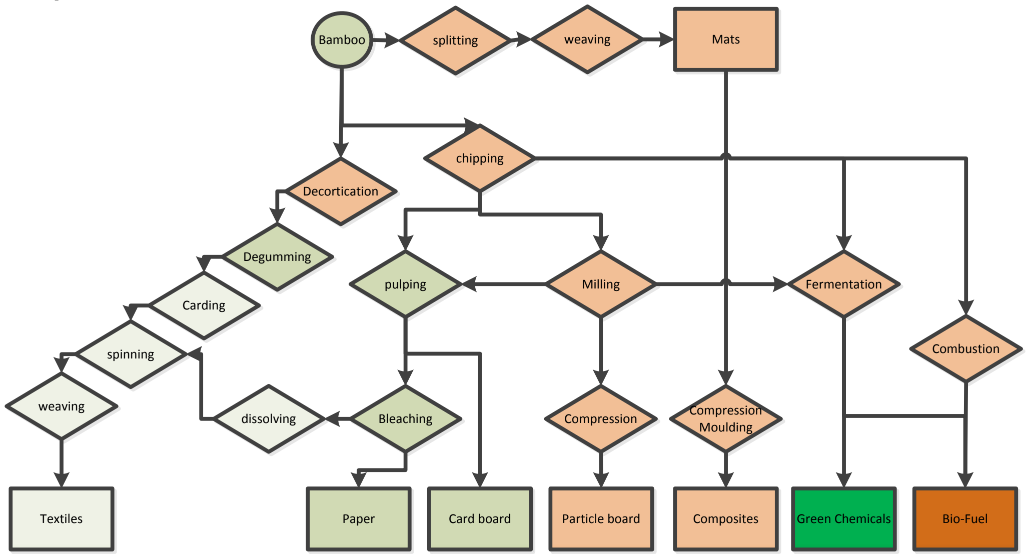
Bamboo is well known as a building material and for production of pulp and cellulose products. The use of bamboo for energy is less prominent but may also become relevant. We will first discuss current and innovative uses before discussion of energy applications for bamboo.

3.1 Bamboo for the biobased economy

Bamboo is considered one of the most sustainable biomass crops for energy and materials production. As abundantly available non-timber crop, it finds traditionally a wide application throughout the tropical and subtropical parts of the world where bamboo substitutes for timber products. The use of bamboo biomass is far from optimized and its potential as industrial product and bioenergy feedstock is under investigation. Whole crop use, bio-cascading and recycling of the different products are relevant aspects for enhanced ecological performance.

In Figure 5 a general overview is given of the applications of bamboo. Global scenarios for transition towards the bio-based economy include promises of new crops and innovative bio-refinery methods for better use of these abundant CO_2 neutral and sustainable resources (Keijsers et al 2013).

Figure 5: Simplified scheme of processes and market products of bamboos (Ref: Keijsers et al 2013).



When <u>whole crop biorefinery</u> is targeted, the aim is to utilize the fixed CO_2 in the biomass at its full potential. Biorefinery is often primarily designed to extract valuable constituents such as flavors, sugars, proteins, or fatty acids, while the remaining biomass residues are disposed of as low value waste and commonly are burned. Whole crop biorefinery, however, will also exploit these residues, such as pentosan, or lignin, as source for manufacturing "green chemicals". In the biorefinery processing of lignocellulose feedstock for second generation ethanol production, increased interest in combined technologies such as acid and solvent pre-treatments are reported sometimes also with enzymatic treatments. In Figure 5 a general overview is given of the applications of bamboo.

Table 1 gives an overview of the trade in bamboo and bamboo products over 2007 to 2011.

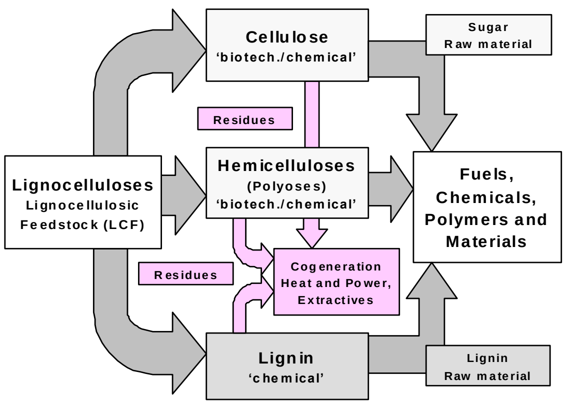
Table 1: bamboo and bamboo products, world trade statistics 2007-2011 (INBAR, 2012)

Product	2007	2008	2009	2010	2011
	----------------------------- kton per year --------------------------------				
Bamboo	153	154	136	157	122
(China)	*112*	*101*	*79*	*93*	*96*
Charcoal	75	62	57	30	32
Flooring	60	58	43	55	54
Panels	94	170	97	171	96
Mats	44	47	43	41	31
Plaits	17	19	14	16	17
Basketwork	51	67	53	54	50
Pulp	27	14	61	92	18

3.2 Bamboo pulp and paper

Only about 7% of the world's virgin cellulose pulp is made from non-wood sources (mainly straw, bagasse, and bamboo). In the EU, US and Canada paper industries practically only wood pulp is currently used. Globally dwindling forests and shortage of wood supply is the driver for the search for sustainable alternatives. In 1998 China produced still ca. 17 million tons of non-wood pulp (FAO statistics), which was 84% of the total pulp production, including ca. 1 million ton of bamboo pulp. Due to environmental concerns many of the small bamboo and rice straw pulp mills were closed since then. Most bamboo pulp is used in the internal Chinese market. Currently less than 100 kT/yr is exported world-wide. (Table 1)
Different pulp grades can be made from bamboo pulp that find various markets for value addition. Lower grades milled or refined fibers can be converted to building boards (cement bonded or glued particle board) or fiber reinforced polymer composites. Kraft pulping yields pulp for liner board and paper bags. Bleached fibers can be used in pulp blends for printing and writing grade papers. In the production of Kraft paper 20 to 25% of the pulp mix can be replaced by bamboo pulp, as was reported by one of Colombia's principal pulp and paper plants. Highly purified bamboo cellulose fibers may be converted to dissolving pulp and bamboo textile fibers (Fig.5). New fiber lines with adapted chemical pulping have been installed in China in the last decade for the production of bamboo pulp.

Figure 6: Lignocellulose biorefining scheme and bamboo paper factory



The presence of silica in the bamboo is a major technical obstacle for efficient chemical recovery of the pulping liquor. The silica contents of bamboos increase with maturity while the overall ash content of mature bamboo is lower than in younger samples.

3.3 Bamboo textiles

Like wood based pulp, bamboo pulp can be further purified into dissolving cellulose, which is used as feedstock for the production of cellulose textiles and cellulose derivatives. Regenerated cellulose (viscose-rayon) is by far the largest of the cellulose derived biopolymers (ca. 3.5 million tons world-wide), followed by cellulose esters (> 1 million ton) and cellulose ethers (< 1 million ton). More than 60% of chemical grade pulp is used to produce regenerated cellulose, mostly from wood cellulose. Regenerated cellulose is used to produce both fibers and films. The textile fibers are economically much more important than films.

Bamboo viscose fiber is marketed in China as a very versatile textile raw material that competes with synthetic textile yarns and natural fibers like cotton, wool, linen and silk. Exceptional qualities have been claimed for bamboo fabrics. In apparel, it offers a high wearing comfort by being soft, cool and highly moisture absorbent. Bamboo fiber fabrics have a silk like feel and appearance. The fabrics are advertised to be extremely cool and moisture absorbing due to the micro-structure in the fiber, and combined with anti-ultraviolet properties it is especially suitable for comfortable and safe clothing in warm climates. The anti-bacterial and bacteriostatic properties of bamboo textiles are ascribed to a biological active non-allergenic component called “bamboo kun” that is reported to be present in the bamboo stems. This substance that is believed to protect bamboo plants from diseases and pests is (re)combined with the bamboo cellulose for obtaining these antimicrobial properties.

Because of the relative short fiber cells of bamboo the fission process of bamboo into small and even fiber bundles like in bast fiber crops (flax, hemp) is difficult to achieve. However, in China some bamboos have been shown suitable for bamboo linen production. The use of retting procedures and enzymes in the degumming process provides tools for controlled fiber bundle production.

Figure 7: Example of bamboo textiles

3.4 Bamboo composites, panels and boards

The current industrial bamboo fibre composite materials, panels and boards and veneers are manufactured by utilizing synthetic resins to glue the particles (PF / UF). In the process of cellulose extraction the intrinsic original glue (Lignin, hemicellulose) is chemically removed. These polyphenols (lignin) and pentosans (xylan) can be converted to glue and materials. For example the steam explosion method has been studied to manufacture binderless fiber board from bamboo. The production of furan resins from the hemicellulose (now largely produced from sugar cane bagasse) has been demonstrated to yield high quality resins for production of thermoset composites.

Much research has been done on the manufacturing of cellulose fibre reinforced plastic composites as (interior) car parts. Combined with polypropylene, bamboo fibre was demonstrated to have excellent material properties. Synthetic or biobased plastics may utilize bamboo cellulose fiber as reinforcement (length 2.5 mm, diameter 12.4 μm), but also mineral bonded boards are produced with bamboo fiber.

Novel developments in the area of biocomposites are reported with renewable polyesters (polylactic acid, polyhydroxyalkanoates), polyamides or biobased polyethylene.

3.5 Bamboo chemicals

In biorefinery and pulping processes the focus is on the production of valuable components that are extracted for economic utilization. The residues preferably are disposed of or at the most burned for generation of process heat. These fractions may contain various components with interesting properties. So far the enhanced use of extractives from the process for cellulose production has been investigated for different related resources such as sugar cane bagasse, *Miscanthus* or sarkanda grass. The black liquor from bamboo pulping or digested fermentation feedstock from biorefinery has potential use as feedstock for 'green chemicals' and resin production.

Bamboo non-cellulosic polysaccharides or hemicellulose is mostly composed of xylan. Xylan is a C5 sugar (pentosan) that has been studied for conversion into many food and non-food applications, sweeteners (xylitol) or liquid fuel solvents or chemicals. For example, furfural is produced in acid catalyzed processes from pentosan and may be converted into furan resins by hydrogenation and controlled polymerization of the furfury alcohol. New catalysts for the hydrogenation process are patented.

Another approach for the production of 'green' chemicals from biomass are the hydrothermal cracking processes, similar as is common in petrochemical industries.

Figure 8: Examples of bamboo based products

3.6 Bamboo for energy applications

Conversion of bamboo to energy and energy carriers is much less publicized. Still, quite a number of dedicated energy applications or evaluations are reported. Here we will review the most relevant experiences and review the main issues that may exist when using bamboo for dedicated large scale bioenergy production.

Traditional combustion of bamboo as cooking fuel is somewhat more complicated (compared to using wood) due to the high density of bamboo, making it hard to cut or chip. Bamboo charcoal and briquette production is a simple technology that is used in China and promoted in Africa for example in Ethiopia, Kenya and Ghana.

Thermal conversion of bamboo
A limited number of evaluations of bamboo for large scale combustion have been made (Scurlock et al 2000). More recently Daza Montaño et al (2012) evaluated in detail the bamboo variety *Guadua angustifolia* for thermal conversion in Colombia (see text box below).
In Table 2 fuel analysis is given for a number of bamboo samples and reference materials. The ash contents of bamboo samples are reported between 1% and 3.5%. which lies between clean wood and herbaceous material such as grass and straw. Scurlock also reported that bamboo has higher heating values (HHV), ranging between 19.0-19.6 GJ /t on a dry basis. These heating values are slightly lower than, most woody biomass feedstocks and higher than most grasses and straws.
Another critical aspect for thermal conversion is the alkali K (and Na) and chloride content. Which increases the risk of slagging, fouling, corrosion, and ash agglomeration.

Table 2: Average proximate analysis of bamboo, typical proximate analysis of bagasse, straw, willow and pine (ref: Daza Montaño et al 2012)

Material	Ash	C	H	N	O	LHV
	% DM	------------------ % DM -------------------				MJ/kg daf
Bamboo	0.8 to 3.5	44 to 51	5.1 to 6.1	0.07 to 0.78	40.9 to 46.5	17.1 to 18.7
Bagasse	3.1	46.6	5.7	0.2	44.5	18.2
Straw	10.6	42.2	5.7	0.4	41.0	17.3
Willow	1.7	47.7	6.0	0.4	44.3	17.4
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

Scurlock (2000) reported that K_2O in the bamboo ashes ranges from 30 to 50%, which is high. Still since the overall ash content of ash in the biomass was low the overall K_2O content of the biomass was only 0.2 to 0.6% on a dry basis.

Daza Montaño et al (2012) concluded in a recent study that 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 favorable 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 feedstock's containing significant amounts of undesirable alkali components for combustion or gasification, as is the case of bamboo.
From the fuel characterization results it was concluded 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.

The study by Daza Montaño et al was carried out in the framework of the Netherlands Programmes Sustainable Biomass.

Pyrolysis

Bio-oil or pyrolysis oil is a liquid energy carrier, which is produced by fast or flash pyrolysis where biomass is heated to between 400 and 600 °C. In the process char, pyrolysis oil and some gas (CO, H_2) is produced. This technology for thermal conversion of biomass has also been tested for bamboo. Bio-oil was found to be comparable in composition and liquid fuel quality to most other ligno-cellulosic resources.

Bioethanol

Different bamboo species have been investigated for the production of (second generation) bioethanol. Various chemical (alkaline and acidic) and enzymatic (e.g. cellulase, xylanase) pre-treatments to liberate the sugars for fermentation were subject of study. The effect of growth stage on the ease of saccharification and fermentation was demonstrated. As can be expected young shoots are easier digestible. Steam explosion, ultra-sonication, and organosolv pre-treatments were studied in many laboratories, mostly in China, Taiwan and other east Asian countries. The maximum amount of liberated reducing sugar was found at approximately 55 wt. %.

The use of bamboo as energy crop for Europe was reviewed and it was concluded that bamboo can be grown under European climate conditions with good yields and it is useful as crop for phytoremediation on marginal contaminated lands. At the same time there is no indication that bamboo would be a more attractive crop than other biomass crops such as *Miscanthus* or short rotation willow coppice.

4 Bamboo stand management and harvesting

4.1 Selective harvesting (mature culms only)

Clear-cutting of bamboo is rarely recommended, except for small species, or for salvaging stands that face mass deterioration as a result of flowering. Clear-cutting is thought to decrease the vitality of bamboo stands and recuperation of the stand takes considerable amount of time.

Selective harvesting is far more sustainable, resembling uneven-aged forest management of timber species. Bamboo culms appear as shoot from the rhizome system with their final diameter already reached, whereas their maximum height may be reached in less than a year. Depending on its use, the culm needs several years to attain its harvestable quality, usually up to five years. Given its heterogeneity, with culms in all age classes, bamboo stands are suitable for short-cycle harvesting systems. In this way, bamboo stands can supply steady revenue streams for local producers and also ecological benefits are guaranteed, through permanent bamboo coverage. A disadvantage, however, may be the impossibility of reduced harvesting costs through mechanization. This is important when bamboo is considered for energy production purposes only. For example for combustion or for large scale ethanol production. For bamboos adapted to higher, temperate latitudes, mechanical harvesting may work according to Gielis (http://www.bamboonetwork.org/downloads/gielis01.pdf)

The national bamboo harvesting standard in Colombia prescribes that only mature culms be cut, up to 25% of the bamboo stand each year. With an optimal stand density of around 4000 culms per hectare, each year 1000 culms can be sustainably harvested on every hectare. This equals approximately 40m^3 or 26 tons dry matter per hectare per year. These figures, however, vary greatly among species, growth site and seasons. The following pictures show the four stages of bamboo development (Guadua bamboo).

Figure 9: Bamboo growth stages.

Shoot | Green <3 yrs | Mature >3yrs | Dry >5 yrs

4.2 Harvesting and post-harvest treatment

Bamboo culms are usually cut with some type of knife. At least for hollow bamboos, it is imperative that a clean cut is realized, with no chance for water to collect in cavities of the remaining stump. This could lead to rotting of the rhizome system and subsequent deterioration of the bamboo stand. Also heaps of organic matter and dead culms should be removed, to give space to development of new shoots.

Figure 10: Harvesting of Bamboo culm.

There is a correlation between stand density and diameter size. The more dense the bamboo stand, the smaller diameters are produced. Which diameter is best depends on the application.

Harvested bamboo material is subject to early decay, especially under tropical conditions. Depending on applications, safe and economic preservation methods may be applied, such as with boron salts. At all times, transport distances and storage time should be kept minimal.

5 Bamboo propagation and establishment

There are two propagation methods for bamboo: seed propagation and vegetative propagation, also called cloning.

5.1 Seed propagation

From bamboo seed, seedlings can be produced and easily multiplied in nurseries before planting in the field. Although suitable for large-scale propagation, seed propagation has serious limitations. Many bamboos flower infrequently or gregariously, often at very long intervals, or produce seeds with low survivability. Among our three species, seed propagation is only feasible for Moso bamboo. For Guadua bamboo and Savannah bamboo, producers must rely on cloning.

Figure 11: flowering bamboo and seeds

5.2 Vegetative propagation (cloning)

The advantage of cloning is that the producer can select propagation material from mother plants of known characteristics. This is not necessarily the case with seed propagation. The disadvantage of cloning is that it is much more laborious and therefore expensive. Most used cloning techniques for tropical bamboos are through rhizome cuttings, branch and culm cuttings. In these methods, new plantlets are grown from healthy buds on sections of rhizome, culm or branches. Temperate bamboos are cloned by clump division. Either way, cloning methods are very laborious and not suitable for large-scaled commercial plantations. Potential alternatives include in-vitro propagation, where large quantities of bamboo material could be produced in short period of time. However, this requires large investments and achieved qualities are often still insufficient.

Figure 12: Planting steps

Culm cutting *Developed clump* *Transplanting* *Nursery beds*

For Guadua bamboo, a much more convenient and efficient method is available: propagation with *chusquines*. These are small plantlets that naturally appear from the underground rhizome after the Guadua clump has been harvested or damaged otherwise. They are collected and reproduced in a nursery bed. After 2 to 3 months, stems have multiplied and can be separated and transplanted into planting beds or pots. This process can be repeated until plants are obtained with sufficient size and diameter for planting in the field. Though commonly used for Guadua bamboo, this method may not be available for other bamboos. It may take seven years before Guadua culms of sufficient quality are obtained.

6 Bamboo economics

6.1 Applying the cascading principle: bamboo market diversification

The world market for commercialized bamboo products has grown fast and, according to some predictions, may be worth 20 billion US dollars by 2015. Despite the current economic recession and slight decline of the trade statistics of bamboo and bamboo products in recent years (Table 1) it is expected that prospects for bamboo markets are good and expanding (INBAR). Although relied on for thousands of years by rural households, bamboo is quickly becoming a popular feedstock for commercial products such as flooring, furniture, plywood, pulp, paper, linen, building materials and other products. Currently, 80% of bamboo products are produced China, particularly in 10 counties of China's southeast. This region has been showing the way in developing a true "bamboo-based economy". Bamboo has been developed there as prime feedstock for high-end commercial products for export, whereas residues and inferior qualities are used for lower-value bulk processing. This cascading principle ensures maximum use of available feedstock, with optimal benefits for rural economies, industries and the environment alike.

6.2 Bamboo shoots and premium processing

By 1980, Linan county in China's Zhejiang province had a per capita income of only 50 US dollars. But, since in 1983 degraded hills have been planted with bamboo mainly for shoot production, the per capita GDP had increased to 1100 US dollars in 2002. Once dependent on agriculture, by 2002, 60% of Linan's rural households were engaged in the bamboo sector. The county had become the world's largest producer of bamboo shoots. The output of bamboo culms and fresh bamboo shoots had reached 206.700 and 180.481 tons respectively, with a combined value of 50 million US dollars. Both products support high value manufacturing industries, focusing on domestic and export markets and generating much revenues. Neighboring counties have shown similar developments.

6.3 Bamboo bulk products and raw material

Industrial diversification means opportunities for increased value of bamboo through cascading effects. For example, in bamboo flooring only the middle lower sections of Moso bamboo are used. The remainder parts are sold by Linan farmers to other factories where they make toothpicks, chopsticks, curtains, scaffolding, charcoal and other products. This has enabled local farmers to increase the value of their bamboo with a factor 2 to 3. Similarly, fibre and chemical based industries could be supplied with lower grade bamboo qualities, such as in the manufacturing of paper, pulp, biobased plastics and fine-chemicals.

Apart from China, Colombia has shown that there is good market potential for bamboo culms as building material. When combined with basic processing such as preservation, producers may earn 12 dollars per culm on the housing market. With 1000 culms available per hectare per year, and considering a worldwide housing deficit among millions of the urban poor, bamboo could become a major income source for rural communities. And here too, lower quality bamboo as well as residues can be used as feedstock in other biobased industries.

Figure 13: Example of bamboo building application and industrial product in Colombia.

7 Social and Environmental Sustainability

7.1 Socio-economic benefits of bamboo

In many developing countries, bamboo is considered “poor man’s timber” for it is readily available for poor classes at often very low costs. Yet, as demonstrated in China’s Linan county, bamboo is capable of moving entire communities from the poorer to the richer classes, based on its versatility in applications. Bamboo groves can be managed by individual farmers, who need only basic tools for harvesting. And with processing plants for shoots, flooring, paneling and many more products for domestic and export markets, bamboo can provide much needed revenues in developing economies around the world.

7.2 Environmental and ecological benefits of bamboo

It seems more and more governments appreciate bamboo’s quality in protecting soils and regulating water levels. In Mali, Savannah bamboo (Bindura bamboo as it is known there) is officially protected and in Colombia, Guadua bamboo harvesting is strictly regulated by the environmental authorities. Bamboo groves also support important biodiversity, which can be retained as long as sustainable, selective harvesting systems are applied. Bamboo management requires few input of biocides, as few problems with pests and diseases have been reported.

Figure 14: a) bamboo manual harvesting; b) power washing guadua bamboo Colombia

7.3 Contribution to climate change mitigation

Bamboo may be important in helping reduce global climate change effects, albeit that this claim is backed by scarce research. Bamboo may be more efficient than some other crops in sequestration of carbon dioxide, but this aspect may be partially neutralized by a shorter life cycle of bamboo products. Bamboo products often last shorter periods of time in their applications compared to other materials, before decay sets in and greenhouse gas emissions are returned to the atmosphere. Also transport of (hollow) bamboo may be less efficient, which increases the overall energy use throughout the chain. At all times, the entire life cycle of bamboo products should be analyzed, if one is to make any claims on the real impact of bamboo on climate change mitigation.

7.4 Competition with food

There is a growing concern worldwide about biomass crops competing with agriculture over available land. If good agricultural land is demanded for biomass cultivation, less land will become available for agriculture and price increase of food products may be the result. This will lead to exploitation of new land, with possibly negative consequences for people, climate and the environment.
This aspect is also relevant for bamboo. For example, large scale Moso plantations have decreased the available agricultural land in China’s Linan county. And in Colombia, Guadua bamboo is found on fertile volcanic soils, very suitable for food production. On the other hand, if Moso and Guadua are cultivated on steep slopes, inaccessible for agriculture, this negative sustainability aspect could be effectively neutralized. The most sustainable alternative, from this perspective, is perhaps the cultivation of Ethiopian Lowland Bamboo, as it grows on relatively poor soils in dry savannah areas.

8 Conclusions and recommendations

8.1 Strengths, weaknesses, opportunities and threats analysis of bamboo

There is no such thing as a perfect biomass crop. Each crop, including bamboo, has its specific properties that make it suitable for specific circumstances. Hereafter, bamboo is analyzed for its strengths, weaknesses, opportunities and risks to be taken into account by (future) biomass project developers.

General SWOT analysis

Strengths
- Bamboo is a rapidly growing biomass source, with a wide range of species, making it suitable for growing in most temperate and tropical climate conditions.
- Current global trade in bamboo and bamboo products amounts over 100 million €.
- Bamboo is a perennial crop that can be managed through short-cycled harvesting systems, with only basic tools, making it ideal for community based development.
- Bamboo groves and forests can provide steady revenues as well as important ecological services, including carbon sequestration.

Weaknesses
- Bamboo is difficult to propagate, for lack of seeds and dependence on laborious cloning techniques.
- Bamboo management and harvesting requires hard labor and much knowledge regarding culm selection and quality control.
- Bamboo is a very heterogeneous material even within the same clump, with properties varying among species, growing sites and seasons.
- Bamboo is very perishable after harvest, requiring preservation methods and short supply chains.

Opportunities
- Bamboo can replace fossil oil based products, chemicals and fuels in a diversity of market products and thus hold a key for realizing the biobased economy.
- Bamboo can replace wood in almost all uses and thus help reduce pressure on the world's forests.
- Bamboo can be grown on steep slopes and rehabilitate degraded lands, whilst not competing with agriculture.
- For the production of bamboo and bamboo products, diversified employment, in cultivation, processing and manufacturing is required.

Threats
- Demand for bamboo products may lead to mass conversion of natural forests into bamboo monocultures, possibly leading to biodiversity loss and pests and diseases.
- Bamboo may compete with food production when grown on fertile land.
- Transport of bamboo biomass, particularly intact (hollow) culms, may be too costly for bulk processing.

8.2 Bamboo as a dedicated energy crop?

Using bamboo as a dedicated energy crop for large scale biomass production for thermal conversion or for (second generation) biofuel (i.e. ethanol) production has the following drawbacks at this moment:

- It is difficult to mechanize harvesting of bamboo, as only mature shoots should be harvested selectively. This process can hardly be mechanized. Clear-cutting will in most cases severely damage the stand.
- Non-energy applications will in most cases have a more attractive market.
- Bamboo has to be established vegetatively rather than from seed, making large plantings relatively expensive. It also takes several years before a stand can start producing. This means that it takes several years before investments in a plantation start paying back.
- Quality for thermal conversion is lower than for wood due to higher ash and K contents. Albeit compared to most herbaceous crops (grasses, straw) the quality for thermal conversion should be better.
- Using by-products from bamboo processing as energy or fermentation feedstock is an option only when the material has not been glued with synthetic glues or impregnated with conservation agents such as boric acid. This will generally exclude building material by-products.

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