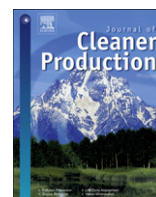




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The sustainability of bamboo products for local and Western European applications. LCAs and land-use

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ARTICLE INFO

Article history:

Received 19 June 2009
Received in revised form
11 March 2010
Accepted 25 April 2010
Available online 3 June 2010

Keywords:

Life cycle assessment
LCA
Land-use
Eco-costs
Bamboo

ABSTRACT

Bamboo has some positive aspects compared to wood:

- it can grow on slopes and other areas where foresting of wood is not possible, and it grows fast.
- it can replace tropical hardwood, so it can mitigate the decrease of tropical forest area.
- it can support the local economies in the third world.

This article is based on a bamboo species from China (*Phyllostachys Pubescens*, also called Moso), and its industrially processed products: Plybamboo and Strand Woven Bamboo. Life Cycle Assessment (LCA) is used in this paper to compare the environmental impact of bamboo materials, shipped to Western Europe, with commonly used materials such as timber. The calculations are based on the LCI databases of Ecoinvent v2 (2008) and Idemat 2008, applied to the eco-costs 2007 method for LCIA. The annual yield of harvesting is calculated as well, and compared with other wood products.

General conclusions are:

- bamboo products have less eco-costs than tropical hardwood (FSC certified)
- bamboo products imported in Europe have more eco-costs than local European softwood.
- the yield of bamboo is high compared to most other wood species: the yield of bamboo for production of biofuel is extremely high.

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1. Introduction

1.1. Bamboo and sustainability

The growing human population on our planet in combination with an increase of consumption per capita, is putting more and more pressure on global resources, which results in materials depletion, ecosystem deterioration and human health problems.

This paper will focus on two aspects of sustainability:

- a. Life Cycle Assessment (LCA), coping with all environmental effects along the production chain

- b. Yield of land, comparing the yield of bamboo plantations to the yield of forests

Life Cycle Assessment (as defined in the ISO 14040 series) is the common method to analyse the environmental pollution and materials depletion of the production chain (ISO 14040, 2006). The core of the method comprises two basic steps: the Life Cycle Inventory (a list of emissions and used materials) and the Life Cycle Inventory Analyses (a system to express the result of a LCI in one score, the so called “single indicator”) (ISO 14044, 2006).

A useful indicator for ecosystem deterioration, human health problems and depletion of metals and fossil fuels is the LCA based “eco-costs 2007” (Eco-costsvalue website). As a “prevention based” indicator model, it shows to what extent a product or production system is not in line with the maximum carrying capacity of our earth (Vogtländer and Bijma, 2000); (Vogtländer et al., 2001). The

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Fig. 1. Bamboo Mat Board applied for corrugated sheets for roofing.

eco-costs 2007 includes the issue of land-use in terms of decrease of biodiversity, published in this journal (Vogtländer et al., 2004). Wood from tropical rain forests has a high eco-costs score since harvesting results in severe losses of local biodiversity.

Transport is an important issue in LCA of wood and non wood forest products, which also applies to bamboo materials, and in particular a high volume per mass product such as the bamboo stem.

Yield of land is a specific aspect of sustainability, related with the fact that land is becoming scarce, especially when current materials (metals, fossil fuels) will be replaced by renewable materials like wood and non wood forest products like bamboo. A useful indicator for materials depletion in the sense of land-use is the Ecological Footprint, which is defined as “a measure of how much biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates using prevailing technology and resource management practices” (WWF International, 2006).

In 2003 the Ecological Footprint was 14.1 billion global hectares, whereas the global productive area is 11.2 billion hectares. This means that man is currently consuming more than 1.25 times the amount of resources the earth can produce according to this calculation method. So, renewable materials with a high yield of land are required.

Bamboo seems to be a good solution:

- It can grow in areas which are non-productive at this moment (e.g. eroded slopes)
- It is a fast growing material (it has a high yield)



Fig. 2. Low cost bamboo housing in Latin America (In terms of durability the mud/mortar clad housing (right) is strongly preferred over the version in which all the bamboo is directly exposed to climatic circumstances (left)).

- Its root structure stays intact after harvesting, generating new shoots

A third issue of sustainability which is important, but not dealt with in this paper, is the issue of the social aspects of production systems. An advantage of Plybamboo (board material consisting of laminated strips) and Strand Woven Bamboo (compressed bamboo composite material) is that the value of the product is added locally. Therefore, these industrial bamboo materials can make a good contribution in terms of local employment. A well managed bamboo industry may combine the P of People, the P of Planet, and the P of Profit, from the Triple P Model (Elkington, 1998).

1.2. Current use of bamboo in local markets

It is important to realise that bamboo is perceived as a low value material in the local markets. The most important applications of local bamboo are its stem and bamboo mats. Bamboo mats are also pressed in Bamboo Mat Board (See Fig. 1).

An important market segment for the stem is housing, especially in China, India and Latin America (Fig. 2). Without any doubt, this is a very sustainable solution, however, not applicable to the markets of Western Europe.

The fact that the current local applications of bamboo are perceived as low value in Western Europe as well, resulted in an effort at the Delft University of Technology to create innovative solutions which can be introduced in the markets of Western Europe (Van der Lugt, 2008); (Van der Lugt, 2007), see for an example Fig. 3. The basic idea is called “eco-efficient value creation” (Ecocostsvalue website); the customer value is to be enhanced by innovation, so that bamboo becomes more attractive to the people in Western Europe.

In this effort, new high quality bamboo materials, such as Plybamboo and Strand Woven Bamboo are applied in high end consumer durables. Plybamboo consists of boards and veneer made of laminated bamboo strips. Strand Woven Bamboo, is a very hard and dense composite bamboo material, see Fig. 4.

However, an important question is whether or not bamboo materials are more sustainable than industrial wood products, when transported to Western Europe. This article deals with this basic question.

2. The system for LCA calculations

2.1. Eco-costs as a single indicator in LCA

The eco-costs method is used in LCIA to express the amount of environmental burden on the basis of prevention of that burden. Eco-costs are related to the costs which should be made to reduce the environmental pollution and materials depletion in our



Fig. 3. Bamboo chair designed by Tejo Remy and René Veenhuizen during the project “Dutch Design meets Bamboo” (Van der Lugt, 2008; Vander Lugt, 2007).

economy to a level which is in line with the carrying capacity of our earth (Ecocostsvalue website; Vogtländer et al., 2009). Eco-costs are “marginal prevention costs”. As such, the eco-costs are virtual costs, since they are not yet integrated in the real life costs of current production chains (Life Cycle Costs). According to Vogtländer (Ecocostsvalue website; Vogtländer et al., 2009), eco-costs should be regarded as hidden obligations.²

The Eco-costs model is based on the sum of the marginal prevention costs during the life cycle of a product for toxic emissions, material depletion, energy consumption and conversion of land, see Fig. 5. The advantage of eco-costs is that it is expressed in a standardised monetary value which appear to be easily understood “by instinct”, published in this journal (Vogtländer et al., 2002). The calculation is transparent and relatively easy compared to damage based models which have the disadvantage of extremely complex calculations with subjective weighting of the various aspects contributing to the overall environmental burden (Bengtsson and Steen, 2000).

For emissions of toxic substances, the following set of multipliers is used in the eco-costs 2007 system:

- Prevention of acidification 7.55 €/kg SOx equivalent
- Prevention of eutrophication 3.60 €/kg phosphate equivalent
- Prevention of ecotoxicity 802 €/kg Zn equivalent
- Prevention of carcinogens 33 €/kg PAH equivalent
- Prevention of summer smog (respiratory diseases) 8.90 €/kg C2H4 equivalent
- Prevention of fine dust 27.4 €/kg fine dust PM2.5
- Prevention of global warming (GWP 100) 0.135 €/kg CO2 equivalent

The eco-costs of abiotic depletion is 0.7 €/kg for fossil fuels.

The eco-costs of material depletion of tropical hardwood are based on the change of biodiversity before and after harvesting (Ecocostsvalue website; Vogtländer et al., 2004; Vogtlander, 2001).³ To determine the biodiversity, global maps of Barthlott et al. (2005) have been applied.

For wood from plantations this change of biodiversity is set to zero,⁴ but for wood from rain forests the degradation of biodiversity is severe, resulting in high levels of eco-costs:

- For FSC⁵ certified wood the assumption is that 40% is from plantations, and 60% is from rain forests in areas with lower biodiversity (on average 1/3 of the maximum biodiversity in the country), harvested according to the RIL (Reduced-Impact Logging) method
- For logging in rain forests, RIL is assumed, with 50% degradation of biodiversity.
- For illegal logging 100% loss of biodiversity is assumed (total devastation)

2.2. The production system and its boundary limits

The production system of bamboo “from cradle to site” is depicted in Fig. 6. The required heat for drying is produced by combustion of sawdust.

The case which was studied is based on the actual product chain of a large bamboo importer in the Netherlands:

- Plantation and first processing: the Anji region, the province of Zhejiang, China
- Final processing (Plybamboo, SWB, veneer): Huangzhou, the province of Zhejiang
- The product is shipped via Shanghai and Rotterdam to a warehouse in The Netherlands (Zwaag)
- Time period of data collection: July 2007⁶

⁴ For plantations, a “steady state” is assumed, i.e. for every tree which is harvested, a new tree is planted. The result of such a steady state is that, on average, biodiversity of the plantation will not change over time. The same applies to carbon sequestration: the total amount of CO₂ which is captured in such a plantation does not change over time either. Biodiversity might increase in some mountain areas by expanding plantations, see Chapter 4, Fig. 14. However, this is not the case in this typical study (the Anji region in China).

⁵ FSC is an independent, non-governmental, not-for-profit organization, established to promote the responsible management of the world's forests. FSC certification provides standard-setting and accreditation of companies and organizations in the wood industry. See www.fsc.org.

⁶ This study started with site visits in March 2006. The main data were collected a year later. The reader should be aware of the fact that China is catching up with modern Western technology quite rapidly, having positive effects on the LCA. E.g. introduction of cogeneration of electricity and heat can have considerable positive effect on the eco-costs of electricity, since the feedstock is bamboo waste material.

² Prevention measures will decrease the costs of the damage, related to environmental pollution (e.g. damage costs related to human health problems). The savings which are a result of the prevention measures are of the same order of magnitude as the costs of prevention. So the total effect of prevention measures on our society is a better environment at virtually no extra costs, since costs of prevention and costs of savings will level out.

³ Details on the calculation of other wood species are given at Ecocostsvalue website tab “data”, Excel file “eco-costs calculations wood”.



Fig. 4. Industrial bamboo materials, Plybamboo (left) and Strand Woven Bamboo (right).

- Type of bamboo: *Phyllostachys Pubescens* (density 700 kg m^{-3} , length up to 15 m, diameter on the ground 10–12 cm, wall thickness 9 mm), also called Moso.

The required heat for the process is generated locally by combustion of sawdust and bamboo waste. There is more sawdust and bamboo waste available, than it is needed for heat. This surplus of feedstock is not transported to an electrical power plant, but is discarded. A cogeneration plant for electricity and heat is an opportunity for the future, to enhance the energy efficiency based on the sustainable fuel. The LCA of this paper, however, is based on the existing situation.

The calculations for the LCAs have been made with the computer program Simapro, applying LCI databases of Ecoinvent v2 (2008) and Idemat 2008 (a database of the Delft University of Technology, partly based on Ecoinvent Unit data). The assumption here is that the equipment for transport and production in modern China does not differ much from the equipment used in Western Europe, however, the oil refineries for diesel are polluting twice as much.

The environmental damage of electrical power in China is considerably higher than that of power plants in Western Europe. However, the eco-costs of electricity is not based on end-of-pipe prevention measures, but on system integrated measures (i.e. the prevention costs of renewable energy sources like windmills and solar power systems). The assumption is that the costs of these systems do not differ considerably from the costs in Western Europe.

The eco-costs of construction materials (from cradle to gate) and transport can be found in the open access tables provided at [Ecocostsvalue website](#), or can be calculated with special databases in Simapro.

3. Bamboo products⁷

3.1. Bamboo stem

The tubular form of the bamboo stem offers some major advantages. Janssen (2000) has proven that bamboo in terms of the relation between the moment of inertia and the diameter is 1.9 times more effective than the rectangular solid cross section of a wooden beam, which leads to material savings and a light construction weight, see Fig. 7. Disadvantages of the stem are its round, irregular, tapering form, and its susceptibility to splitting.

The disadvantage that the bamboo stem has not a standardised end, has been resolved by several engineers. An example of one of the few commercial solutions is given in Fig. 8.

As noted in Section 1.2, the bamboo stem is mostly used in low-end housing in developing countries. However, modern architects such as the Columbian Simon Vélez have started applying bamboo as a high-grade material in exclusive buildings as well. In his

structures, Vélez makes maximum use of the lightness and efficient mechanical design of bamboo, for example, by applying the bamboo stem in roof structures with large eaves and bridges with large spans, see Fig. 9.

The base element for LCA which is used for the stem, is one 5.33 m-long bamboo stem with a diameter of 10 cm at bottom, 7 cm at top, and a dry weight of 7.65 kg (the “Functional Unit”, FU).

The stem is transported (15 km) from the plantation to a site where it is preserved and dried. Approximately 1000 stems are loaded in a 40-foot container (67.7 m^3). The container is then transported with a 28-ton truck over a distance of 600 km to the harbour of Shanghai.

The calculation to determine the environmental burden for sea transport was based on transport with a trans-oceanic freight ship in a 40-foot container, with a travel distance Shanghai–Rotterdam of 19 208 km.

The environmental burden of transport in LCA is usually based on the weight of the load, however, the calculation must be based on volume when the weight/volume ratio⁸ of the freight in the 40-foot container is less than 415 kg m^{-3} , ([Ecocostsvalue website](#)).

A walking bridge in a park in Amsterdam was taken as a design case (see Fig. 10.), in which the transversal supporting beam (2.1 m) in the bridge was used as FU to compare 4 material alternatives fulfilling the same mechanical requirements:

- 2 bamboo stems from China (diameter 9 cm, length 2.1 m, lifespan 10 years)
- 1 beam of Azobé ($0.1 \times 0.2 \times 2.1 \text{ m}$, lifespan 25 years)
- 1 beam of Robinia ($0.12 \times 0.225 \times 2.1 \text{ m}$, lifespan 15 years)
- 1 beam of steel (IPE 100, length 2.1 m, lifespan of 50 years)

In this particular application, the durability differs for the various materials. So the lifespan needs to be taken into account for a correct comparison. The results of the eco-costs per FU of bamboo compared to the alternatives are represented in Table 2 and Fig. 11.

The conclusion of this case is that the bamboo stem, used as a construction material in Europe, does not score very well in terms of eco-costs. This is mainly caused by the high volume bamboo stem during transport, which accounts for 89% of the total environmental burden, see Table 1. However, the bamboo stem has the best score for a local application in China.

Note that “local” in the case is “with in a radius of 600 km”. To a maximum of up to 1400 km bamboo is better than the alternative solutions.

3.2. Plybamboo

Since transport of the bamboo stem is not an environmental friendly solution, it is a logic step to analyse Plybamboo made in China. This features two advantages:

⁷ A detailed description of the production system, the calculations and the background of the Tables in this Chapter can be found in (van der Lugt et al., 2008).

⁸ 1 FU has a weight of 7.65 kg and a transport volume of 0.0677 m^3 , so a transport weight/volume ratio of 114 kg m^{-3} .

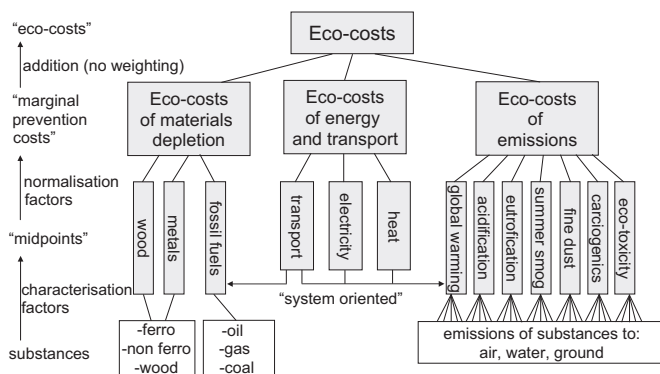


Fig. 5. Calculation structure of the eco-costs 2007.

- Plybamboo is a compact product, so efficient for container transport
- Plybamboo is made locally, so the value is added locally (positive for the local economy)

The basic length for most industrial bamboo materials is 2.66 m, based on which the complete Chinese industrial bamboo industry is standardised. Usually about 8 m (3×2.66 m) of a harvested bamboo stem will be used for the development of bamboo products. The bottom two parts of 2.66 m are mostly used as input for the manufacturing of industrial bamboo materials such as Plybamboo boards, while the upper part may be used for smaller bamboo products such as blinds and chopsticks.

The bottom segments of the stem will first be processed into rough strips (approximately $2630 \times 23 \times 8$ mm). This is done near the plantations. The strips are then transported to the manufacturing site of the Plybamboo, see Fig. 6. In the case which has been studied, the distance to the manufacturing site of Plybamboo was 300 km.

Plybamboo, a hard aesthetic material which is often used in flooring or tabletops, is manufactured in various varieties (see Fig. 4): 1, 3, or 5 layers, bleached or carbonized,⁹ side pressed or plain pressed. Table 3 provides data for 3 layer carbonized Plybamboo. A comprehensive description of the production processes and Tables for the other varieties can be found in (van der Lugt et al., 2008).

To get some feel how Plybamboo compares with other alternatives, see Fig. 12. In this figure the eco-costs of Plybamboo and some relevant wood alternatives are compared for use in a $1220 \times 1220 \times 20$ mm tabletop, based on a 700 kg m^{-3} density for Plybamboo and Oak, 690 kg m^{-3} for Walnut and 650 kg m^{-3} for Teak. Bamboo scores good in comparison to tropical hardwood from FSC-sources (in this case Teak), but a factor 5–6 worse than European grown wood.

During the design project “Dutch Design meets Bamboo” (Van der Lugt, 2008; Van der Lugt, 2007), it was found that the bendability can also be acknowledged as a competitive advantage for Plybamboo (see for example lounge chair designed by Tejo Remy and René Veenhuizen in Fig. 3). Therefore, this chair was chosen as another FU to compare the eco-costs of bamboo with wood.

The chair consists of seven slabs of 1-layer carbonized, side pressed Plybamboo (three slabs of approximately $1.25 \times 0.15 \times 0.005$ m, four

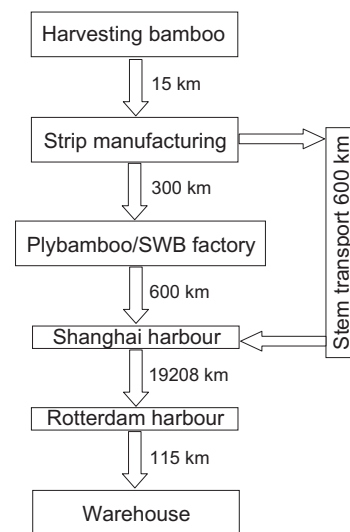


Fig. 6. The production system of bamboo (cradle to gate).

slabs of $1.25 \times 0.15 \times 0.005$ m; in total 0.0088 m^3 of material). For bending, Beech is usually chosen as the most appropriate wood species. As an additional alternative plywood topped with a veneer layer of an aesthetic wood species (e.g. Walnut) may be used in this application. For both the Beech and plywood alternatives it is assumed that the same volume of material is required as for Plybamboo. In Fig. 13 the eco-costs/FU for Plybamboo and the various alternatives are represented.

3.3. Strand Woven Bamboo (SWB)

Strand Woven Bamboo (SWB) is a relatively new industrial bamboo material that can be used indoors and outdoors, with a high hardness (2800 lbf) and density (1080 kg m^{-3}), see Fig. 4. This high hardness and density is caused by the fact that the bamboo strips are compressed by a factor 1.54 and used in combination with a high resin content.

The eco-costs of SWB are higher than for Plybamboo, mainly because of the fact that 23% Phenol Formaldehyde resin is applied in this product, causing 36.4% of the eco-costs in the production phase of this resin. See Table 4.

One of the unique features of SWB is that, if manufactured and processed in the right manner, is suitable for use outdoors, unlike other industrial bamboo materials. For this reason, the eco-costs of

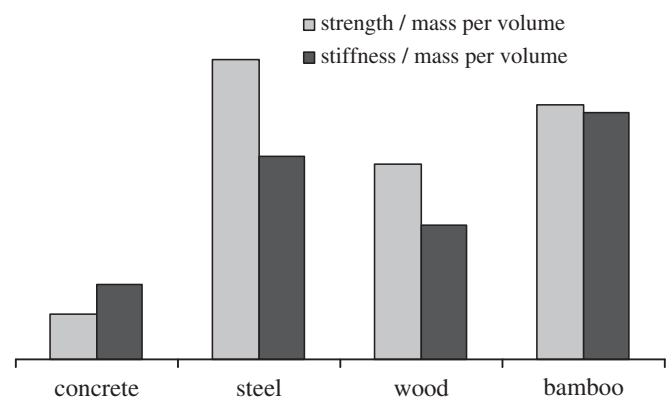


Fig. 7. Comparison in strength and stiffness relative to their densities of bamboo with other commonly used building materials (Janssen, 2000).

⁹ Carbonization is the commonly used term in the bamboo industry to denote the process in which the sugars in the bamboo are released through steam treatment through which the bamboo material acquires a darker colour. Not to be confused with “making charcoal” or “thermally modification of wood”.

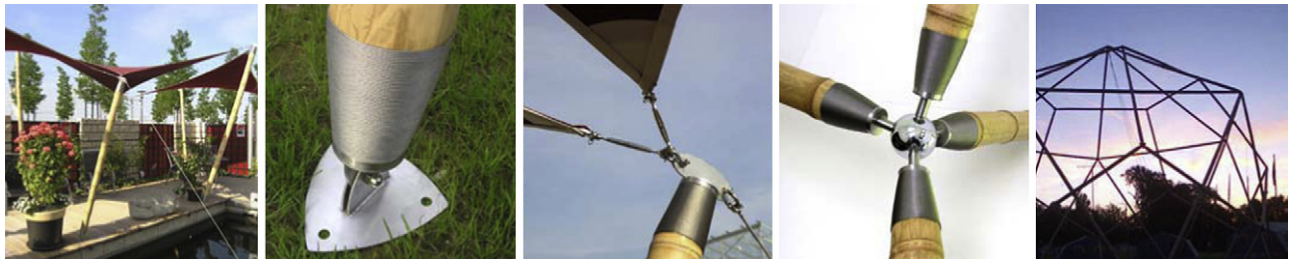


Fig. 8. CONBAM® building system developed by Christoph Tönges www.conbam.de.



Fig. 9. The strength of bamboo shown through various constructions in Colombia designed by Simon Vélez with spectacular eaves and spans.



Fig. 10. The bamboo walking bridge in the Amsterdam Woods.

carbonized SWB were compared with hardwood alternatives in the function of terrace decking for outside use with dimensions of $1900 \times 100 \times 15$ mm (FU = 0.00285 m^3). SWB was compared with FSC certified Teak since Teak is the commonly used wood species for this application, see Table 5.

4. Yield of land-use

The importance of the yield of land is fully in line with the philosophy of the ecological footprint, as has been mentioned in the

introduction. This is the notion that the consumption of people is to be supported by the production of land: more consumption leads to less nature. See Fig. 14.

For designers, architects and engineers it means that yield is an additional sustainability issue (apart from LCA) in the selection of the type of wood, since every type of wood has its own yield in forestry.

The calculation for both wood and bamboo is based on numbers for average plantation sites and processing facilities. Note that depending on geographical and climatic circumstances (e.g. soil, precipitation, elevation, etc.), yields may be considerably higher or

Table 1
Input data and results for the environmental impact assessment of a 5.33-m long bamboo stem (cradle to gate).

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation. Gasoline consumption	0.016	liter/FU	1.04/liter	0.017	0.0022	0.25%
2. Transport from to stem processing facility; Eco-costs of a 5-ton truck (transport 320 FUs)	30	Km (empty back)	0.243/km per 5t truck	0.0228	0.0030	0.34%
3. Preservation & drying; Energy consumption	1	kWh/FU	0.109/kWh	0.109	0.0142	1.59%
4. Transport from stem preservation facility to harbor (28-ton truck), 600 km	40,64	$\text{m}^3 \text{ km}/\text{FU}$	$0.0125/\text{m}^3 \text{ km}$	0.508	0.0664	7.42%
5. Transport from harbor to harbor Eco-costs (volume based; 400ft container in a trans-oceanic freight ship)	1300	$\text{m}^3 \text{ km}/\text{FU}$	$0.0041/\text{m}^3 \text{ km}$	5.330	0.795	89.00%
6. Transport from harbor to warehouse Eco-costs (28-ton truck)	0.88	$\text{m}^3 \text{ km}/\text{FU}$	$0.0125/\text{m}^3 \text{ km}$	0.097	0.0126	1.40%
Total eco-costs (€)				6.08	0.893	100.0%

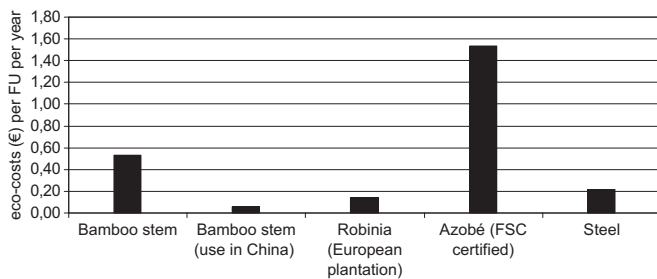
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Table 2

Eco-costs per year for bamboo, wood and steel used as a transversal beam in a walking bridge (cradle to grave). The wood is unpainted.

Material	Density (kg/m ³)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs (€) per FU per year	Eco-cost per FU per year (ratio)
Bamboo stem	700	0.89	6.0	5.34	0.53	100%
Bamboo stem (use in China)	700	0.086	6.0	0.52	0.052	10%
Robinia (plantation)	740	0.05	42.2	2.11	0.14	26%
Azobé (FSC certified)	1060	0.86	44.5	38.27	1.53	287%
Steel	7850	0.487	22.3	10.86	0.22	41%

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**Fig. 11.** Eco-costs per year for bamboo, wood and steel used as a transversal beam in the walking bridge (cradle to grave).

lower, so data is only meant to be indicative of the average yields of the specific species in question.

The annual yields have been calculated for the giant bamboo species Moso from China, and *Guadua* from Latin America. *Guadua* is bigger than Moso. It may reach heights up to 20–25 m and diameters up to 22 cm (Riaño et al., 2002). Like most bamboos, it reaches its final height in the first half year of its growth (with a growing speed up to 21 cm a day), and will come to maturity in the following 4–5 years.

Guadua, like other tropical bamboo types, has a higher yield (approx a factor 2) than Moso from the Chinese subtropical area of

Zhejiang. However, the biodiversity of areas where *Guadua* grow is a factor 2.5 higher than the biodiversity of the Zhejiang area. Therefore, from the point of view of saving nature, it seems wiser to expand Moso plantations rather than *Guadua* plantations for future demand of bamboo products.

The maximum annual yield of bamboo and wood may differ depending on the kind of semi finished materials produced. Calculations have been made on 3 scenarios (qualities), depicted in Fig. 15:

- High value products (sawn timber, veneer, Plybamboo, SWB, taped mats)
- Medium value products (MDF, chipboard)
- For combustion as an energy source and for pulp (bamboo compared with eucalyptus)

The comparison of the A-quality scenario is made between bamboo, Teak, Oak and (modified) Radiata Pine, see Fig. 16.

Moso has a slightly higher annual yield in terms of A-quality materials compared to fast growing and early harvested Teak (so-called baby Teak), which is one of the fastest growing hardwood species that is used in high end interior decoration (e.g. flooring).

SWB is suitable for outdoor applications such as decking, and therefore to be compared with hardwoods such as regular Teak. In

Table 3Input data and results for the environmental impact assessment of carbonized 3-layer Plybamboo board (cradle to gate). The FU used as the base element for this assessment is one board of 2440 × 1220 × 20 mm (2.98 m²), with a weight of 41.7 kg (based on a density of 700 kg m⁻³).

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation. Gasoline consumption	0.224	liter/FU	1.04/liter	0.233	0.0056	1.4%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 23.1 FUs)	30	Km	0.243/km per 5t truck	0.316	0.0076	1.9%
3. Strip making: Energy consumption	1.38	kWh/FU	0.109/kWh	0.150	0.0036	0.9%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 77.6 FUs).	600	Km	0.32/km per 10t truck	2.474	0.0593	15.0%
5. Rough planing: Energy consumption	8.62	kWh/FU	0.109/kWh	0.940	0.0225	5.7%
6. Strip selection						
7. Carbonization: Energy consumption	4.73	kWh/FU	0.109/kWh	0.516	0.0124	3.1%
8. Drying: Energy consumption	34.6	kWh/FU	0.109/kWh	3.771	0.09	22.9%
9. Fine planing: Energy consumption	5.8	kWh/FU	0.109/kWh	0.632	0.0152	3.8%
10. Strip selection						
11. Glue application (1-layer boards) Added amount of Urea formaldehyde (wet)	0.894	Kg/FU	0.57/kg	0.510	0.0122	3.1%
12. Pressing strips to 1-layer board: Energy	1.89	kWh/FU	0.109/kWh	0.206	0.0049	1.3%
13. Sanding 1-layer board: Energy	1.62	kWh/FU	0.109/kWh	0.177	0.0042	1.1%
14. Glue application (3-layer board) Added amount of Urea formaldehyde (wet)	0.983	kg/FU	0.57/kg	0.56	0.0134	3.4%
15. Pressing three layers to one board: Energy	1.65	kWh/FU	0.109/kWh	0.18	0.0043	1.1%
16. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.032	0.0008	0.2%
17. Sanding 3-layer board: Energy	0.86	kWh/FU	0.109/kWh	0.094	0.0022	0.6%
18. Dust absorption (during all steps) Energy consumption	8.67	kWh/FU	0.109/kWh	0.945	0.0227	5.7%
19. Transport from factory to harbor Eco-costs (28-ton truck)	12.51	ton.km/FU	0.033/ton.km	0.413	0.0099	2.5%
20. Transport from harbor to harbor Eco-costs (20 ft container in a trans-oceanic freight ship)	801	ton.km/FU	0.0052/ton.km	4.165	0.0999	25.3%
21. Transport from harbor to warehouse Eco-costs (28-ton truck)	4.80	ton.km/FU	0.033/ton.km	0.158	0.0038	1.0%
Total eco-costs (€)				16.47	0.395	100.0%

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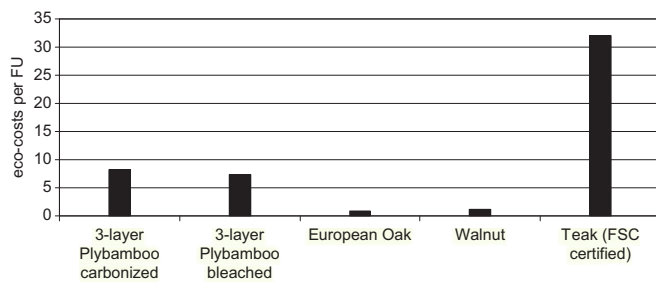


Fig. 12. Eco-costs per tabletop of $1220 \times 1220 \times 20$ mm (FU = 0.0298 m^3) based on solid material. (cradle to gate).

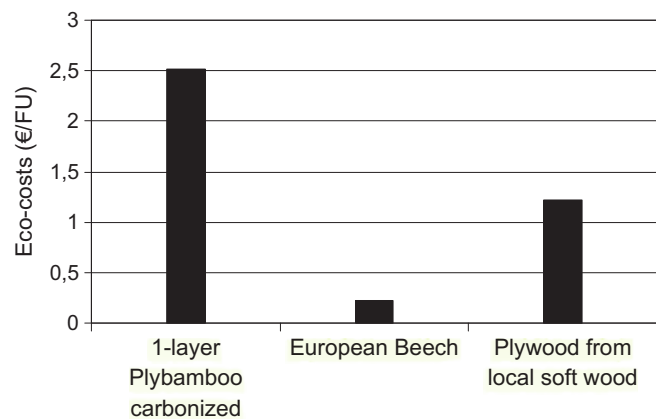


Fig. 13. Eco-costs per year for 1-layer Plybamboo (carbonized) and wood alternatives used in the bended lounge chair (=FU) of Fig. 3 (cradle to gate).

this respect it has to be mentioned that the bamboo material is compressed by a factor 1.54 to make SWB.

The comparison of the B-quality scenario is made for MDF. For MDF production based on wood, only fast growing softwood species such as Eucalyptus and Radiata Pine are advised to be

used, due to the relative low value character of MDF. Fig. 17 shows that Moso based MDF has an annual yield which is around half the yield of fast growing softwoods such as Eucalyptus and Radiata Pine, while Guadua based MDF is competitive. Note that the density of Radiata Pine and Eucalyptus ($450\text{--}550 \text{ kg m}^{-3}$) is lower than the density for bamboo (700 kg m^{-3}). Taking into account a similar compression rate (factor 1.5), the bamboo based MDF will therefore have a higher density (1050 kg m^{-3}), and possibly better mechanical properties, than softwood based MDF (750 kg m^{-3}).

For biofuel production (e.g. biocoal) the total dry weight that can be produced annually from a plantation must be used as a base of comparison. The energy production is $16\text{--}20 \text{ MW kg}^{-1}$ at a CO_2 emission of $1.45\text{--}1.5 \text{ kgCO}_2/\text{kg}$ (Lamlom and Savidge, 2003). The annual yields in terms of dry tons of wood and bamboo biomass for biofuel are depicted in Fig. 18.

The annual yields differ from the annual yields for semi finished products, since the bamboo does not have to mature and can be harvested based on a 2-year cycle instead of a 4–5 year cycle. For Moso, the yield is based on $1500 \text{ stems/ha} \times 9.52 \text{ kg}$ per debranched stem $\times 1.25$ to include additional biomass in form of branches and leaves = 17.9 dry tons. The annual yield for Guadua is based on a yield of $2500 \text{ stems/ha} \times 16.43 \text{ kg} \times 1.25 = 51.3$ dry tons. The annual yield for Eucalyptus is based on the annual increase in standing volume (25 m^3) $\times 500 \text{ kg/m}^3 = 12.5$ dry tons. Fig. 18 shows that, because of the high growing speed, bamboo has a lot of potential for this application.

A general benefit of bamboo as a reforestation crop compared to wood, is the short establishment time of a bamboo plantation. While the establishment time of a plantation of tropical giant bamboo species such as Guadua to come to maturity will not take longer than 10 years, the establishment time of a wood plantation to maturity may range from 15 years (Eucalyptus), 30 years (baby Teak), 70 years (regular Teak) to 80 years (European Oak). This means that a bamboo plantation will be able to deliver the annual yield of a mature plantation faster than any wood species can.

Note that in case of sustainable harvesting, the root structure stays intact, so the bamboo stems grow from new shoots.

Table 4

Input data and results for the environmental impact assessment of one carbonized SWB plank (cradle to gate) with dimensions of $1900 \times 100 \times 15$ mm (FU = 0.00285 m^3).

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation. Gasoline consumption	0.010	liter/FU	0.104	0.001	0.0004	0.1%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 492.3 FUs)	30	km/truck	0.243	0.014	0.0045	0.9%
3. Strip making: Energy consumption	0.1	kWh/FU	0.109	0.011	0.0035	0.7%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck. (transport of 1277.7 FUs)	600	km/truck	0.32	0.132	0.0429	8.2%
5. Rough planing: Energy consumption	0.66	kWh/FU	0.109	0.072	0.0234	4.5%
6. Splitting strips in half	0.10	kWh/FU	0.109	0.011	0.0035	0.7%
7. Carbonization: Energy consumption	0.35	kWh/FU	0.109	0.038	0.0124	2.4%
8. Drying: Energy consumption	2.58	kWh/FU	0.109	0.281	0.091	17.4%
9. Crushing strips	0.17	kWh/FU	0.109	0.019	0.006	1.1%
10. Glue application: Added amount of Phenol formaldehyde (wet)	0.710	kg/FU	0.827	0.587	0.191	36.4%
11. Pressing strips to beam	0.29	kWh/FU	0.109	0.032	0.0103	2.0%
12. Activating glue in oven	0.35	kWh/FU	0.109	0.038	0.0124	2.4%
13. Sawing beams: Energy consumption	0.044	kWh/FU	0.109	0.005	0.0016	0.3%
14. Sawing planks: Energy consumption	0.091	kWh/FU	0.109	0.010	0.0032	0.6%
15. Sanding planks: Energy consumption	0.094	kWh/FU	0.109	0.010	0.0033	0.6%
16. Transport from factory to harbor Eco-costs (28-ton truck)	0.93	ton. km/FU	0.033	0.031	0.0100	1.9%
17. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	59.60	ton. km/FU	0.0052	0.310	0.1006	19.2%
18. Transport from harbor to warehouse Eco-costs (28-ton truck)	0.360	ton. km/FU	0.033	0.012	0.0039	0.7%
Total eco-costs (€)				1.613	0.524	100.0%

Table 5

Eco-costs per year for SWB and alternatives for outside terrace decking (cradle to site).

Material	Density (kg/m ³)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU
SWB	1080	0.52	3.08	1.61
Teak (FSC certified)	650	1.70	1.85	3.15

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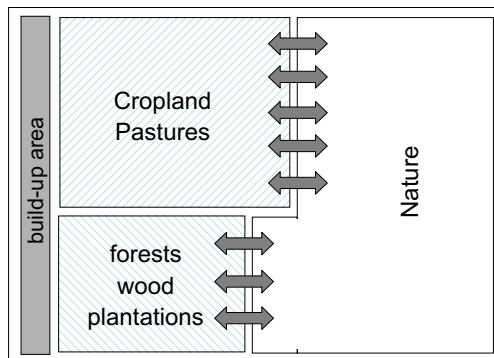


Fig. 14. Yield of cropland, pastures and forests for wood production is important, especially in areas where nature has a high biodiversity (more yield = less pressure on nature). (Although the general message of Fig. 14 is that the yield must be as high as possible to achieve a minimum ecological footprint, Fig. 14 has an additional meaning in the case of bamboo plantations. In mountain areas and eroded hills, where trees cannot grow on the slopes, or in other areas where cultivation of land is not possible and where the biodiversity is low, expanding bamboo plantations can result in increasing biodiversity and carbon sequestration).

5. Discussion

The bamboo **stem** is the most environmentally friendly material compared to all alternatives which have been studied, when it is used directly in bamboo producing countries. However, when it is to be transported to Europe, it loses its environmental advantage, because of the environmental burden of the transport. The reason is the low transport efficiency, due to the high volume/weight ratio of the hollow stem.

If the stem is industrially processed into **Plybamboo** and transported to Western Europe, the environmental edge of bamboo compared to the European grown wood species is lost mainly because of the extra transport. However, the quality of Plybamboo for floors in houses is better than the quality of these softwood species.

SWB (Strand Woven Bamboo) scores better in eco-costs than tropical hardwood from FSC certified sources. The eco-costs of SWB can be lowered considerably when bio resin would be used instead of the Phenol Formaldehyde resin deployed now.

Therefore, from an eco-costs perspective, it is recommended to only use bamboo materials in Western Europe in applications in which the specific competitive advantages of bamboo materials (e.g. hardness, bendability, aesthetic properties, and outside durability) are utilized.

In terms of annual **yield** it was found that bamboo was the best performing renewable resource around, if used as “A-quality” semi finished material in a durable application (e.g. for housing, and use outdoors). For “B-quality” semi finished material, like wood based boards (MDF, particle board), fast growing softwood species, like

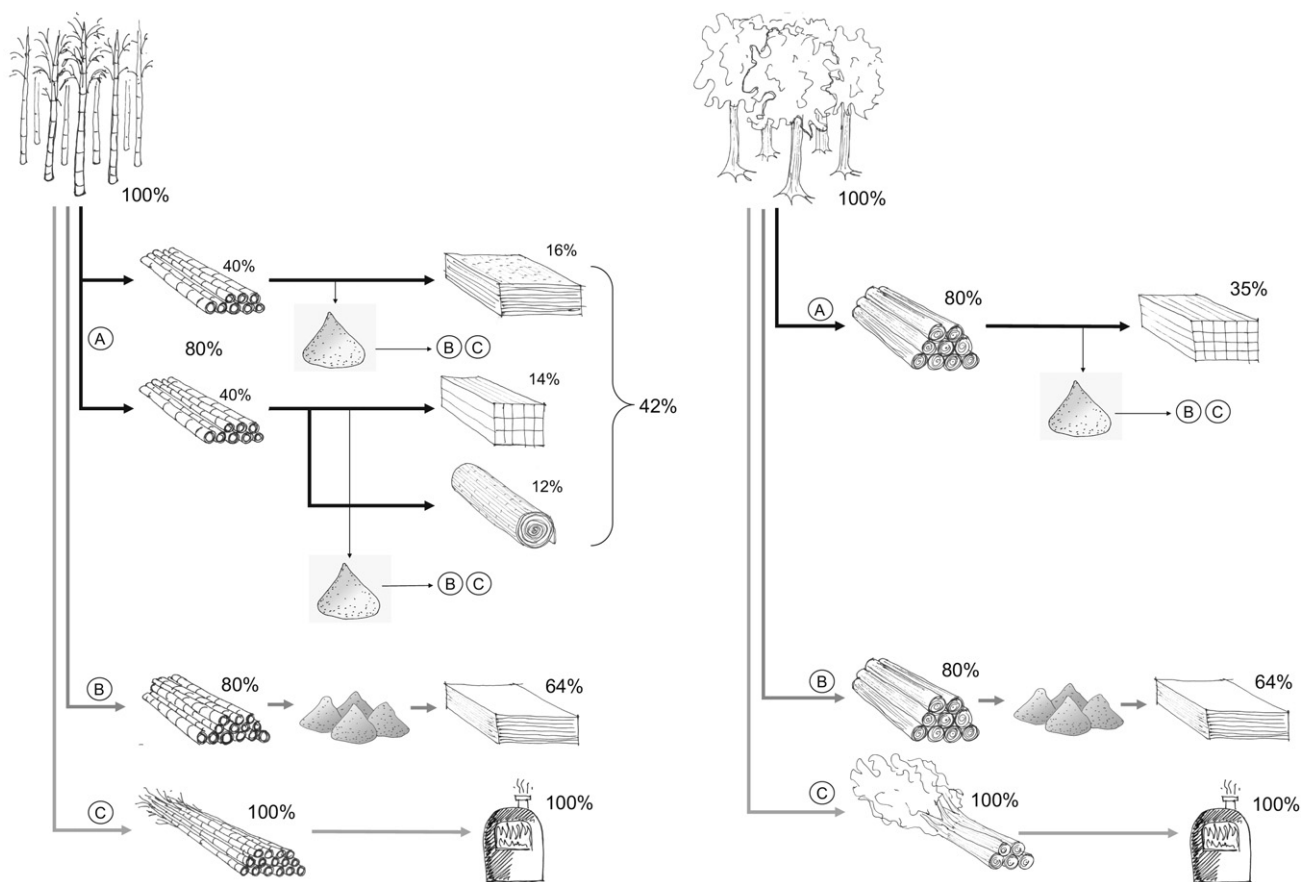


Fig. 15. Efficiency during the conversion of bamboo (left) and wood (right) resources to semi finished materials for 3 scenarios, A-quality, B-quality and C-quality; all percentages related to harvestable standing volume (100%).

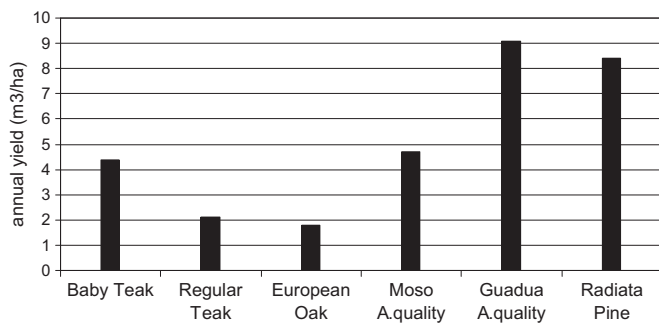


Fig. 16. The annual yield in m³/ha A-quality semi finished materials, sourced from plantations (Riaño et al., 2002; MAF, 2008).

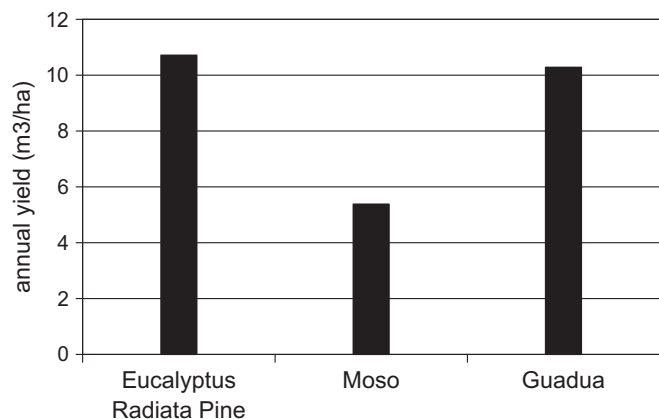


Fig. 17. The annual yield in m³/ha B-quality semi finished materials (MDF), sourced from plantations.

Eucalyptus and Radiata Pine, are competitive compared to Guadua, but perform better compared to Moso in terms of annual yield.

Various bamboo species may also be used as **biofuel** for combustion in power plants. They have the best fast growing characteristics for this type of application. Bamboo has a low ash content and a low alkali index. Its heating value, however, is 5–10% lower than softwood. For more fuel characteristics, see Scurlock et al., 2000.

In future, there might also be good prospects for the production of biodiesel.

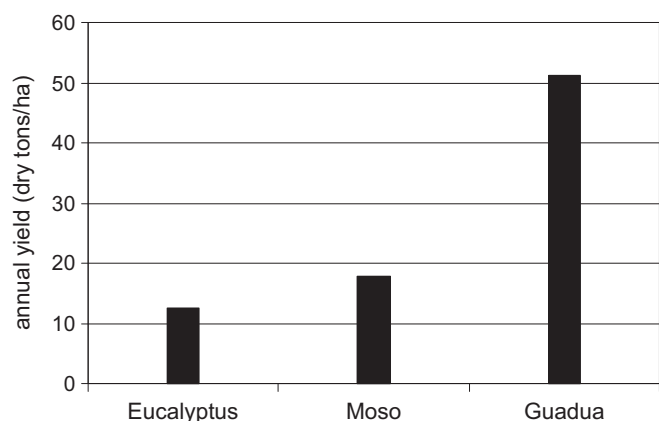


Fig. 18. The annual yield in tons/ha biofuel, sourced from plantations.

6. Conclusions

General conclusions of this analysis are:

- The bamboo stem is a sustainable solution for local applications. The transport distance to Europe, however, is the main hurdle in terms of environmental impact. For Europe, local species are more sustainable
- Industrial bamboo materials in Europe in the form of Ply-bamboo and SWB (Strand Woven Bamboo), score well compared to FSC hardwood in terms of eco-costs as well as yield.
- Second grade bamboo products, like MDF and chipboard from bamboo are a good solution for local applications. However, they cannot compete in Europe with the European second grade products from European softwood.
- The annual yield of bamboo, in combination with its durable root structure, is its big advantage. In terms of land-use, bamboo seems to be one of the promising solutions in the required shift towards renewable materials.
- Bamboo seems to be an excellent source for biofuel, because of the extremely high yield which can be achieved.

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