INBAR Working Paper

INTERNATIONAL BAMBOO AND RATTAN ORGANISATION

Technical Paper

Potential of Bamboo for Renewable Energy: Main Issues and Technology Options

Claudia Daza Montaño, Jan E.G. van Dam

2021

RESEARCH PROGRAM ON Forests, Trees and Agroforestry

CGIAR

About the International Bamboo and Rattan Organisation

The International Bamboo and Rattan Organisation (INBAR) is an intergovernmental organisation dedicated to the promotion of bamboo and rattan for sustainable development. For more information, please visit www.inbar.int.

About this Working Paper

This research was carried out by the International Bamboo and Rattan Organisation (INBAR) as part of the CGIAR Research Program on Forests, Trees and Agroforestry (FTA). FTA is the world's largest research for development programme for enhancing the role of forests, trees and agroforestry in sustainable development and food security and addressing climate change. CIFOR leads FTA in partnership with Bioversity International, CATIE, CIRAD, INBAR, ICRAF and TBI. FTA's work is supported by the CGIAR Trust Fund: http://www.cgiar/org/ funders

International Bamboo and Rattan Organisation

P.O. Box 100102-86, Beijing 100102, China Tel: +86 10 64706161; Fax: +86 10 6470 2166
Email: info@inbar.int

© 2021 International Bamboo and Rattan Organisation (INBAR)

List of Abbreviations

CNG	Compressed natural gas
CO_2	Carbon dioxide
FSC	Forest Stewardship Council
GHG	Greenhouse gases
GJ	Gigajoules
Gt	gigaton = 10^9 ton
ha	Hectare
HTL	Hydrothermal liquefaction
IEA	International Energy Agency
INBAR	International Bamboo and Rattan Organisation
ILUC	Indirect land use change
ISCC	International Sustainability and Carbon Certification
ISO	International Standards Organisation
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LPG	Liquified petroleum gas
Mt	Million ton = 10^6 ton
MWh	Megawatt-hour = 10^9 Wh
NDC	Nationally determined contributions
PEFC	Programme for the Endorsement of Forest Certification
PES	Payment for ecosystem services
R&D	Research and development
RE	Renewable energy
RED (I & II)	Renewable Energy Directive (I & II)
REDD+	Reduce emissions from deforestation and forest degradation
SBP	Sustainable biomass partnership
SDG	Sustainable development goals
t	Metric ton
TWh	Terawatt-hour = 10^{12} Wh
y	Year

Table of Contents

List of Figures

List of Tables

Executive Summary

Bamboo is potentially a highly sustainable biomass resource and can contribute to domestic and global renewable energy targets, such as those set by the European Union (EU) within the Renewable Energy Directive (REDII). The increasing bioenergy markets call for the development and organisation of sustainable value chains and feedstock supply diversification to effectively deploy sustainable biomass.

This report provides an overview of the bioeconomic potential, technology options and opportunities of bamboo for bioenergy production. As such, this report aims to support relevant decision-makers and the bamboo sector stakeholders in their understanding of the potential and challenges of bamboo to meet key requirements towards the development of sustainable bioenergy supply chains.

Bamboo is a resource widely available in the Global South. Currently, millions of tons of bamboo resources remain underutilised. Additionally, millions of hectares of degraded and potentially available land are suitable for the establishment of new plantations. If 10% of the estimated current global bamboo resources can be economically exploited, approximately 50 Mt/year can be produced and play a role in the diversification of the biomass feedstock portfolio. As some bamboo-producing countries (e.g. Colombia, Brazil, Indonesia, Nigeria and South Africa) are also fuel exporters (e.g. coal and biofuels), bamboo biofuels offer these countries an opportunity for developing new supply chains towards a green and more diverse traded fuel portfolio, thereby supporting the ongoing transition from fossil fuels to biofuel trade.

Bamboo, like other lignocellulosic biomasses, can be biochemically and thermochemically converted to solid, liquid and gaseous fuels. As a biomass feedstock, bamboo can comply with the sustainability requirements for biofuel markets through the related forest certification schemes recognised by the EU (e.g. FSC and PEFC). Compared to other lignocellulosic biomass resources, bamboo offers competitive advantages as well as challenges. The main advantages of bamboo are the high crop productivity (10–40 t_{dw}/ha/year) and the high biomass density (300–900 kg/m^3), both of which are highly relevant characteristics for logistics cost and thus key for economic conversion of biomass to bioenergy. The fuel properties of woody bamboos are superior to those of herbaceous materials and similar to those of wood, and bamboo can comply with the technical specifications for solid biomass fuels.

In the medium term, the establishment of new bamboo plantations *contributes to carbon sequestration, climate-change mitigation and restoring of degraded lands*. *The carbon-storage potential of bamboo plantations is equivalent to the potential of tree plantations, but the annual carbon sequestration of bamboo is very high*. To ensure the positive long-term impacts of land restoration projects, incentives are required for an appropriate management of the established plantations. Resource management can be achieved by valorising the residual material in bioenergy production. Furthermore, bamboo plantations contribute significantly more to greenhouse gas (GHG) emission reduction when bamboo biomass energy is also used for substituting fossil fuels. The proper use and management of bamboo plantations provides ecosystem services, including climate-change adaptation and mitigation. Bamboo plantations create alternatives for rural and small entrepreneurs, reduce the vulnerability of agro-ecosystems and prevent deforestation. Because of its fast growth and annual regeneration, using bamboo as a source of bioenergy can take pressure off from other forest resources, reducing deforestation.

The GHG emission savings achieved by replacing fossil fuels with bamboo biofuels can comply with and even exceed the requirements stipulated by the EU. The potential GHG emission reduction of electricity production from bamboo, as compared to coal, are estimated to be between 70% and 300%, depending on whether the supply chain is based on residues or bioenergy crops.

In terms of cost, the selective and manual harvesting of bamboo leads to the collection of a clean feedstock without contaminants, whose presence increases the cost of the pre-treatment steps for biofuel production. In addition, the high GHG emission reduction potential of bamboo fuels, as well as the high carbon stock of bamboo crop systems, provides opportunities within carbon-emission trading mechanisms. Thus, the economy of the complete value chain may be more favourable for bamboo as compared to other biomass resources.

The current commercial status of bamboo conversion into bioenergy mainly relates to solid fuels (e.g. charcoal and pellets), which are commercialised in some countries (e.g. China and Ethiopia).

Few applications of gasification exist for rural electrification (e.g. in Indonesia). An example of power generation from bamboo combustion can be found in Japan. Furthermore, anaerobic digestion is at a pilot and demonstration stage (e.g. in India) to produce biogas as a transport fuel. Commercialisation of bamboo pellets (Brazil) and bioethanol (India) is planned. The commercial production of bamboo chips for bioenergy applications has not been frequently explored.

The trade of bamboo fuels is limited to some producing countries, and the trade within key biofuel commodity markets is still in its infancy. The uptake of bamboo by biomass processors and energy users will provide incentives for supply chain development and trade, for the proper management of existing bamboo resources and for the establishment of new plantations.

Bamboo has been included in national political strategies for socio-economic development, environmental management and tackling climate change in some countries. China, India, Ecuador, Colombia, Peru, Japan, Ethiopia, Ghana, Indonesia, Madagascar, Uganda and Viet Nam have taken policy steps, and some countries have developed plans and strategies for bamboo sector development. However, in many countries, the resources required for implementing these strategies are not allocated, and hence, the implementation and success rates are low. Furthermore, bamboo is often overlooked as an important agricultural and biomass resource for biocommodity production, and the regulatory framework of some producing countries poses a challenge for the exploitation of bamboo resources at its full potential.

To tap into the full potential of bamboo and develop sustainable value chains, the following challenges need to be addressed:

(i) **Mobilise investment, multi-stakeholders and intersectoral partnerships:** Due to its multiple uses and potential applications, the development of bamboo value chains offers opportunities to establish strategic partnerships as well as intersectoral and international cooperation.

To mobilise investors for the development of sustainable bamboo value chains, it is important to remove existing barriers (e.g. legislation and techno-economic) and to arrange partnerships of multiple stakeholders from the public and private sectors and civil society. Therefore, bamboo should be included in national strategies for biocommodity production, for reaching the UN-sustainable development goals (UN-SDGs) and for tackling climate change (within nationally determined contributions (NDC), reducing emissions from deforestation and forest degradation (REDD)). Furthermore, the strong cooperation with policy institutions, as well the engagement of the different stakeholders along the complete biomass chain (producers, processors, fuel traders and energy users), is key for the successful development of biomass value chains.

Partnerships are possible with not only the energy sector but also other sectors (e.g. agro-industrial with co-generation capacity), fossil fuels and emission-intensive industrial sectors (e.g. cement), chemicals and materials sectors, which can support the development within their strategies of business innovation and corporate social responsibility (CSR). Furthermore, the cooperation with civil society, as well as research and academic sectors, is essential, as multidisciplinary and intersectoral approaches are required to assess and design sustainable value chains and bankable business models.

(ii) Make bamboo-based energy products an integral part of the developing bioresource commodity market: A long-term vision and a strategic approach are required to develop new biomass supply chains within the biocommodity market. Bioenergy production from bamboo is key in the development of integrated value chains, and bioenergy products improve the sector's competitiveness through product diversification; the conversion processes of bamboo to consumer products show low resource efficiency and can convert high volumes of discarded residues to energy products. Furthermore, bioenergy applications can create incentives for sustainable resource management and the establishment of plantations. A strategic stepwise development of integrated value chains may entail initially developing a sufficient production volume chain for the supply of bioenergy and traditional markets, both local and international, while developing the local capacity to establish competitive processing industries for higher-value application markets.

In short, the main biofuel market opportunities are related to the solid fuels trade (e.g. chips, pellets and charcoal), which is an established market; in contrast, advanced biofuels (e.g. liquid and gas) from lignocellulosic feedstocks are expected to become competitive in the longer term. The bamboo crop production and processing into solid fuels (e.g. charcoal, chips and pellets) must be promoted to supply small-, medium- and large-scale systems to both local and international markets. At the same time, large-scale and biorefinery concepts are required for an economically feasible production of advanced biofuels (e.g. bioethanol and renewable diesel), calling for partnerships with existing oil refineries, petrochemical clusters, chemical factories and pulp/sawmills.

(iii) Promote research and development (R&D) with interdisciplinary approaches: Developing bamboo value chains will promote technology development and innovation whilst integrating local knowledge in producing countries. Further R&D is required to develop sustainable bamboo production systems. Optimising and developing biofuel value chains include the adoption of proper practices and technologies that can improve efficiency, cost and sustainability. Multidisciplinary research is required for a detailed assessment (techno-economic and sustainability) of the total cost and benefits of biofuel production from bamboo. Moreover, bamboo biofuel value chains (biomass production, logistics strategies, pre-treatment to improve fuel properties and conversion technologies), as well as the carbon-sequestration potential and emissions of woody bamboo crop systems and the sustainability of associated biofuel value chains, need to be further researched. Finally, efforts are required to develop bamboo carbon methodologies and their inclusion at appropriate platforms.

Providing sufficient and reliable information from biomass supply areas is a prerequisite to having access to international bioenergy commodity markets. To this end, multiple disciplines and stakeholders are required, and the exchange of know-how and background information should be promoted.

*The conversion of **bamboo as a sustainable biocommodity** for future generations asks for promotion of **international cooperation** between experts and stakeholders of many disciplines along the **supply chain*** (van Dam, 2018)

1. Introduction

According to the International Energy Agency (IEA, 2019a), bioenergy will continue to play a key role in the expansion of renewable energy (RE) technologies globally, and millions of tons of biomass are required to fulfil the demand and targets. Ensuring the sustainability of this biomass is a requisite and one of the key steps for successful development of biofuel value chains (IEA, 2019a). At present, the main lignocellulosic commodities globally traded for bioenergy production are wood forest resources (chips and pellets), while agricultural residues (as well as municipal waste) remain underutilised (van Dam et al., 2019). However, new supply chains of alternative biomass feedstocks are required due to the expansion of global bioenergy markets, increasing concerns about biomass feedstock availability and the sustainability of forest resources (Searchinger et al., 2018; Ceccherini et al., 2020). Bamboo has the potential to be a major resource for the biobased economy and to become a strategic biomass commodity that drives green growth and sustainable development. The growing global bioenergy markets require the development and organisation of sustainable value chains and feedstock diversification to effectively deploy sustainable biomass energy options.

Why bamboo?

EXCELLENT BIOMASS CROP

- One of the fastest growing crops
- Resistant to changing climate conditions
- Perennial grass. Regenerates itself if properly managed
- Does not require the use of pesticides
- Low (or no) consumption of fertilizers

CLIMATE CHANGE

- High carbon sink
- Provides ecosystems services
- Water and biodiversity preservation
- Counteracts soil erosion
- Excellent reforesting crop

SUSTAINABLE DEVELOPMENT

- Low cost of establishment
- Easy propagation
- Creates rural jobs
- High global availability and potential
- Feedstock and product diversification

Bamboo has the potential to be a highly sustainable biomass source, growing on approximately 35 Mha land (FAO, 2020a) mainly located in the Global South, with a wide range of species and having its presence in different agro-climatic conditions (Vorontsova et al., 2016). Bamboo is among the most productive biomass crops and a multipurpose species with multiple traditional and new applications (e.g. construction, chemicals and materials, food, fibres, clothing, paper, energy and ecosystem restoration). Some giant species of bamboo can reach over 30 m in height in only a few months' time, and some species can grow up to 1 m per day (van Dam, Elbersen and Daza Montaño, 2018). Woody bamboo systems can yield 10–40 t_{dw}/ha lignocellulosic biomass each year (Scurlock, Dayton and Hames, 2000; Shanmughavel and Francis, 2002; Hong et al., 2011; Van Dam, Elbersen and Daza Montaño, 2018). Once matured (3–7 years of planting), bamboo can be harvested annually without replanting, and the annual selective harvesting does not result in deforestation or degradation. Furthermore, bamboo systems are high carbon sinks due to their aboveground and belowground biomass (Scurlock, Dayton and Hames, 2000; Liese, 2009; Lobovikov et al., 2009). Bamboo systems can store up to 1400 tCO_2/ha; this carbon storage potential is equivalent to that of tree systems (Drawdown.org, 2019; Yuen, Fung and Ziegler, 2017; van der Lugt, ThangLong and King, 2018).

Sustainable bamboo production systems can directly contribute to tackling climate change and achieving goals of the UN sustainable development agenda (Yiping, Buckingham and Guo-mo, 2010; INBAR, 2015b; 2015a). Bamboo as a sustainable biomass source can contribute to achieving domestic and global RE targets, such as those set by the European Union (EU) within the Renewable Energy Directive (REDII). In the REDII, the overall EU target for RE source consumption by 2030 has been set to 32%, and Member States must ask fuel suppliers to supply a minimum of 14% of RE in the transport sector. The RE targets in transport, electricity, heating and cooling are specific for each EU country, which set out how to meet these targets within their RE policy in their national RE action plans. The REDII defines a series of sustainability and GHG emission criteria that biofuels must comply with to be counted toward the overall RE targets and to be eligible for financial support by public authorities. In particular, the REDII introduces sustainability requirements for forestry feedstocks as well as GHG criteria for solid and gaseous biomass fuels. Bamboo biofuels have the potential to comply with RED sustainability and GHG requirements (Daza Montaňo et al., 2013).

There is a large untapped potential to produce millions of tons of bamboo as a versatile resource for RE and the bioeconomy. The global production and consumption of bamboo products has increased over the last decades; the trade was estimated to be worth 72 billion USD/year in 2019 and is expected to reach about 98 billion USD/year by 2026, with China being the major global market player (Zion Market Research, 2020). Despite its large potential and increasing interest and markets, bamboo remains an overlooked and underdeveloped biomass and agricultural resource in many countries, mainly due to the lack of awareness of its potential and the lack of infrastructure or incentives for sector development (Jayaraman et al., 2018; INBAR, 2017; Daza Montaňo et al., 2013; Kalyan, Durai and Odour, 2018). Bamboo-producing countries require technologies, investments and additional market outlets to stimulate the production, processing and management of bamboo resources, as well as the development of competitive value supply chains, for both the local and the international markets. Bioenergy applications (e.g. charcoal, briquettes, pellets, chips, heat and power and advanced biofuels) can provide incentives and opportunities for bamboo sector development, diversifying the product portfolio and optimising the related value chains at the global level.

The use of bamboo as an RE commodity is relatively limited, and there is scarce and scattered information on its specific properties, related technology options and development state, as well as the key economic and environmental sustainability requirements for the development of sustainable bioenergy supply chains. The presented information in the report is sourced from a literature review, from the authors' experience in research and consultancy on the topic and from interviews with stakeholders from the bamboo sector and experts from both the research and industrial sectors.

This report provides an overview of the potential, technology options, challenges and opportunities of bamboo for RE production, and aims to support relevant decision-makers and the bamboo sector stakeholders in their understanding of the different bamboo energy options and conversion technologies, as well as the key requirements for the development of sustainable bioenergy supply chains. Furthermore, we aim to provide recommendations for the strategic integration of bioenergy production in the development and optimisation of bamboo value chains within the bioeconomy in alignment with the UN-sustainable development goals (SDGs) and related climate actions.

Structure of this report

Chapter 2 provides an overview of the overall potential of bamboo as a biomass source within global bioenergy markets. Chapter 3 presents the main requirements for bioenergy value chains, describes the properties of bamboo as a biomass crop and relevant feedstock properties for bioenergy applications and provides an overview of the sustainability potential of bamboo systems, with a focus on EU regulations. Chapter 4 describes the relevant bioenergy conversion technologies for bamboo. Chapter 5 provides an overview of biofuel production costs. Chapter 6 provides an outlook on the strategic development of RE from bamboo within the biobased economy. Conclusions and recommendations are presented in Chapters 7 and 8, respectively, while the Appendix showcases three case studies of operating systems of bamboo conversion to bioenergy.

2. Potential of bamboo within global bioenergy markets

Bioenergy accounts for approximately 13% of the world's primary energy supply and 70% of global RE consumption, mainly used for heating, electricity and transport fuel production. The share of biomass among RE sources is 96% in Africa, 65% in Asia, 59% in the Americas and 59% in Europe (WBA, 2019). In developing countries, biomass is primarily used for cooking and heating. In 2017, the use of biomass for bioenergy was approximately 56 EJ, mainly for heating applications, with a share of 86% for primary solid biofuels (e.g. wood chips, wood pellets, fuelwood and charcoal), 7% for liquid fuels and 2–3% for biogas (WBA, 2019).

Bioenergy is critical for meeting strict climate mitigation targets in the long term. The projected required growth of primary bioenergy energy supply is approximately 138 EJ/year by 2050 (Junginger et al., 2019), constituting approximately 23% of the global primary energy supply. The increasing global demand and targets of bioenergy production, in the short term and in the future, require the development of new biomass supply chains as well as an increasing role of international biomass trade.

As a bioenergy source, bamboo can contribute to the deployment of modern biomass solutions in the form of solid (e.g. chips, pellets, briquettes and charcoal), liquid and gaseous fuels for heating, electricity and transport applications.

Heat consumes almost half of the global energy, and biomass is the most used RE source for direct heating, with a 96% share of the global renewable heat market. In 2017, 40 EJ of biomass (mainly pellets, chips and charcoal) were used by different sectors (e.g. residential and commercial) for heating and cooking purposes (WBA, 2019).

Renewable electricity generation is the world's fastest-growing source of electricity, with a forecasted increase in share from 25% in 2018 to 30% by 2024 with the greatest expansion capacity in China, India and the EU (Figure 1) (IEA, 2019b). Biopower or electricity generation from biomass is a sustainable and renewable option for reducing fossil fuel demand in the electricity sector. Biopower production in 2017 was 566 TWh, accounting for approximately 2% of the global power generation (Proskurina, 2018). Biopower is mainly generated by solid biofuel combustion technologies in combined heat and power (CHP) and dedicated power plants. Biopower production is expected to grow to approximately 750 TWh by 2024 (Figure 1). This estimated growth requires over 50 Mt/year of additional biomass.

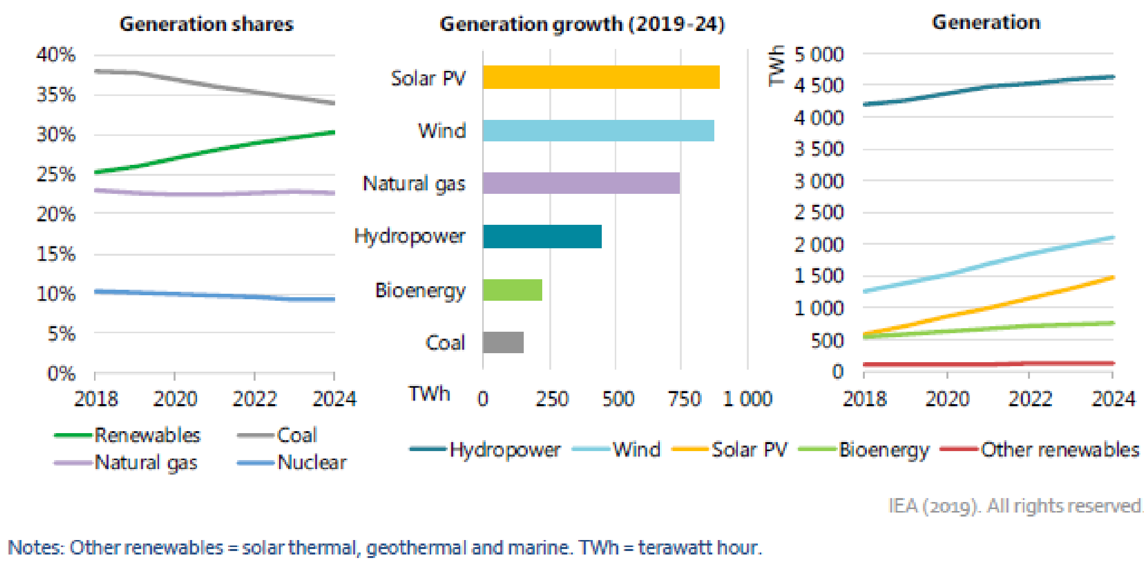


Figure 1. Global generation shares by fuel and growth by RE technology (IEA, 2019b).

Solid fuels

Charcoal has multiple uses, such as cooking fuel, industrial and metallurgical fuel, carbon black for purification and filtration, horticulture growth medium and medicinal uses. It is the most produced biomass fuel at global level. The global annual production of charcoal, mainly from wood, is approximately 55 Mt, which is mainly produced in Africa, followed by the Americas (mostly Latin America) and Asia (FAO, 2020b; Nabukalu and Gieré, 2019). Africa is the main producer and consumer of charcoal, accounting for 65% of the global production. Charcoal from bamboo is also produced in different regions, mainly in Asia and Africa, for local and export markets.

The international trade of charcoal (including bamboo charcoal) is rapidly growing, and approximately 2.83 Mt of wood charcoal was traded in 2019, valued at 1.31 billion USD (FAO, 2021). The largest charcoal producer is Brazil, followed by Nigeria, Ethiopia, India, China and Congo. In Brazil, charcoal is mainly used for industrial purposes, whereas in African countries, it is mainly used for cooking in urban households. Europe is a large importer of charcoal, with approximately 40% of charcoal used as barbeque fuel imported mainly from Africa (i.e. Nigeria).

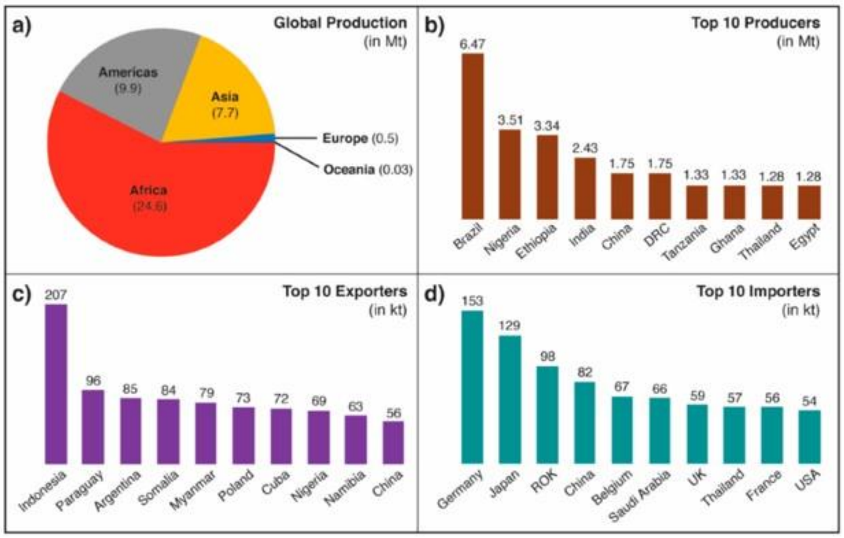


Figure 2. Global charcoal production and trade (Nabukalu and Gieré, 2019).

Unsustainable charcoal production from forest wood is associated with high GHG emissions, deforestation and environmental degradation, which is highest in Africa, followed by Latin America and the Caribbean (FAO, 2020b; Nabukalu and Gieré, 2019). However, sustainable charcoal production can significantly contribute to environmental sustainability and poverty reduction (Chidumayo and Gumbo, 2013). Bamboo charcoal is considered a high-quality fuel associated with low emissions during combustion, and the production of charcoal from bamboo offers alternative opportunities for the development of sustainable charcoal value chains.

Biomass chips are the most traded solid biofuel commodity, with growing markets in industrial applications. In 2019, approximately 275 million m^3 of wood chips were produced, out of which approximately 70 million m^3 are exported at a value of 6 billion USD/year (FAO, 2021). In Europe, wood chips account for approximately 30% of bioenergy consumption from solid fuels (Figure 3).

Biomass pellets are mainly produced from wood and agricultural residues. Wood pellets made from compacted saw dust are the most common type of fuel pellets. The global annual pellet production was approximately 50 Mt in 2019 (Gauthier et al., 2020; IEA, 2019b; Fritsche et al., 2019). Europe accounts for 55% of the global pellet production, and the Americas (mainly the USA) account for approximately 31% (WBA, 2019).

The EU is the major global consumer of pellets for heat and power generation. Pellet consumption in the EU was approximately 26 Mt in 2018, of which 60% was for heat production (residential, commercial and heat generated from CHP) and the remaining 40% was for power production (from CHP and dedicated power plants) (EPC, 2021). Pellets are either produced locally or imported from the USA and Canada. The main exporting regions will broaden by 2040, with an increasing role of Latin America, Oceania and Africa (Mai-Moulin et al., 2019). Although Europe's solid biomass production and consumption are almost balanced, the bioenergy markets are increasing. Furthermore, the pressure on resources and sustainability concerns are increasing (Malico et al., 2019; Searchinger et al., 2018; Ceccherini et al., 2020); therefore, new sustainable biomass supply chains need to be developed.

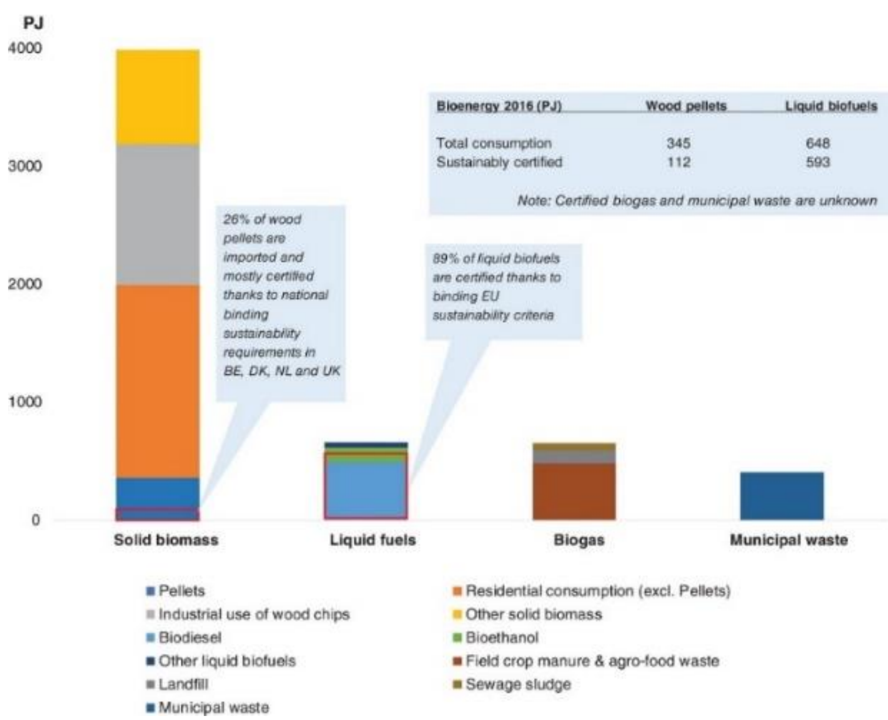


Figure 3. Overview of total consumption of bioenergy and the estimated sustainably certified share in the EU (Junginger et al., 2019).

The trade of bamboo chips for bioenergy applications has not been reported, while bamboo pellets can be found on the market and are often manufactured from residues of manufacturing other bamboo products.

Liquid fuels are essential for not only transportation and heating but also many industrial processes (Bioenergy, 2020). Liquid biofuels, such as bioethanol, are mainly produced from sugar crops (e.g. sugarcane), while biodiesel is mainly produced from either oil crops (e.g. palm oil) or residual fats and waste oils (e.g. used cooking oil). In 2017, 138 billion litres of biofuels, including bioethanol, biodiesel and hydrogenated vegetable oil, were produced (WBA, 2019). The global ethanol production was approximately 91 Mt in 2019, and the United States and Brazil are the leaders in ethanol production, with exports of approximately 1.7 and 1.5 Mt/year, respectively (Proskurina et al., 2018).

Second-generation or advanced biofuels, from lignocellulosic feedstocks, are expected to be competitive in the longer term (Brown et al., 2020). For advanced biofuels, such as ethanol, different feedstocks are being used, depending on the local availability; these include sugarcane bagasse and straw, cereal straws, corn stove and wood residues (Brown et al., 2020). Bamboo, as a lignocellulosic biomass, can be transformed by second-generation biofuel technologies into liquid fuels, such as bioethanol, and by thermal processing into, for example, pyrolysis biocrude oil (Chin et al., 2017). Bioethanol production from bamboo is approaching commercialisation in India.

At the EU level, the implementation of REDII mandates to increase the share of advanced biofuels (e.g. ethanol, biodiesel and renewable diesel) over the next decade. In the transport sector, fuel suppliers are required to supply a minimum of 14% of RE by 2030, and the contribution of advanced biofuels and biogas produced from the feedstock listed in Part A of Annex IX must be at least 3.5% of the final consumption of energy in the transport sector by 2030. Within REDII, the energy content of advanced biofuel chains (listed in Annex IX) are double counted when accounted for by the region's RE targets as an incentive to deploy advanced biofuels (Henke, 2018). Bamboo falls into the category of eligible feedstocks laid in Annex IX-part A of REDII, together with other lignocellulosic biomass and residual feedstocks.

Gaseous fuels are produced through biological conversions, such as anaerobic digestion (e.g. biogas and biomethane), or thermochemical conversion processes, such as gasification (syngas), and can be used for transport, cooking, heat and power production or further upgraded to liquids (fuels and chemicals). In 2017, 1.33 EJ of biogas was produced globally (WBA, 2019), accounting for approximately 3% of bioenergy and 0.4% of global energy consumption.

Bamboo potential within the international bioenergy trade

Globally, sustainable bioenergy production and international biomass trade are expected to increase in the coming years, and new sustainable biomass supply chains need to be developed (Junginger et al., 2019). There are opportunities for bamboo-producing regions to develop bamboo bioenergy value chains within their RE developments. In addition to domestic market potential, there is a large global trade of biofuel commodities in the form of solid and liquid biofuels (**Figure 4**). Within the global trade of biofuels, Europe is a key import region, from which the largest traded volumes of biomass, within and to the EU, are related to solid biomass mainly for heat and power production (**Figure 3**).

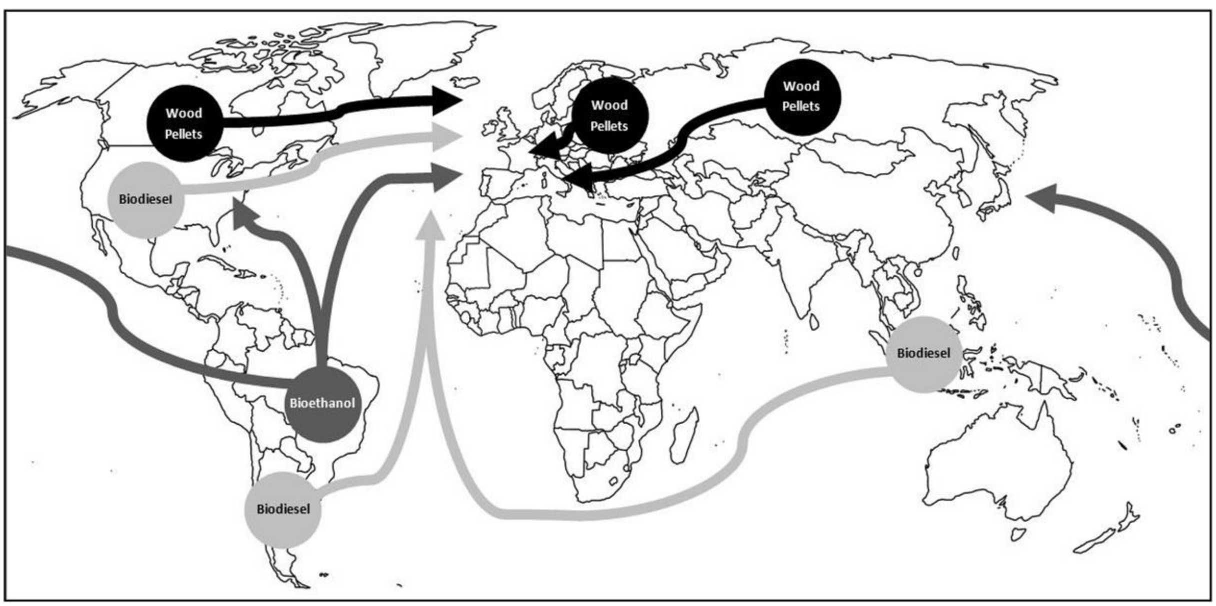


Figure 4. Overall biofuel trade streams and regions (Welfle, 2017).

Although Europe's solid biomass production and consumption are almost balanced, the pressure on resources and sustainability concerns are increasing (Malico et al., 2019; Searchinger et al., 2018; Ceccherini et al., 2020). *Bamboo bioenergy chains comply with (and even exceed) the EU sustainability requirements (section 3.3.1) and can therefore enter the European market as fuel for heat and power production and as advanced biofuels.*

In the past, bamboo, as other types of herbaceous biomass crops and agricultural residues (e.g. straw), was often not considered for large-scale combustion and gasification processes because of logistics and cheaper fossil fuels. Nowadays, the use of agricultural residues (from crops such as maize, rice and wheat) is identified as the most promising sector for growth in global bioenergy production, with an estimated maximum global potential of 18–82 EJ/year, which can meet 3–14% of the total global energy supply (WBA, 2019). As a bioenergy feedstock, bamboo presents techno-economic and sustainability advantages over agricultural residues and other biomass crops (Daza Montaňo et al., 2013) (section 3), and there is a large untapped potential to produce millions of tons of bamboo as a versatile resource for bioenergy production within a biobased economy (section 2.1).

2.1 Bamboo resource potential

The key issues for the adoption of biomass sources include feedstock availability and security of supply (van Dam et al., 2005; Malico et al., 2019). Bamboo is a resource with large global availability, with approximately 35 Mha of forests in the world, 71% of which are in Asia, 16% in the Americas and 13% in Africa (FAO, 2020a). Most of these resources are natural stands and forests, and a smaller proportion are established plantations[1], mainly of species of commercial interest for manufacturing high-end products. Significant bamboo forest resources are not under sustainable management regime, and the poles from unmanaged forests are not suitable for the production of high-end industrial products.

If 10% of the estimated existing global bamboo resources[2] can be sustainably harvested for bioenergy production, approximately 50 Mt_{dw}/year can be produced (~1 EJ/year) and play a role in the diversification of the biomass feedstock portfolio. Furthermore, there are millions of hectares of degraded and potentially available land for the establishment of plantations where bamboo can

1 https://www.ecoplanetbambooplantations.com/; https://www.plantationsinternational.com/bamboo/

2 Assuming a woody bamboo conservative estimate of crop yield of 15 t_{dw}/ha.

be efficiently used. Estimates of maximum potential suggest approximately 70–174 Mha of degraded forest lands where bamboo can be planted (Drawdown.org, 2019).

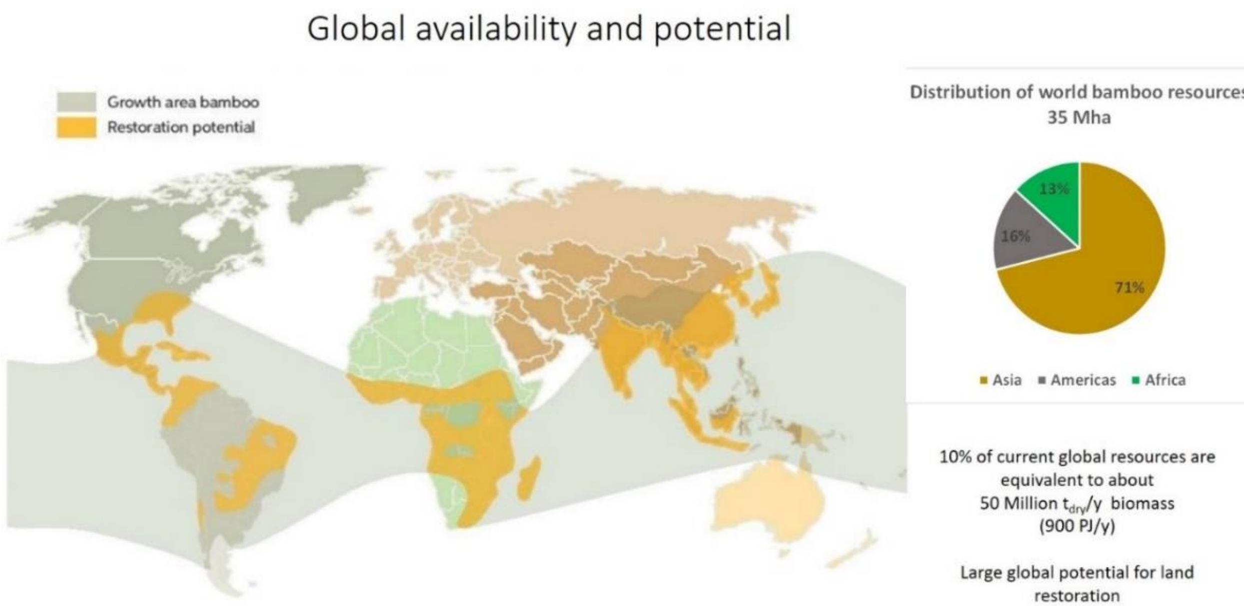


Figure 5. Global bamboo areas and energy potential (Map source: INBAR).

China is the largest producer of bamboo, with approximately 6.4 Mha of bamboo forests, including 2.5 Mha established plantations of MOSO bamboo. In recent years, other countries (e.g. India, Brazil, Cameroon, Colombia, Ecuador, Ethiopia, India, Madagascar, Uganda, Viet Nam, Indonesia, Ghana and Philippines) have taken policy steps to support the development of the bamboo sector (Tambe et al., 2020; Gawande, n.d.; Lin et al., 2019; Akwada and Akinlabi, 2018; Dolom et al., 2019; Sharma, Wahono and Baral, 2018; Balduino Junior et al., 2016; Zhu and Jin, 2018), and interest has arisen in the promotion of bamboo plantations in the EU (BambooLogic 2021; Prosperity Bamboo 2021) and the USA (Henderson 2018).

Where the bamboo sector is developed, large amounts of residues become available from processing sites (e.g. cuttings and saw dust), plantations and forest management. These resources can be used for bioenergy and materials production, providing a potential economical use for this material and creating incentives to properly manage natural forests and stands and to establish plantations.

Some bamboo-producing countries (e.g., Brazil, Colombia, Indonesia, Nigeria and South Africa) are also biofuel (e.g. ethanol and charcoal) and fossil fuel exporters (e.g. coal and crude oil) (IEA, 2020a) (Cunningham, Uffelen and Chambers, 2019). Bamboo biofuels offer an opportunity to develop new supply chains to diversify their traded fuel portfolio and support the ongoing transition from fossil fuels to biofuel trade.

Figure 6. Bamboo anatomy and typical uses of plant parts (Daza Montaño, 2020).

2.2 Bamboo RE in a biobased and circular economy

Bioenergy, chemicals and materials production can be integrated in bamboo processing industries as well as other sectors, substituting part of their fossil-based materials and energy inputs (van Dam, Elbersen and Daza Montaño, 2018). The future demand for biogenic fuels and the focus on advanced biofuels provide biorefineries a significant market opportunity in the medium term. Through the combined production of high-quality biomaterials and biofuels, the raw material potential is optimally used, whereby the biomaterials and biochemicals expand the value-addition (Hingsamer and Jungmeier, 2018). Furthermore, fertilisers and soil improvers (e.g. biochar) can be co-produced and returned to forest and plantations (Daza Montaňo et al., 2013), thus contributing to circular economy business models.

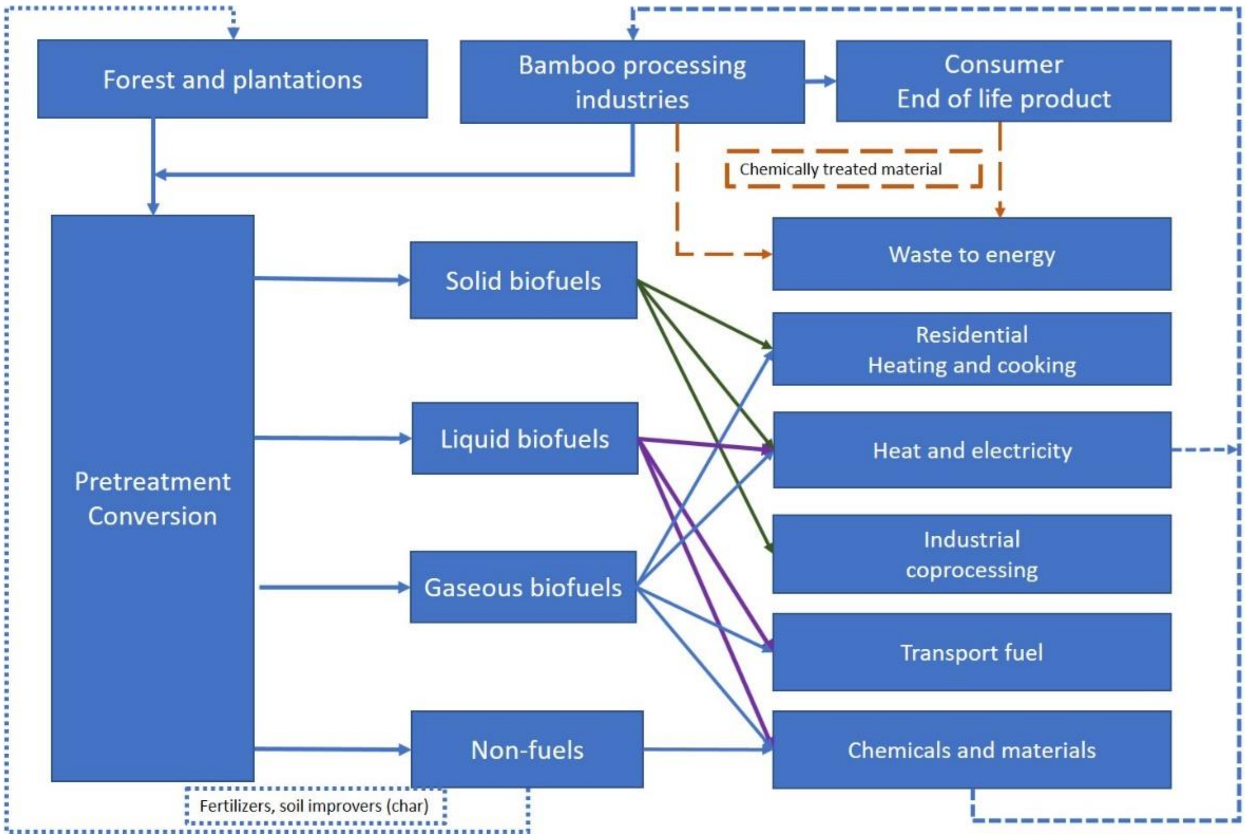


Figure 7. Schematic view of suitable bamboo streams for bioenergy production.

3. Bamboo as a bioenergy feedstock

The development of competitive biomass chains for domestic and international bioenergy markets (similar to finished products and materials) requires compliance with market and end users' requirements (van Dam et al., 2019; Malico et al., 2019). As depicted in Figure 8, end-users' requirements include (i) feedstock security of supply and scaling-up potential, (ii) technical specifications (of both feedstock and product) and (iii) sustainability requirements (economic, social and environmental) along the complete biomass chain (from feedstock production to end use).

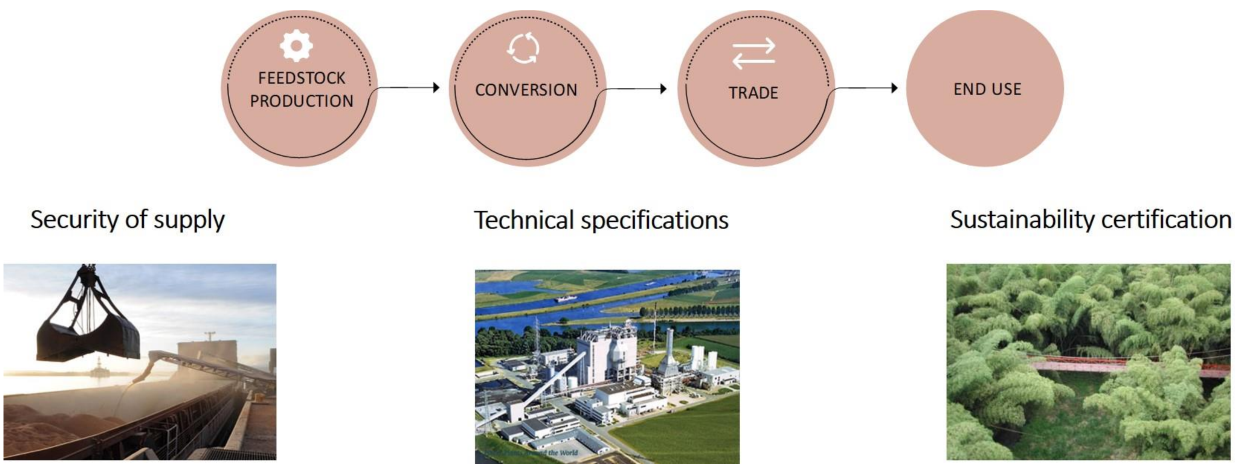


Figure 8. End user requirements in biofuel markets.

3.1 Feedstock security of supply and crop properties

In terms of feedstock availability and security of supply, the potential for scaling-up bamboo production and processing systems is significant at a global level, as described in section 2.1. Ten percent of the estimated existing global bamboo resources account for approximately 50 Mt_{dw}/year of biomass (equivalent to ~900 PJ/year). Furthermore, given the high rate of deforestation in many developing countries and limited sustainable rural development alternatives, managing and establishing bamboo production systems offer the opportunity to restore millions of hectares of degraded land and to conserve strategic ecosystems.

3.1.1 Crop properties

Bamboo belongs to the family of grasses (Poaceae), just like important food crops such as rice, wheat, other cereals and sugarcane (van Dam, Elbersen and Daza Montaño, 2018). Some bamboos are herbaceous (*Olyreae spp*), but most have woody stems. Especially woody bamboos are known for their high versatility, with numerous traditional, modern and potential new uses (**Figure 6**), and due to their properties, are most suitable for bioenergy applications.

Bamboo stands are suitable for short-cycle harvesting systems. Once the plantation has reached maturity (3–7 years, depending on the species) and when properly managed, the bamboo crop has a continuous productivity. This is an advantage over other biomass feedstocks; for example, the period of rotation for short-rotation forestry (e.g. aspen, alder and birch) is between 8 and 20 years and for short-rotation coppice (e.g. willow and poplar) is between 2 and 4 years (Aylott et al., 2008).

Bamboo crop quality and yields are related to the development and maturity stages, which depend on the species. The maturity stages for commercially important species like *Guadua, Dendrocalamus* are new shoot (0–6 months), young or green (1–3 years), mature (3–5 years) and over-mature and dry (more than 5 years). When the culm reaches the over-maturity stage, it loses strength, and then dies, decays and decomposes. The proper management of bamboo forests requires the continuous removal of mature culms.

The establishment of bamboo production systems is a low-cost process (Jiang and XiaoSheng, 2001). 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. This property enables sustainable, regular harvesting of culms and, thus, generates stable income for producers, with low investments, but restricts the full mechanisation of harvesting (van Dam, Elbersen and Daza Montaño, 2018). Selective harvesting of bamboo requires manual labour, which promotes rural job creation and alignment with rural development agendas. The clear felling method for harvesting has been used; however, it is generally not recommended, due to slow recovery and low above-ground biomass production (Banik, 2015). Recommendations of sustainable harvesting methods have been provided in the literature (Durai and Long, 2019; Boissiere, Beyessa and Atmadja, 2019).

In terms of cost, and depending on the local conditions, the cost of bamboo harvesting can be higher than that for other biomass if harvesting is carried out selectively and manually (van Dam, Elbersen and Daza Montaño, 2018). However, this harvesting method allows for the collection of a clean feedstock in the absence of contaminants such as stones and soil. Additionally, in bamboo logistics, no plastic for baling and storage is required, unlike in the production and processing of agricultural residues (e.g. corn stover and straw). The baling material and feedstock impurities (e.g. soil and stones) are known to create serious problems in the pre-treatment equipment of lignocellulosic biofuels, which can hamper the technical and economic feasibility of related conversion processes (Slupska and Bushong, 2019; Pavlenko, 2018). Furthermore, the high carbon storage potential (van der Lugt, Trinh and King, 2018) and the sustainability performance of bamboo systems have advantages over traditional biomass feedstocks (section 3.3.1). Bamboo systems also provide numerous ecosystem services (INBAR, 2019c), such as water regulation. Producers can benefit from potential market mechanisms, such as carbon trading and payment for ecosystem services (PES) (Grima et al., 2016; Juan, Camargo and Thang, 2020; Paudyal et al., n.d.). Thus, despite potential harvesting costs, the benefits and economy of the complete value chain may be more favourable for bamboo than other biomass resources. Detailed assessments are required to evaluate the total cost and benefits of RE obtained from bamboo.

Bamboo can withstand climate vagaries. In events of forest fire, bamboo can recover more rapidly than trees and other crops, as the underground rhizome survives fire and the stored resources of the rhizome allow for vigorous regrowth (Ferreira, Kalliola and Ruokolainen, 2020). This enables bamboo to win over other plants competing for space in the burned area.

Some bamboo species are flowering plants with a distinctive life cycle; they remain in the vegetative phase for decades, followed by mass synchronous flowering, often worldwide, and subsequent death (Liese, 2009; Zheng et al., 2020). This mass flowering phenomenon remains a mystery and needs to be further studied and understood to be considered in the planning and risk management of establishing plantations, to avoid economic losses and negative environmental impacts. Furthermore, the gregarious flowering and death of some species can constitute large CO_2 emissions, due to the biomass decomposition (Liese, 2009), and pose a risk for fires caused by the accumulation of dry biomass (Liese, 2009; Ferreira, Kalliola and

Ruokolainen, 2020). Strategies to minimise fire risk and negative environmental impacts (including GHG emissions) include the proper management of bamboo forest, where the removed material can be used for bioenergy applications.

In general, bamboo complies with the following characteristics of an ‘ideal biomass crop’ (Cosentino et al., 2018): high biomass yield; stable biomass yield under changing climatic conditions and stand age; high resource use efficiency (radiation, nutrient and water); pest resistance; once established, bamboo competes well with weeds due to its rapid growth and crop properties which contributes to weed control; resistance to abiotic stresses (dryness, high or low temperatures, excess of soil moisture or under soil deficit conditions) and ability to thrive under unfavourable biophysical conditions (e.g. steep slopes).

3.1.2 Crop yield: Bamboo vs. other biomass

The productivity of bamboo plantations varies considerably depending on the species, location and silvicultural practices. The most productive bamboo species can yield up to 40 t_{dw}/ha lignocellulosic biomass each year (Liu and Yen, 2021). On average, the yield of the most common bamboo crop in China (MOSO, *Phyllostachys edulis*) in well-managed forests or plantations can be up to 25 t_{dw}/ha/year. The moisture content of freshly cut bamboo varies, mainly depending on the harvesting season (section 3.2.3).

Crop yields influence biomass production costs and emissions related to land use or harvesting areas and transport distances. **Figure 9** compares the required harvesting areas for different feedstocks, based on average productivity values of lignocellulosic biomass crops and residues suitable for solid and advanced biofuels (i.e. corn cobs without stems and empty palm fruit bunches without oil, stems and fronts). The depicted feedstocks are among the relevant alternatives for bioenergy chains and for advanced biofuel production, as listed in the Annex IX-part A of EU REDII.

For a woody bamboo crop with average high productivity (20 t_{dw}/ha/year), the required productive cultivation area is much lower than that for typical biomass sources, such as bioenergy crops and agricultural and forest residues.

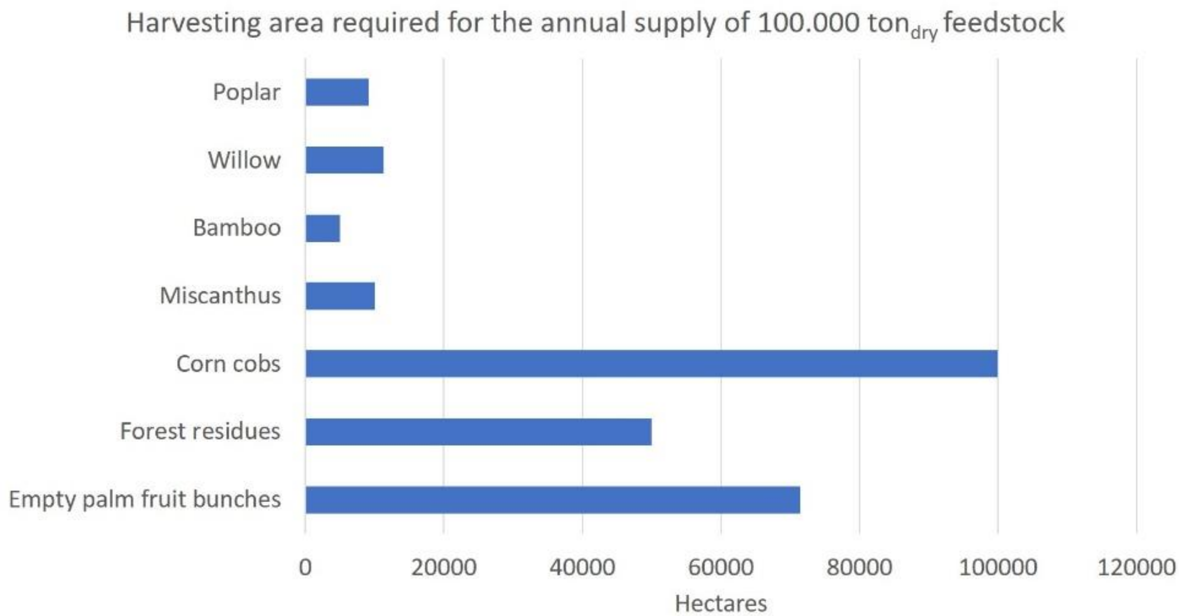


Figure 9. Comparison of required biomass supply areas.

3.2 Technical specifications and relevant properties for bioenergy production

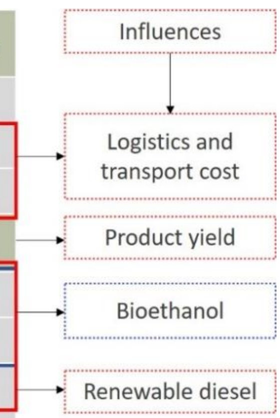
In general, solid biomass feedstocks are challenging materials to handle, transport, store and process, owing to their physical and chemical properties (**Figure 10**).

Figure 10. Challenging properties of solid biomass.

Bamboo offers competitive advantages as well as challenges compared to other biomass resources in the implementation of sustainable production systems. Bamboo exhibits common characteristics with many other biomass feedstocks, and its overall composition and heating value lie between those of clean wood and herbaceous biomass (**Figure 11**). The ash and alkali contents in some bamboo species are higher than those in commonly used fuel wood (Fryda et al., 2014) but similar to other biomass such as straw or palm oil residues. The properties of bamboos may vary according to the species, plant section, maturity stage, season, cultivation practices (e.g. fertiliser application) and production site. The cellulose, hemicellulose and lignin contents in bamboo are comparable to those in wood, which makes some bamboo species a useful feedstock for paper production and processes that convert cellulose, hemicellulose and lignin into fuels and chemicals (van Dam, Elbersen and Daza Montaño, 2018).

FEEDSTOCK		BAMBOO CHIPS	CANE BAGASSE	WHEAT STRAW	WOOD CHIPS
HHV (dry)	MJ/kg	17-20	18-20	16-19	17-20
Bulk density	kg/m^3	300-700	150-200	160-300	200-500
Crop Yield	t_{dry}/Ha-year	10-40	7-15	3-12	5-20
OVERALL COMPOSITION (dw%)					
Cellulose		40	35	38	50
Hemicellulose		20	25	36	23
Lignin		20	20	16	22
Ash and others**		2-10	20	10	5

** Resins, etc.



Yields and composition mainly depend on: Species, age of the plant and plant section

Figure 11. Average properties of some biomass feedstocks for bioenergy applications[3]. Modified from (van Dam, Elbersen and Daza Montaño, 2018).

The advantages of bamboo over other lignocellulosic feedstocks, for bioenergy applications, include **(i) high crop productivities** (10–40 t_{dw}/ha/year) (section 3.1) and (ii) **relatively high specific** (max 900 kg/m^3) **and bulk densities** (~400 kg/m^3), both of which are relevant characteristics in feedstock costs of production, transport and storage. Feedstock logistics is a major challenge for biomass to be (economically) converted into bioenergy.

[3] Bulk density for biomass in the form of chips and of bales for wheat straw.

Bulk density is a key property for transportation cost and the size of fuel storage and handling equipment, and therefore, for the overall feedstock logistics costs. Bamboo stems are usually hollow; thus, whole culms have a low bulk density. Therefore, strategies for transport are required to avoid the higher cost of transport of low-bulk-density feedstock. These strategies include the pre-processing of culms at harvesting or pre-processing sites, where culms are flattened or chipped.

The density of bamboos varies among species, and the specific density can range from 400 to 900 kg/m^3 (Wang et al., 2019). A conservative range value of bulk density of woody bamboo chips is 300–500 kg$_{wet}$/m^3 (Temmerman et al., 2005; Daza Montaňo et al., 2013).

Figure 12. a) Flattened bamboo culms at harvesting site. b) Chipped Bamboo pieces. c) Entire bamboo culm transport in China.

3.2.1 Energy density

Energy density is the volumetric energy content of fuel per volume (GJ/m^3) from the perspective of the volume required to store and transport an amount of primary energy, and is calculated by multiplying the heating value with its bulk density. The energy density of solid fuels influences the required capacities and cost of feedstock transport, storage, handling and feeding equipment, which are higher for low-energy-density fuels than for high-energy-density fuels.

Figure 13 compares the energy density of woody bamboo chips with those of coal and different biomass fuels (Alakangas et al., 2016), calculated using the following conservative values for bamboo: density of 400 kg_{wet}/m^3, lower heating value of 18 GJ/t and moisture content of 30 wt% (Temmerman et al., 2005; Daza Montaňo et al., 2013). The energy density of bamboo chips is superior to that of most of the biomass due to the combination of a high heating value and high bulk density.

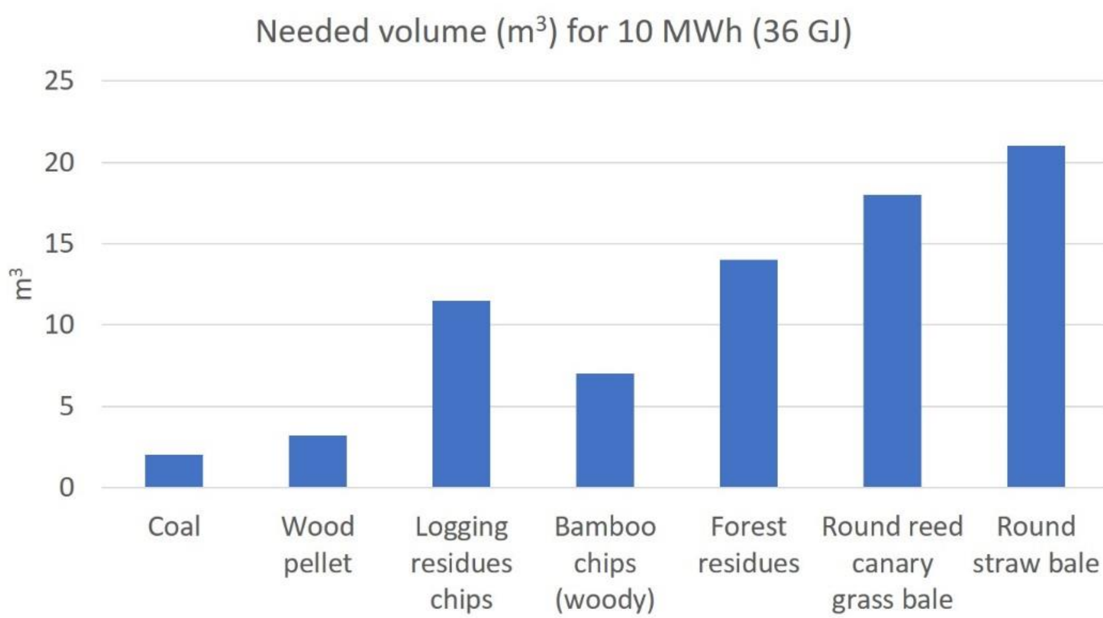


Figure 13. Energy density of relevant fuels.

3.2.2 Bamboo structure

The structure of bamboo differs from those of other biomass feedstocks in terms of density and tissue arrangement. The bamboo plant adopts growth strategies to fulfil various functions, such as mechanical support and water transport (Zhan et al., 2020). In contrast to trees, bamboo has no secondary thickness growth, which restricts its geometric adaptation and results in a hierarchical structural arrangement (Gangwar and Schillinger, 2019). Bamboo is a fibre-reinforced cellular material in which the fibres are aligned parallel to the stem, forming an orthotropic composite. The distribution of load-bearing fibres in bamboo is not uniform but rather creates a gradient of density and modulus, with fibre density being the highest at the outer periphery, where the stresses are the largest (Wegst et al., 2015).

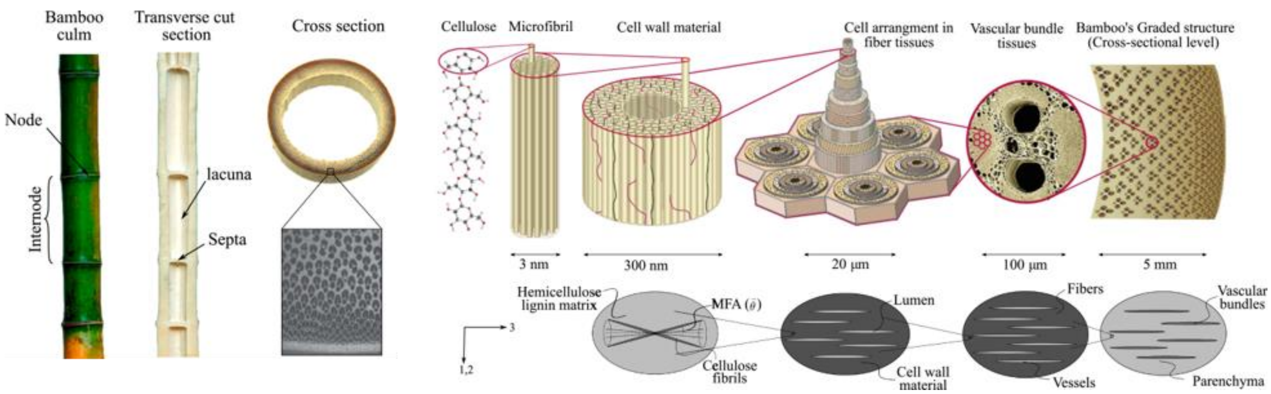


Figure 14. a. Macroscale anatomy of a bamboo culm. b. Hierarchical structure of bamboo and its micromechanical representation (Gangwar and Schillinger, 2019).

From an application perspective, the specific structure of bamboo (and biomass in general) influences several properties (e.g. moisture, density and fibre length) relevant for biochemical or thermochemical processing into fuels:

- Drying
- Ease of size reduction
- Access to chemicals and enzymes
- Ease of fractionation and separation
- Densification

Bamboos exhibit structural changes while aging (Liese and Tang, 2015b); therefore, their physical and chemical properties also vary, which is relevant to define the most suitable bamboo streams for biofuel production (section 3.2.5).

3.2.3 Moisture content and drying

The moisture content in biomass influences the production cost of biofuels. The required moisture content of the most traded solid fuels (e.g. chips) is <10–25% wt. High moisture content in biomass increases the cost of logistics, pre-treatment (e.g. drying) and fuel processing through thermal conversions. However, for some bioenergy pathways or processing (e.g. anaerobic digestion), high moisture content is not counterproductive (Sánchez et al., 2018).

The moisture content of freshly cut, or green bamboo, is influenced by its age, by the species and by culm section and the felling season. The harvesting season significantly influences the moisture content, being the lowest at the end of the dry period and the highest in the rainy season. During the rainy season, the stem can double its water content (Liese and Tang, 2015b).

The documented moisture content[4] of some bamboo species ranges from 28 to 138 wt% (Liese and Tang, 2015c). Air drying of bamboo reaching a moisture content of 12 wt% has been reported (Liese and Tang, 2015a), and the average moisture content[5] of woody bamboo chips has been reported to be approximately 10 wt%, based on a fuel composition analysis (Fryda et al., 2014; Yan, Perez and Sheng, 2017) (**Table 2**).

In terms of bamboo age and culm section, young culms have a higher relative moisture content than mature culms, and nodes show lower values than internodes. In mature culms, the bottom part has a higher moisture content than the top, and the moisture content across the culm wall is higher in the inner part than that in the outer part (Liese and Tang, 2015b). The water content varies among species even in the same location; this is mainly due to the variation in the number of parenchyma cells, which relates to the water-holding capacity (Liese, 1985; Liese and Tang, 2015b).

Physical properties are particularly relevant when defining harvesting strategies in combination with processing needs, such as drying and feedstock size reduction. Size reduction steps play a significant role in energy consumption and related costs in bioenergy production (section 3.2.4). The energy required for particle size reduction and densification (Kadivar et al., 2019) is affected by the moisture content, brittleness or age. The effect of moisture content on strength and brittleness is similar to that in timber. Generally, the strength is higher under the dry condition than that under the green condition (Wang et al., 2019). Furthermore, a maximum strength under the dry condition is reached for mature bamboo (approximately 3–8 years, depending on the species) and decreases towards old culms (Liese, 1985).

[4] Defined as: (wet weight – dry weight)/dry weight)

[5] Defined as: (wet weight – dry weight)/wet weight)

The drying of bamboo for bioenergy applications is little documented, and most research focuses on bamboo processing for products (e.g. construction) (Zhan et al., 2020). The drying of bamboo is influenced by its structural properties, and species with a low specific density and shorter internodes are reported to dry faster. In the initial stages, drying occurs quite rapidly. The rate of drying of immature culms is generally faster than that of mature ones, but as young culms have a higher moisture content, they need longer time. Natural drying of culms placed vertically is faster than drying horizontally oriented culms. The bamboos to which water soaking is applied by removing water-soluble extractives dry faster and take up moisture slower than the untreated ones; moreover, the water absorption of dried bamboo is quite rapid compared to that of timber (Liese and Tang, 2015c; Liese, 1985). However, the drying of bamboo is much quicker than that of wood in bioenergy applications (Chakrabarti, 2018).

Assessing moisture-related properties in bamboo is relevant for the evaluation and optimisation of bamboo conversion processes and technologies (Zhan et al., 2020). The physical properties of biomass influence the costs of a biofuel chain. R&D is required to implement the most suitable strategies for harvesting and pre-processing (e.g. drying and chipping) of bamboo for bioenergy applications.

3.2.4 Feedstock handling, chipping, grinding and feeding

Biomass handling, chipping and feeding into processing equipment are relevant for biomass conversion processes. Bamboo can be chipped and successfully handled and fed into biofuels' processing equipment. As an example of bamboo chipping, Figure 15 depicts the handling of bamboo in a lignin production plant in China, which processes 300 kt/year of bamboo to produce 30 kt/year of lignin, with cellulose as a by-product. The pictures below (Figure 15) show the key process steps, such as whole culm chipping and wet pre-treated material pre-processing and transport.

In contrast, the test samples of air-dried *Bambusa vulgaris* (<10 wt% moisture content) are very difficult to chip with standard wood chipping machinery (Wild, 2015). Assessments are required for the proper selection of size-reduction machinery and strategies while simultaneously selecting the most suitable bamboo resources (species, age and moisture content; section 3.2.3), considering the relevant processing needs.

Figure 15. Bamboo chipping and feeding to process. Photo: Daza, C.M.

Grindability of biomass is a relevant property for thermal conversion technologies where the feedstock needs to be pulverised. Pulverised coal combustion and entrained flow gasification are two of the main technologies worldwide where biomass can directly replace coal. However, the poor grindability of biomass is a limiting factor for its use in thermal power plants on a large scale. Bamboo, like other herbaceous and woody biomasses, is tenacious and fibrous, which makes these fuels extremely energy consuming to grind to the required end-user specifications. The brittleness and grindability of bamboo are considerably improved with torrefaction pre-treatment (Fryda et al., 2014) (section 4.2).

In a coal-fired power plant, the pulverised fuel is transported pneumatically with air in the dilute phase to the boiler, whereas in the entrained flow gasification, the fuel is entrained into the gasifier in the dense phase.

Pneumatic transport of biomass poses limitations in biomass-co-firing with coal, due to the physical properties of biomass. An assessment of the behaviour of pneumatic transport of pulverised torrefied biomass samples (eucalyptus, cedar, bamboo, spruce and poplar) (Vilela and Abelha, 2019) as compared to coal suggests that the pneumatic transport of bamboo is feasible, and its flowability is similar to that of eucalyptus and cedar and superior to that of other biomass, such as of poplar and spruce. These preliminary results suggest that bamboo can be fed into pulverised fuel technologies.

Limited information exists on the chipping, grindability and flowability of bamboo fuels, and research is required to evaluate the most suitable bamboo streams and properties for size reduction, transport and flowability for bioenergy applications.

3.2.5 Biomass composition

The main constituents of bamboo culms are cellulose, hemicellulose and lignin; the minor constituents comprise resins, tannins, waxes and inorganic salts (Liese and Tang, 2015c; Liese, 1985). The culm composition varies according to age and bamboo section. The chemical content and specific density of bamboo stabilises at approximately 3 years of age in most sympodial bamboo, which is an appropriate time for harvesting for traditional construction applications (Li et al., 2007).

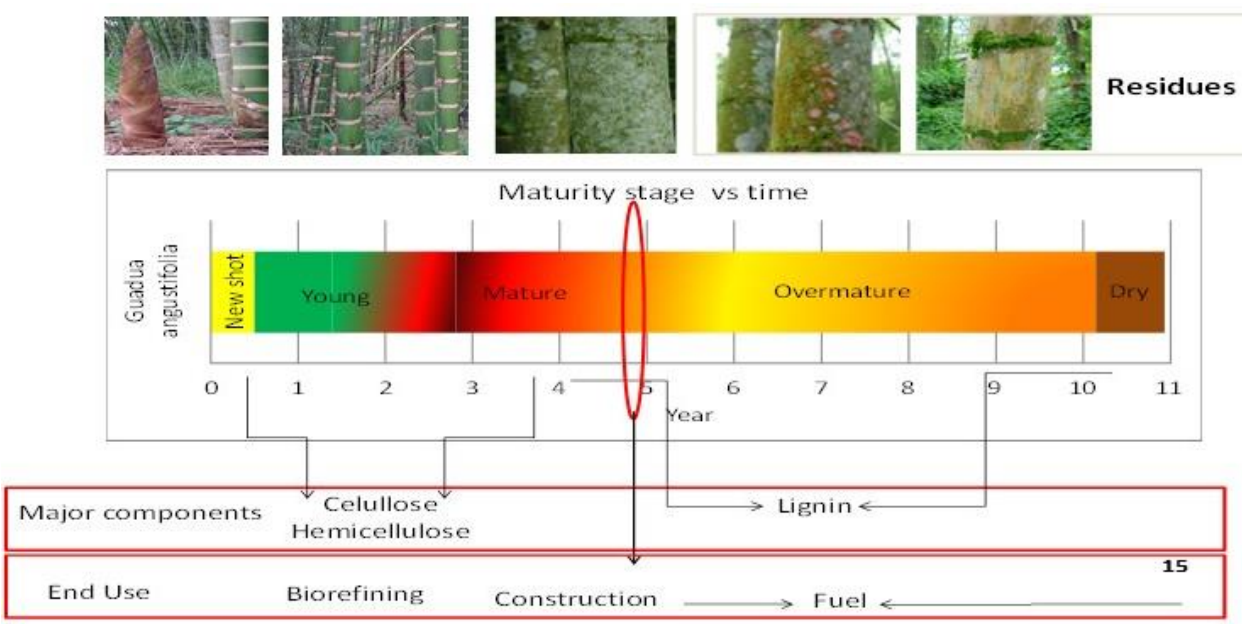


Figure 16. *Guadua angustifolia* growth stages and suitable applications.

Culms of woody bamboos, which are mature or old, are the most suitable fuel for thermal conversions. By then, the bamboo culm has reached its maximum weight, and its moisture and starch levels have lowered (van Dam, Elbersen and Daza Montaño, 2018). The hemicellulose and cellulose are the major components in young culms, while the lignin content increases with maturity. In general, the percentage of hemicellulose is higher in the bottom parts of the culm (van Dam, Elbersen and Daza Montaño, 2018). The nodes contain less water-soluble extractives, pentosans, ash and lignin but more cellulose than the internodes (Liese, 1985).

Biochemical composition

The biochemical composition of biomass is relevant for biorefinery processing, particularly fermentation processes to produce ethanol or butanol. After biomass pre-treatment and fractionation to break down the lignocellulosic matrix of the cell wall structure, the polysaccharides are enzymatically hydrolysed into fermentable sugars, mainly glucose and xylose. Table 1 presents the measured biochemical composition of culm samples of different bamboo species. Bamboos are composed of approximately 75% of carbohydrates. The water extractives include saccharose and starch, which are fermentable carbohydrates. The presence of high lignin interferes with saccharification and fermentation processes; therefore, pre-treatment methods have been developed to remove and degrade lignin (He et al., 2014; Zhang et al., 2018).

Table 1. Biochemical composition of culm samples of different bamboo species wt% (Daza Montaño et al., 2013).

Species		***Guadua angustifolia***		***Bambusa vulgaris var. vulgaris***	***Dendrocalamus strictus***	***Guadua amplexifolia* Preslt**
Maturity stage		Young	Mature	Mature	Mature	Mature
Extractives	**Water**	7.74	5.63	15.03	9.26	15.35
	Ethanol	2.96	1.25	1.42	1.19	2.26
	Total	12.23	10.21	18.02	11.97	21.21
Polysaccharides	**Arabinan**	0.66	0.60	0.69	0.67	0.59
	Xylan	16.38	13.95	16.62	15.34	13.47
	Galactan	0.23	0.14	0.16	0.14	0.24
	Glucan	41.29	40.21	36.04	36.60	32.16
Lignin	**AIL[6] - ash**	20.27	23.72	21.22	24.80	19.17

[6] AIL: Acid insoluble lignin

	ASL[7]	0.90	1.00	0.87	0.82	1.09
Ash	**Ash**	4.04	5.25	2.91	5.69	4.43

Proximate and ultimate analyses

The proximate analysis and heating values of woody bamboo species are comparable to those of wood (**Table 2**). However, the ash content of some bamboo species can be higher than that of wood and roughly lies between clean wood and herbaceous material.

Table 2. Proximate and ultimate analyses of culm samples of mature bamboo and reference biomass feedstocks (Modified from Fryda et al. (2014) and van Dam, Elbersen and Daza Montaño (2018)).

Bamboo species/ other	***Guadua angustifolia***	***Guadua amplexifolia***	***Dendrocalamus Strictus***	***Bambusa vulgaris***	***Chusquea subulata***	**Wheat straw**	**Wood Willow**
Age (years)	5	NA	NA	NA	NA	NA	NA
HHV (MJ/kg)	18.35	18.78	18.73	19.05	18.56	16.57	19.35
Moisture (wt%)	9	11	9.6	9.3	11		
Proximate & ultimate (mass%, dry fuel)							
Volatiles	74	74	75	76	74	71	81
ash @ 815°C	4.9	3.8	5.6	2.7	6.9	7.8	1.5
C	47.00	47.00	47.00	48.00	46.10	43.82	44.70
H	5.90	6.00	5.90	6.10	5.40	5.28	5.70
N	0.70	0.80	1.20	0.60	0.80	0.42	0.20
O	42.00	43.00	41.00	43.00	42.20	43.31	46.15
S	0.07	0.19	0.16	0.05	0.13	0.11	3.00
Cl	0.11	0.09	0.04	0.02	0.12	0.27	0.01
Ash composition (mg kg^{-1} fuel, dry fuel) (main elements)							
Si	16453.0	6209.0	21105.0	7570.0	20259.6	20271.0	69.1
Na	6.3	11.8	13.5	5.0	13.5	48.3	127.2
K	10684.0	16402.0	3656.0	6907.0	7158.4	15466.0	1420.0
Cl	1086.0	859.0	438.0	213.0	1205.0	2682.0	100.0
S	736.0	1861.0	1579.0	548.0	1283.0	1100.0	30000.0
P	869.0	1283.0	1786.0	892.0	2766.2	1030.0	651.0
Mg	253.0	290.0	1617.0	225.0	481.9	642.0	378.0
Al	8.5	13.0	5.0	5.9	20.8	109.9	18.9
Ca	260.0	380.0	346.0	215.0	379.5	2282.0	3899.0

[7] ASL: Acid soluble lignin

The ash content and composition of a solid fuel determines its quality and suitability for large-scale thermal conversions, such as combustion and gasification; certain ash properties, such as the formation of low-melting-point solutions, can have a detrimental effect on the process (Obernberger et al., 1997; Nuamah et al., 2012; Shojaeiarani, Bajwa and Bajwa, 2019). The major ash-forming elements in biomass include Si, Al, Ca, Mg, Na, Fe, K, S and P. Potassium (K) reacts with other ash-forming elements (i.e. Si, Cl, S and P), leading to ash-related operational problems, such as low ash melting temperatures, slagging, fouling and corrosion, as well as agglomeration in fluidised bed systems.

Some bamboo species, as well as other fast-growing biomass and materials, such as agricultural residues (e.g. straw and palm oil residues), have a high ash yield with high K and Si contents. The ash content, particularly the Si content, varies between bamboo species and is influenced by age and site (Liese and Tang, 2015b). Most Si is deposited in the epidermis, whereas the tissues of the nodes contain little Si and those of the internodes contain almost none (Liese, 1985; Liese and Tang, 2015c). The Si content increases from bottom to top (Banik, 2015). Furthermore, the ash content is higher in young stems (1 year) than in mature stems (Wi et al., 2017).

From the fuel characterisation results of different bamboo species shown in Table 2, Fryda et al. (2014) concluded that *G. angustifolia* is a potential solid fuel due to its elemental composition and high heating capacity. Furthermore, based on the ash composition and a theoretical evaluation of fouling tendencies, Fryda et al. (2014) suggested that bamboo species like *Bambusa vulgaris* and *Dendrocalamus strictus* can be more suitable candidates for coal substitution in modern pulverised fuel power plants, and addressing the high Si and alkali content of bamboo improves the fuel properties to reduce the ash-related operational problems in large applications.

Improving fuel properties

Addressing the high alkali and Si contents of bamboo by pre-treatment techniques or strategies is required to improve the fuel properties of bamboo for large-scale combustion and gasification applications. Further R&D is required to assess and develop suitable pre-treatment techniques and conditions. The following are some strategies that need to be further assessed and developed:

i. **The use of additives** is an alternative to reduce ash-related operational problems in biomass combustion. Additives refer to a group of minerals or chemicals that can change the ash chemistry, decrease the concentration of problematic compounds and increase the ash melting temperature in biomass combustion processes (Wang et al., 2012). Additives can be Al-silicate-based, sulphur-based, calcium-based or phosphorous-based. Agglomeration trends of bamboo have been improved using halloysite and kaolin mineral additives (De Fusco et al., 2016).
ii. **Removal of soluble salts and minerals** by washing or hydrothermal treatment (section 4.2)
iii. **Mechanical removal of the outer skin layer** (where most silica is present). The culm can be easily split in the longitudinal direction. This is a common practice in bamboo processing, which is done either manually or with standard machinery, but is time- and labour-intensive. Techniques and machinery to remove the outer layer containing the bamboo skin can be developed together with specific applications for silica-rich material (e.g. products, handicrafts and materials). Mechanical desilication of bamboo has been tested (Runge and Paul, 2015), and converting silica-rich biomass into useful materials has been studied by several authors (Zemnukhova, Kharchenko and Beleneva, 2015).

3.3 Bamboo and biomass sustainability requirements for EU markets

According to EU regulations (REDII), the sustainability of biofuels needs to be assured to be considered for achieving RE targets. The sustainability of biofuel chains is defined based on a set of requirements laid in the EU REDII and related recognised certification schemes (e.g. Sustainable Biomass Program, Green Gold Label, Better Biomass, International Sustainability and Carbon Certification (ISCC), Forest Stewardship Council (FSC), Programme for the Endorsement of Forest Certification (PEFC)). Certification systems aim to provide assurance that woody biomass is sourced from legal and sustainable sources, allowing companies in the biomass sector to demonstrate compliance with regulatory requirements. The sustainability certification of bioenergy includes all value chain steps and related stakeholders: biomass production, conversion, transport and end-use.

The sustainability principles and criteria laid in the biomass certification schemes include environmental, social and environmental requirements. Furthermore, within REDII, the following are critical: (i) GHG emission reductions, as compared to fossil fuel references (e.g. 65% for transport fuels and 70–80% for electricity, heating and cooling) and (ii) indirect land-use change (ILUC)[8]. The EU is moving away from using unsustainable biofuels, and REDII pays special attention to the high ILUC risk of biofuels, bioliquids and biomass fuels. The key discussion topics, among stakeholders, related to biomass sustainability certification and REDII implementation include the impacts of expansion into new feedstocks, products and markets, as well as the links to UN-SDGs, within which carbon and climate goals, biodiversity and social safeguards are critical (SBP, 2020).

In the section below, we provide an overview of the sustainability of bamboo as related to the requirements of bioenergy value chains.

3.3.1 Sustainability of bamboo production systems

The sustainability of bamboo production can be certified with recognised standards, such as the PEFC and FSC, which consider the particularities of forests. Furthermore, the utilisation of bamboo resources and the development of efficient and integrated value chains can contribute directly to several UN-SDGs and related climate actions (in producing countries) (INBAR, 2015b).

SDG 1: End poverty in all its forms

SDG 7: Affordable and clean energy

SDG 9: Industry innovation and infrastructure

SDG 11: Access to adequate and affordable housing

SDG 12: Efficient use of natural resources

SDG 13: Address climate change

SDG 15: Protect and restore terrestrial ecosystems.

SDG 17: Partnerships for the goals

Figure 17. Bamboo and SDG. Source figure: SDG business hub.

---

[8] High ILUC-risk feedstocks for biofuels are those with a significant expansion of the production area into land with high-carbon stock, such as forest, wetlands and peatlands. Land use change can cause GHG emissions (CO_2 stored in trees and soil), which negates emission savings from the use of biofuels instead of fossil fuels (Ec. Europa.eu).

Bamboo offers possibilities to local communities for the development of integrated systems, including the production of materials for different applications (from food, housing and clothing to energy). The flexibility and lightness of bamboo makes it an excellent construction material for earthquake-resistant buildings in areas vulnerable to natural disasters, including Colombia, Ecuador and Nepal (INBAR, 2019a). Furthermore, bamboo forests and plantations provide a wide range of environmental services: as a source of carbon storage, a means to stabilise slopes and prevent soil erosion and a crucial part of biological diversity (INBAR, 2019c; Juan, Camargo and Thang, 2020). Biodiverse bamboo forests and plantations can provide additional business opportunities to local communities, such as ecotourism (e.g. http://www.bambuturismo.com). The engagement of local communities is key to developing bamboo supply chains.

In terms of social impacts and gender equality, the inclusion and active participation of women (and youth) are key in the development of the bamboo sector due to its lightweightness and ease of processing (compared to timber). All activities in the value chain can easily be performed and led by women (e.g. establishment of bamboo nurseries and propagation and establishment of plantations, processing, management and marketing), thus providing opportunities for inclusion and improving access to economic resources, land and business management.

3.3.2 Potential of GHG emission reduction with bamboo bioenergy chains

Within REDII, the methodology to assess the GHG emissions of biofuel chains considers all emissions associated with the production, processing, transport and use of bioenergy. The bioenergy scenario is compared with a counterfactual scenario, the replaced energy source, to quantify the net effect on GHG emissions (Berndes, Cowie and Pelkmans 2020). The required GHG emission reductions of bioenergy chains, as compared to fossil fuel references, are 65% for transport fuels and 70–80% for electricity, heating and cooling (by 2030). The GHG savings can be calculated as follows: (ECf – ECb)/ECf, where ECf indicates the emissions of the fossil reference and ECb indicates the emissions of the bioenergy chain. The GHG considered include CO_2, CH_4 and N_2O. The GHG emissions of the biofuel chain are calculated as follows (ECb):

ECb=	$e_{ec}+e_l+e_p+e_{td}+e_u-e_{sca}-e_{ccs}-e_{ccr}$
e_{ec}=	emissions from the extraction or cultivation of raw materials
e_l=	annualized emissions from carbon stock changes caused by land use change (20 years)
e_p=	emissions from processing
e_{td}=	emissions from transport and distribution
e_u=	emissions from the fuel in use
e_{sca}=	emissions savings from soil carbon accumulation via improved agricultural management
e_{ccs}=	emissions saving from carbon capture and geological storage
e_{ccr}=	emissions savings from carbon capture and replacement

Within the RED GHG accounting methodologies, a distinction is made between the requirements for residual biomass streams and bioenergy crops. For using residues, the GHG emissions accounting starts at the biomass collection point, from the biomass transport step, and excludes emissions related to biomass cultivation and production. For dedicated energy crops, the biomass production steps and carbon stock are accounted for, which is a significant advantage of bamboo systems, which can act as efficient and effective carbon sinks (Yuen, Fung and Ziegler 2017).

When establishing bamboo plantations, the carbon stock change will result in a positive contribution in most cases (section 3.3.3). The carbon (C) storage potential can be equivalent to and even superior to trees (Yiping, Buckingham and Guo-mo, 2010). Tree systems can store approximately 0.10–0.22 GtC/Mha (Bastin et al., 2019; Lewis et al., 2019), whereas bamboo systems can store approximately 0.09–0.39 GtC/Mha (Drawdown.org, 2019; Yuen, Fung and Ziegler, 2017; Scurlock, Dayton and Hames, 2000). The values of carbon stock in bamboo systems can vary considerably among species, due to their different growth patterns and specific characteristics.

According to Camargo, Rodríguez and Arango (2011), for a 7-year-old *Guadua angustifolia* system, the measured soil carbon at a depth of 0.5 m is approximately 500 t CO_2/ha. The carbon storage potential, in 20 years, is equivalent to 600–700 t CO_2/ha (0.16–0.19 GtC/Mha), of which approximately 80% is related to the C stored in the underground biomass. This value of carbon stock is superior to most known biomass production systems.

A sustainability assessment of the potential import of bamboo pellets from Colombia to the EU, to be used as a coal substitute in the power sector, was reported by Daza Montaňo et al. (2013). The assessed bamboo chain (*Guadua angustifolia*) has the potential to comply with the EU sustainability criteria for biomass value chains, and the estimated GHG emission reduction potential is above 70% when compared to coal-based electricity. When accounting for the potential carbon stock within plantations, the GHG emission reductions can be as high as **300%,** which exceeds the GHG savings required by the EU (70–80%) (Daza Montaňo et al., 2013).

For most species, limited information exists about the emissions (e.g. N_2O and CH_4) of bamboo systems (L. Xu et al., 2020) and about the carbon stocks for most species (Yuen, Fung and Ziegler, 2017; L. Xu et al., 2020). In addition, uncertainties remain about the true potential of bamboo for carbon sequestration and climate chain mitigation (Liese, 2009; Düking, Gielis and Liese, 2011; Zachariah et al., 2016; Yuen, Fung and Ziegler, 2017).

Further research is required to address not only the carbon stock but also the carbon fluxes and emissions of bamboo systems, and sustainability assessments (including life cycle assessments (LCA)) are required to demonstrate the true potential of bamboo biofuel chains.

3.3.3 Bioenergy with restoration and carbon sequestration

Bamboo forests and plantations can play a significant role within policy approaches to tackle climate change, such as carbon storage by reforestation and land restoration projects. In the context of climate change, the Intergovernmental Panel on Climate Change has pointed out that managed forests that produce bioenergy and other wood products can make a greater contribution to climate change mitigation than forests managed for conservation alone (Berndes, Cowie, and Pelkmans, 2020). With bioenergy production from bamboo, the potential for climate change mitigation of a bamboo system can increase significantly due to the substitution of fossil fuels and related avoided emissions.

Bamboo cropping systems have significant advantages for bioenergy and carbon sequestration over commercial forestry due to their annual selective harvesting possibilities with significant socio-economic benefits in addition to carbon benefits. Due to its continuous productivity (annual growth of new culms/poles) and growing patterns, bamboo provides annual harvesting possibilities and conversion into value-added products or a substitute for carbon-intense products and fuels. When a bamboo forest or plantation is not properly managed or harvested, its carbon storage potential decreases (van der Lugt, ThangLong and King, 2018). The proper management of bamboo forests and plantations requires the continuous removal of mature culms, which results in highly productive systems and prevents forest degradation.

Because of its fast growth and annual regeneration, using bamboo as a source of bioenergy can take pressure off from other forest resources, reducing deforestation. This can be critical in areas such as sub-Saharan Africa, where deforestation of wood fuel remains a primary driver of deforestation (INBAR, 2019b). The restoration of degraded soils can be achieved by planting bamboos. Through a comparison of bamboo and other crops (such as sorghum and pearl millet) as an alternative to biofuel crops on high-salinity and drought-prone land, Patel et al. (2020) suggested that bamboo has the highest net income, lowest GHG emission, highest net energy balance and highest biomass production per USD spent among the other biomass crops. Furthermore, intercropping is feasible in bamboo production systems, which can be a sustainable alternative to large-scale tree monoculture plantations.

Sustainable bamboo value chains can be strategic in contributing to achieving SDGs as well as the targets of RE and climate change (within NDC and REDD). At present, there is a lack of research on the exact carbon sequestration and system emissions of giant woody bamboo and bamboo products (van der Lugt, ThangLong and King, 2018), which hampers the effective adoption of bamboo in national strategies to tackle climate change. Furthermore, there is a lack of research on bamboo potential as a bioenergy crop, and bamboo should be included in plans for land restoration and the development of biomass supply chains.

4. Bioenergy conversion technologies

Bamboo, like any biomass, can be converted to heat and power; to liquid, solid or gaseous fuels and other chemical products through various conversion processes (Figure 18). The available processing routes range from conventional uses of biomass, such as firing for cooking and heating, to modern production processes, such as biorefinery, to yield fermentable sugars for ethanol production (second-generation).

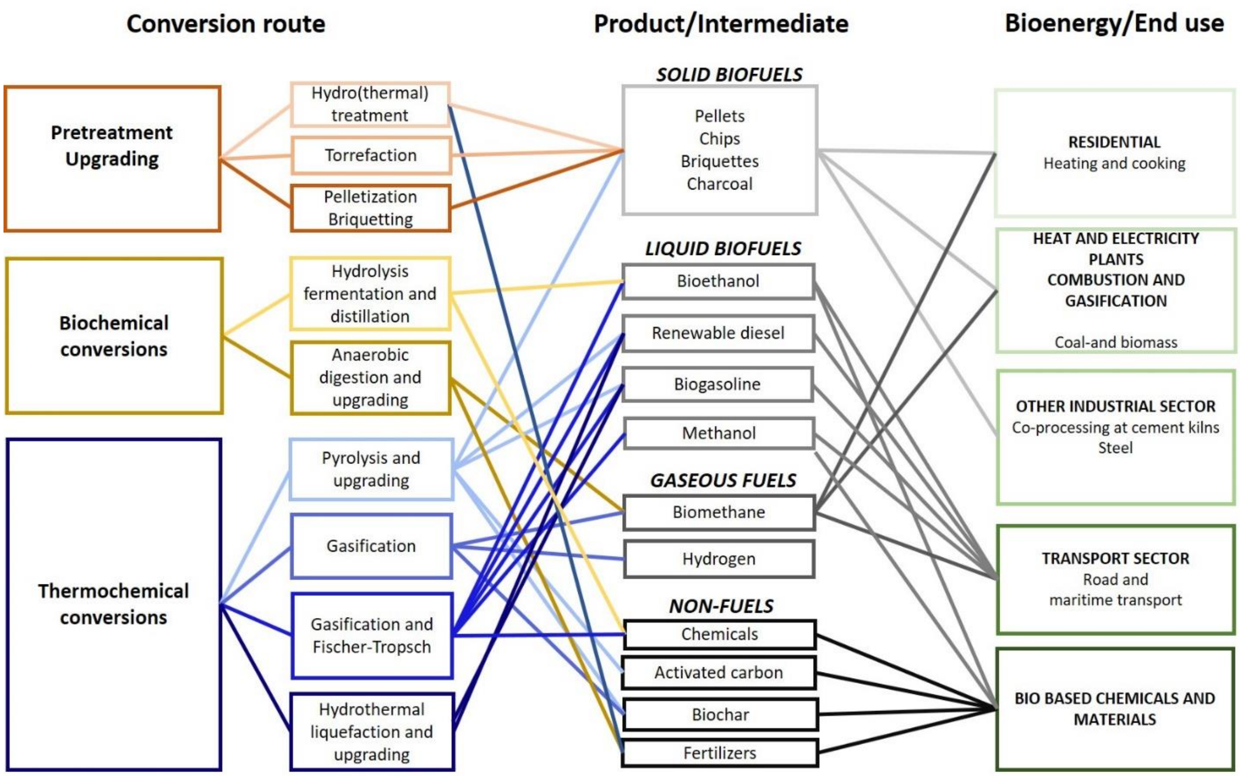


Figure 18. Bioenergy conversion routes, products and applications.

Different technology pathways are fully operational and commercial, such as biomass combustion and co-combustion of biomass with coal for heat and power production. More advanced technologies have been demonstrated, such as biomass gasification and transport fuel production. Technologies that are at an early stage of development and pilot plant facilities include fast pyrolysis and upgrading, hydrothermal liquefaction and biomass gasification with Fischer-Tropsch

(O' Connell et al., 2019). This sections briefly describe biofuel production processes and provides an overview of the state of development of bamboo biofuel production.

4.1 Solid fuels

4.1.1 Densified solid fuels: pellets and briquettes

For biomass densification, small particles of biomass are compressed into pellets, briquettes or cubes to increase its bulk density and reduce transport and logistics costs. Low bulk densities of biomass can create problems in handling and result in high transportation costs. Densification of biomass has other advantages, including consistent particle size distribution, improved flowability for feeding and handling and improved compositional quality for converting biomass into products (Fritsche et al., 2019). Pellets, in particular, are the most commonly used densified products for bioenergy production and have become a common fuel mainly in developed countries, both in households (in the increasingly popular pellet boilers) and industry.

Bamboo pellets can be found on the market, especially in China; are often manufactured from manufacturing residues other bamboo products and are marketed as a boiler fuel for coal substitution (Appendix 2). In Brazil, the implementation of a bamboo pellet industry is under development; the company 'Brasil Biomassa' has announced a project to implement the first industrial unit for the annual production of 36.000 t of international quality pellets (Brassilbiomassa.com.br 2020).

Bamboo pellets with densities of approximately 1200 kg/m^3 (pellets) and 570 kg/m^3 (bulk) were obtained in lab tests (Daza Montaňo et al., 2013). Pellets from bamboo saw dust with bulk densities of 700 kg/m^3 are produced in China (Appendix 2). Mechanical properties of bamboo pellets have been studied (Fei et al., 2013) but limited documentation exists on the properties and conditions for palletisation of bamboo.

According to the experience of bamboo pellet producers in China (Appendix 2), despite having physical properties similar to those of wood, bamboo requires different pelleting machinery than those used for wood pellets, and only large-capacity equipment (>2 t/h) and technology which has been developed independently for bamboo feedstock have proved suitable for bamboo pellet processing. The drying and pelleting technology was provided by Jiangsu Chint Company, China.

Briquettes of bamboo charcoal are also commercialised mainly in Asian and African countries and are mainly used for cooking and heating applications. However, limited information exists on bamboo briquette production and properties. The production of bamboo charcoal briquettes in China, for local and BBQ markets, is described in Appendix 3.

The potential of briquette production from different bamboo species (*Bambusa vulgaris*, *Phyllostachys bambusoides*, *P. edulis* and *P. nigra*) was analysed by Brand et al. (2019); the results suggested satisfactory physical and energetic properties of briquettes obtained from different species: the bulk density of briquettes ranged from 1100 to 1200 kg/m^3, compression strength ranged from 4.68 to 5.82 MPa and energy densities ranged from 1.2 to 1.4 GJ/m^3. *P. nigra* briquettes showed the best energy quality, followed by *P. edulis*, *P. bambusoides* and *B. vulgaris* briquettes (Brand et al., 2019).

4.1.2 Chips

The trade of bamboo chips for bioenergy production has not been reported yet, and limited information on bamboo chips is documented. Different methods for harvesting and processing of bamboo chips have been studied (Temmerman et al., 2005; Salakka, 2014). In rural areas in Laos, conventional manual harvesting and chip production are relatively competitive, due to the low labour costs (Salakka, 2014).

Bamboo chip production is an alternative yet to be explored, due to the relatively high biomass density of woody bamboos. The bulk density of bamboo chips is equivalent to those of wood chips and pellets, and thus, bamboo chips have potentially lower processing cost and associated emissions as compared to palletisation, as chipping is a simpler process.

In general, woody bamboo solid fuels comply with the technical specifications for biomass fuels used for heat and power generation, such as the ash content, biomass density and calorific value (ISO 17225 standard); thus, bamboo chips are a potential bioenergy resource. However, the cost-benefit analysis, further development and/or refining of the chipping and pelletising and briquetting process require further study.

4.2 Pre-treatment and upgrading

4.2.1 Water washing

Washing the material in water is an alternative method for reducing the concentration of troublesome elements (e.g. K and Cl) in biomass. Washing can be performed in the field, or at a processing plant, either by natural leaching with rainfall or by controlled water washing in ponds or flowing water. The natural leaching of herbaceous materials, and controlled water washing have proven effective in the removal of detrimental elements for combustion (Tonn et al., 2012; Deng et al.,2013). Washing of bamboo can be applied in production areas with abundant rainfall and water resources. The resulting aqueous stream, rich in minerals and organic matter, can be used for irrigation. The bamboo subjected to water soaking, to remove water-soluble extractives, has shown to dry faster and take up moisture slower than the untreated bamboo (Liese and Tang, 2015b; Liese, 1985). In many Asian countries, water soaking is commonly applied to remove carbohydrates as a traditional method for culm preservation.

The feasibility and commercial implementation of a biomass washing system depends on a combination of several factors, including scale and cost of production (e.g. cost of drying), agronomic practices, water availability and field-specific factors (van Dam, Elbersen, and Daza Montaño, 2018).

4.2.2 Hydro (thermal) treatment: wet torrefaction

The hydrothermal treatments of bamboo have been studied to produce biochar or activated carbon (Yang et al., 2016; Schneider et al., 2011) and for the pre-treatment of bamboo to facilitate enzymatic degradation (Xiao et al., 2014), or to produce chemicals such as levulinic acid and furfural (Sweygers, Somers and Appels, 2018).

Wet torrefaction is a treatment of biomass under hot compressed pressure within a temperature range of 40–230°C. In this method, biomass undergoes decomposition, which opens the biomass structure and allows the dissolution of salts, improving the fuel characteristics through the removal of problematic minerals such as K and Cl. A lab-scale testing of wet torrefaction of bamboo yields a solid fuel with improved characteristics (Daza Montaño, Pels and Fryda, 2012). Wet torrefaction removes salts and minerals (above 90% of K and ~80% of Cl) from the biomass and renders a fuel with low ash content and a material easier to densify. The aqueous side stream, rich in minerals, can be further valorised, for example, for producing fertilisers (Daza Montaňo et al., 2013).

4.2.3 Dry torrefaction

Torrefaction is a thermal pre-treatment technology that involves heating of biomass in the absence of oxygen at temperatures typically between 200 and 400°C. The liberated gas is used to generate process heat. Torrefaction aims to improve relevant biomass properties, such as grindability, energy density and biodegradability. Advanced handling characteristics of torrefied biomass pellets make them attractive for long-distance transportation. However, no major trade flows for industrial use have occurred yet (Junginger et al., 2019).

Dry torrefaction improves the physical qualities of the fuel, such as grindability and moisture content (Rousset et al., 2011; Chen et al., 2015; Ma et al., 2019; Fryda et al., 2014). However, with dry torrefaction, the relative ash concentration of bamboo increases with decreasing organic content. **Concerning the combustion behaviour of pulverised fuel**, the non-pre-treated material shows fouling potential similar to that exhibited by herbaceous biomass; dry torrefaction reduces the fouling behaviour, and wet torrefaction renders a high-quality product that minimises the risk of fouling and mineral deposition. Therefore, pre-treated bamboo can be a suitable biofuel for coal substitution in modern pulverised fuel power plants (Fryda et al., 2014).

Figure 19. Torrefied and wet torrefied bamboo (Daza Montaňo et al., 2013).

The R&D of suitable pre-treatment strategies, particularly hydro (thermal) treatments for removing minerals and improving fuel properties, densification and grindability properties, is required. Furthermore, the techno-economic feasibility and sustainability of pre-treatment strategies for different bamboo streams (different species and maturity stages) need to be assessed.

4.3 Hydrolysis and fermentation to liquid fuels

The biorefinery for liquid fuel production (e.g. second-generation bioethanol), through fermentation of lignocellulosic feedstocks, is a combination of (thermo)chemical and biological processes. The subsequent main process steps involve feedstock size reduction and (thermochemical) pre-treatment, chemical or enzymatic hydrolysis for fermentation of sugars (saccharification), fermentation into liquid fuel and product recovery.

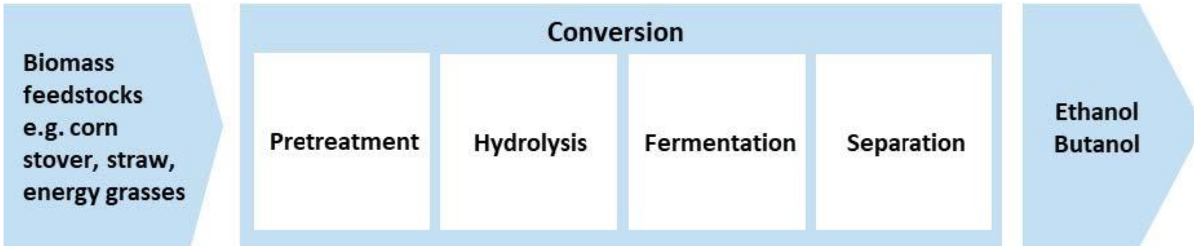


Figure 20. Enzymatic hydrolysis and fermentation value chain (O' Connell et al., 2019).

Various pre-treatments and conditions for hydrolysis and fermentation of bamboo have been investigated (He et al., 2014; Yuan et al., 2017; Sathitsuksanoh, Zhu and Zhang, 2012). The pre-treated bamboo exhibits the same digestibility as other lignocellulosic material (~90%), while the non-pre-treated material exhibits lower digestibility (**Figure 21**). This lower digestibility is attributable to the morphological structure of bamboo, which differs from other biomass feedstocks in density and tissue arrangement.

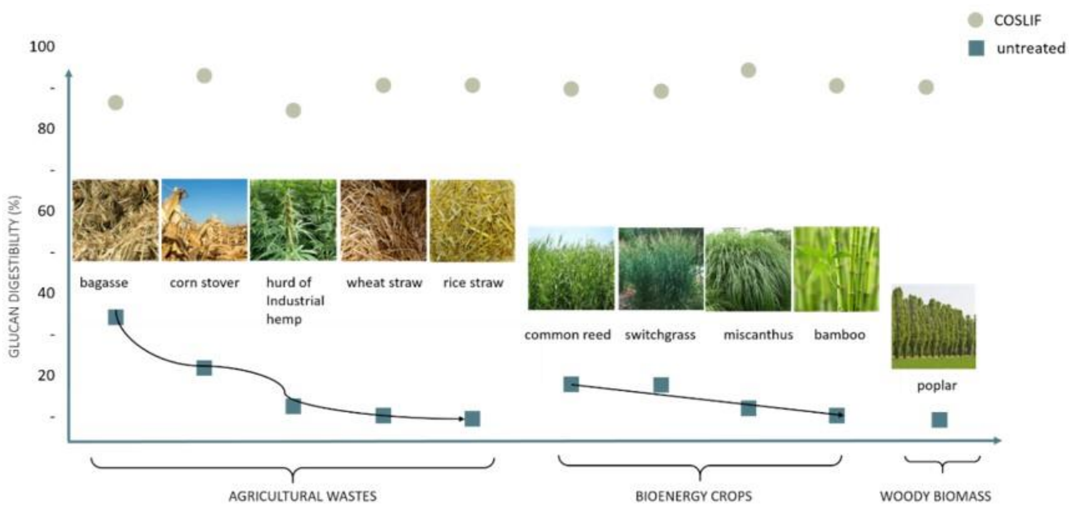


Figure 21. Glucan digestibility of lignocellulosic materials. Modified from (Sathitsuksanoh, Zhu and Zhang, 2012).

4.3.1 Ethanol

Bioethanol production from bamboo is approaching the commercial stage of development with the establishment of the first biorefinery producing ethanol and chemicals. **Assam Bio-Refinery Private Limited (ABRPL)** in **India** is a joint venture among a state-owned Indian oil company, NRL, Chempolis and the Finnish energy company Fortum. The plant requires 300,000 t of bamboo input annually and will produce 60 million litres of bioethanol, 19,000 t of furfural, 11,000 t of acetic acid and 144 GWh of green energy. The plant will use the Chempolis Formicobio technology. It has been advertised as a third-generation biofuel technology of cellulosic biomass for enzymatic conversion to sugar and ethanol production with the co-production of chemicals and solid biofuel. The biorefinery operations are planned to be started in 2021 (Chempolis, 2020).

4.3.2 Butanol

Little information exists on bamboo utilisation as feedstock for ABE[9] fermentation, most probably due to the economic challenges of lignocellulosic biobutanol production. Lab-scale tests have proved the feasibility of butanol production from bamboo hydrolysates (N. Xu et al., 2020; Kumar, Gujjala and Banerjee, 2017; Kolawole et al., 2015).

4.4 Anaerobic digestion

Anaerobic digestion is a commercially available technology and a widely used biological process for converting biomass into biogas, which is a mixture of methane, CO_2 and traces of other gases. Biogas can be used for cooking, heating, power production and as a transport fuel.

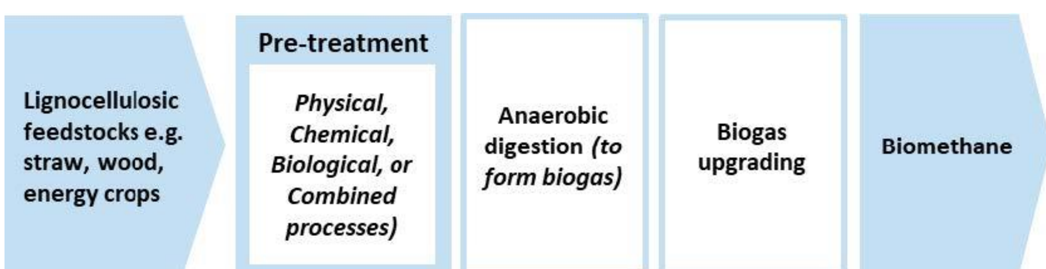


Figure 22. Value chain for AD with pre-treatment (O' Connell et al., 2019).

Biogas can be produced from the anaerobic digestion of residual streams from bamboo processing. This also tackles environmental issues of the bamboo-processing industry, related to its wastewater, mainly generated in the boiling process, which is rich in organic matter content (Wang et al., 2013).

[9] Acetone, Butanol, Ethanol.

Biogas production from bamboo has been demonstrated. According to the company AgroGas® Bio-CNG (compressed natural gas), biogas has been produced in their pilot scale demonstration facilities in India and meets IS 16087 2016 Bio-CNG standard for vehicles.

However, limited information exists about the deployment and integration of anaerobic digestion within bamboo streams, as well as the treatment of (liquid) residual streams. Thus, the techno-economic feasibility of commercial deployment of anaerobic digestion systems within bamboo value chain development needs to be assessed.

4.5 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) utilises elevated temperature and pressure to break the carbon bonds in biomass feedstocks and re-form them into long-chain molecules that take the form of a biocrude oil. The bio-oil can be upgraded into transport fuels, such as renewable diesel. Feedstocks such as pulp mill residues and sewage sludge have been transformed to biocrudes by HTL (Wijeyekoon et al., 2020). To obtain a biocrude oil with low oxygen content, catalytic hydro-deoxygenation conditions have been applied to biomass (Ma et al., 2019) and bamboo has been tested and reported to have the potential to produce a bio-oil with properties superior to those of heavy oil and boat oil (Chang et al., 2016).

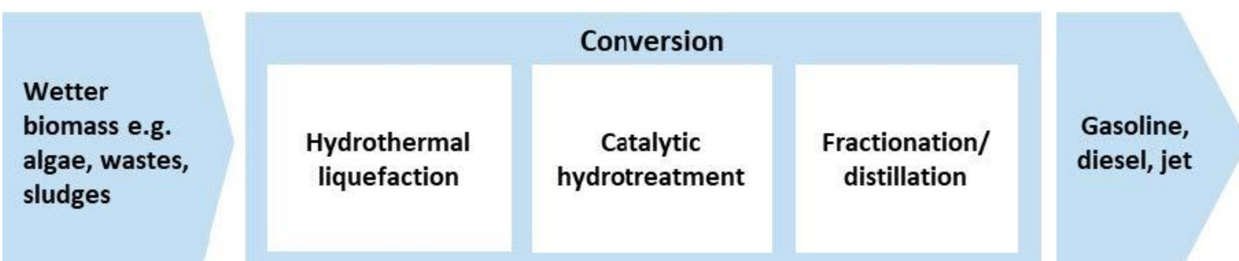


Figure 23. Value chain for HTL with catalytic upgrading (O' Connell et al., 2019).

HTL is an interesting option to produce biocrude oil, which can be further upgraded into biogasoline and renewable diesel. This can be achieved using integrated systems with existing fossil oil refineries. *The potential conversion of bamboo streams through HTL needs to be further researched.*

4.6 Pyrolysis

Pyrolysis refers to a controlled thermal decomposition of biomass occurring between 300 and 700°C in the absence of oxygen, which produces a liquid (bio-oil), a gas (e.g. CO and H_2) and a solid (biochar). The two main types of processes are fast pyrolysis and slow pyrolysis. These are characterised by different residence times in the pyrolysis reactor and lead to different proportions of the gas, liquid and solid fractions. While slow pyrolysis favours the production of biochar, fast pyrolysis favours the production of bio-oil. In slow pyrolysis, the char, bio-oil and gas fractions are approximately 33 wt%, 32 wt% and 35 wt%, respectively, and in fast pyrolysis, they are approximately 12 wt%, 75 wt% and 13 wt% (Wild, 2015). Process performance and product yields and properties are affected by several factors, such as reaction temperature, residence time, heating rate and feedstock composition. The pyrolysis of bamboo is much more faster than that of wood, most probably due to its high potassium (K) content. Potassium is known to be a catalyst for combustion, and it contributes to oil cracking, favouring gas production (Rocha et al., 2017; Nzihou, Stanmore and Sharrock, 2013).

The fast pyrolysis of biomass has been implemented on the commercial scale and the liquid product is commercially used for energy application (i.e., replacement of natural gas for steam production). An example is the demonstration plant of BTG in Hengelo, the Netherlands, where 5 t/h of clean wood are converted into 3.2 t/h of oil, 7.4 MW_{th} of steam and 650 kW of electricity (Beld, 2018). Bamboo slow pyrolysis is an established industry in China for the local and export markets of charcoal, activated carbon and bio-oil-derived products.

In China, large-scale plants produce charcoal and activated carbon, as shown in **Figure 24**. The Zhejiang Province has a well-developed bamboo sector, and approximately 2000 industries from the Anji area provide bamboo residues at a relatively low price of approximately 65 USD/t. The pyrolysis technology is based on rotary metal kilns operating at approximately 600–650°C for charcoal production. Most of the required process heat is provided by the combustion of the produced gas and tar streams, while additional steam is produced from the bamboo drying process.

Figure 24. Bamboo chipping and large-scale pyrolysis in China. Photos: Daza C.M.

Limited literature exists on bamboo pyrolysis gas product characterisation, most of which aims at char characterisation. **Bamboo char has numerous micropores and a very large surface area (approximately 4–10 times larger than that of wood char)** (Kantarelis et al., 2010); therefore, studies have focused on producing activated carbon.

4.6.1 Pyrolysis oil

Bio-oil obtained from bamboo pyrolysis is suitable for not only fuel production but also as a feedstock to produce high-value chemicals (Jung, Kang and Kim, 2008).

Pyrolysis oil cannot be directly used as a transport fuel but needs to be further upgraded to obtain a suitable end product, such as biogasoline or renewable diesel (E4tech, 2018). The further processing of pyrolysis oil can be integrated into existing oil refinery processes.

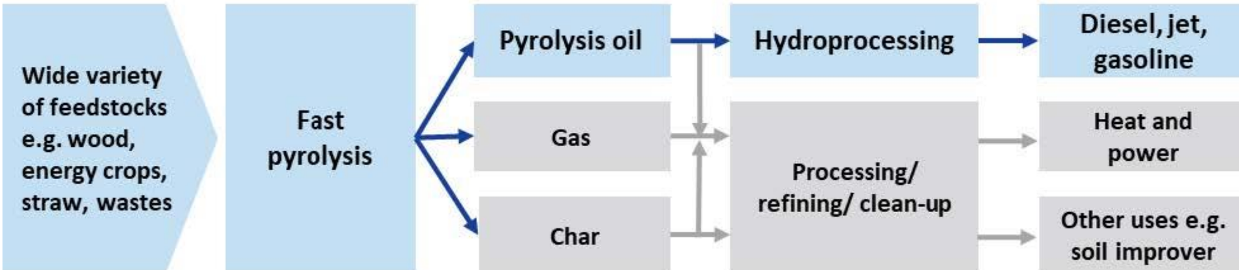


Figure 25. Value chain for fast pyrolysis with catalytic upgrading (O' Connell et al., 2019).

An intermediate pyrolysis test of bamboo (*Bambusa vulgaris)* conducted at 450°C resulted in a 46 wt% oil yield, 30 wt% char and 17 wt% of gas (permanent or non-condensable gases) (Wild, 2015). The obtained high-quality charcoal can be used as fuel for co-firing, as soil improver or for activated carbon production. The liquid organic fraction applications include the production of liquid fuel additives, substitute phenol in resins and bitumen additives, and the liquid aqueous phase can be used as a bioalternative to synthetic pesticides and as a road de-icer (Wild, 2015).

4.6.2 Charcoal as fuel

The use of bamboo charcoal to produce (industrial) heat, power or CHP; for local usage or to produce solid biofuel for the export market is an established technology for implementation in various countries. Bamboo charcoal and briquette production is a simple technology common in China and promoted in Africa (e.g. Ethiopia, Kenya and Ghana) and other regions (e.g. Jamaica). In rural areas, traditional mud ovens are characterised by low efficiencies and high emissions. Improved technologies for charcoal production technology are based on three typical kiln types: brick, metal and retort. Each of these kiln types has its own advantages and disadvantages, and their applicability depends on local conditions, feedstock availability and financial resources. A kiln carbonises biomass in a closed container and releases gas and vapor to the atmosphere. In contrast, a retort carbonises biomass, condenses the gas and vapor and collects the gas or liquid tar in a container. The retort represents one of the most efficient means of producing good-quality charcoal. Depending on the technology, the charcoal yield varies between 10 and 40 wt%. Advanced industrial retorts, applying separate combustion chambers, can achieve efficiencies of up to 40 wt% (Biomass Technology Group (BTG) BV, 2013).

Pilot projects in African countries mainly use brick and metal kilns (of varied sizes), while the industry retort types are commonly used in the Chinese bamboo processing industry. Charcoal briquettes can be produced at various quality levels (low, regular and premium), depending on the fuel quality, the binder and the process technology and conditions (van Dam, Elbersen and Daza Montaño, 2018). Several charcoal briquetting technologies exist, varying from very small to medium capacity, which can be manual (e.g. hand mould or manual screw extruder) or electric (e.g. screw extruder, piston extruder or roller press). In terms of charcoal use as cooking fuel, honeycomb-shaped briquettes require special stoves (BTG BV, 2013).

Standards for bamboo charcoal applications have been released, from which ISO 21626 deals with fuel applications. Bamboo charcoal is considered a high-quality fuel and is associated with low emissions during fuel combustion (Wei and Taotao, 2020). This is particularly relevant for household cooking applications in rural areas.

Charcoal is the most produced solid fuel globally. Improving bamboo charcoal value chains include the adoption of practices and technologies which improve efficiency and reduce emissions.

Figure 26. A charcoal production facility in China. Photo: Daza C.M.

Figure 26 shows a medium-sized company in China which produces charcoal and pyrolysis oil in a brick kiln. The charcoal is sold in other Asian countries (e.g. fuel and activated carbon precursor) and the produced pyrolytic oil is converted into various products.

4.6.3 Char and nonfuel applications

The char (biochar) produced from bamboo is not only a solid fuel but also an activated carbon precursor, or a reducing agent in metallurgical processes. Powdered activated bamboo charcoal has been proven effective for removal of pollutants like nitrate, phenols and heavy metals from waste waters (Mizuta et al., 2004; Wu et al., 2013). Bamboo biochar use as a catalyst support in industrial processes is also of interest (Wei et al., 2020).

Biochar use for soil improvement has also gained interest over the last years. Applying biochar to soil has multiple benefits, from helping mitigate climate change to managing waste to conserving soil (Jeffery et al., 2017). Biochar is also widely assumed to boost the crop yield. The yield-stimulating effects of biochar can especially benefit agriculture in low-nutrient, acidic soils in the tropics (Jeffery et al., 2017).

Biochar production is an interesting option for bamboo-producing regions, for which multiple application possibilities are aligned with circular economy developments. Thus, the techno-economic feasibility and sustainability of biochar production need to be assessed.

4.7 Combustion and gasification

In the past, bamboo, as other types of biomass, was not considered to be suitable for large-scale combustion and gasification processes. Some bamboo species, as well as other biomass materials such as agricultural residues (e.g. straw and palm oil residues), have a high ash yield with high alkali and silica content. These properties lead to ash-related operational problems, such as low ash melting temperatures, slagging, fouling and corrosion. However, the potential low melting temperatures of the ash make these fuels potentially well-suited for slagging thermal conversion systems, such as entrained flow gasification, in which slag formation on the gasifier walls is essential for the operation (Nuamah et al., 2012).

Strategies to improve the fuel quality for combustion and gasification include the use of additives, feedstock pre-treatment for the removal or salts and minerals and the removal of the skin layer of bamboo (which contains most of the Si) (sections 3.2.5 and 4.2.1).

4.7.1 Combustion

Bamboo is a suitable combustion fuel for heat and power production. Results from combustion test of bamboo (virgin and pre-treated) in blends with coal suggest that pre-treated bamboo is a suitable candidate for coal substitution in pulverised coal power plants (Fryda et al., 2014; Z. Liu et al., 2016).

Bamboo pellets, which are mainly produced from saw dust, are used as a substitute for coal in China, mainly for industrial heating applications (Appendix 2). Japan is moving forward to power production from bamboo (DAIICHI JITSUGYO CO., 2019), addressing the ash melting issues (The Mainichi, 2019).

4.7.2 Gasification

Gasification is a thermochemical process performed at 800–1300ºC, which produces syngas, a mixture of methane, hydrogen, carbon monoxide and CO_2, which can be used for not only heating and power but also further processed with the Fischer-Tropsch process for the catalytic production of liquids such as hydrocarbons and methanol. The high investment costs for such plant have so far limited the large-scale development of biomass Fischer-Tropsch conversion. Syngas production from biomass as a substitute to petrol-based fuels, such as liquefied natural gas, is also of commercial interest. Cellulosic feedstocks' gaseous conversion and synthesis into BioLPG is technically feasible and has huge potential (Johnson, 2019). Biomass gasification market implementation is mainly limited to relatively simple power and heat applications. Biomass gasification is commercially available (100 kWth up to 100–300 MWth scale) and biomass-gasification-based production of transportation fuels or chemicals has not yet achieved commercial breakthrough (Kiel, 2019).

Bamboo gasification has been promoted in different countries (e.g., India) mainly at small and medium scales for rural electrification, and scarce information is found about the successful operation of these systems. The local government in India and the company GP Green Systems

Pvt. Ltd., Kolkata, have set up three gasifiers (nominal capacity 600 kg/h). The produced gas is meant to replace high-speed diesel used as fuel in food industry, which according to Chakrabarti (2018) is successful.

The Indonesian company Clean Power Indonesia (CPI), together with the Indonesian government, runs first of its kind bamboo gasification demonstration projects for rural electrification in Indonesia, producing 3000 MWh/year of electricity. The system is described in Appendix 1.

5. Cost of biofuels

Currently, biofuel options are more costly than fossil fuel options, specially advanced biofuels (liquid and gas) from lignocellulosic feedstocks, with a lower price gap for biogas (from anaerobic digestion) and solid fuel options, as depicted in **Figure 27**. Advanced biofuels (e.g. ethanol and FT liquids) are expected to be competitive in the longer term, due to learning effects and increased production capacity (Brown et al., 2020). The competitiveness and large-scale deployment of advanced biofuels largely depend on continuing policy support, including carbon prices, as well as incentives to deploy low carbon fuels. In contrast, solid biofuel commodity trade (e.g. chips and pellets) is an established market; with a competitive and increasing role, particularly in the EU, where several countries have announced intentions to phase out coal[10], this transition requires fuel alternatives in the coming years.

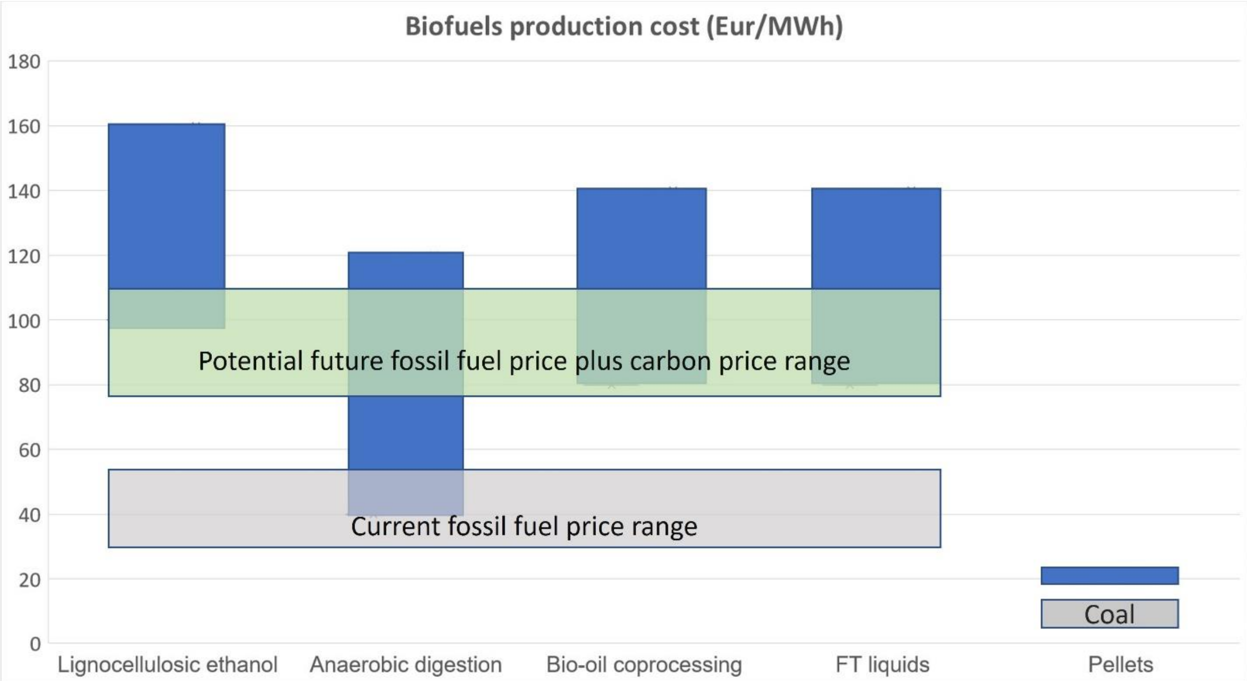


Figure 27. Biofuel cost estimates (Brown et al., 2020; Visser, Hoefnagels and Junginger, 2020; IEA, 2020b).

[10] https://beyond-coal.eu/2021/06/30/overview-of-national-phase-out-announcements/

The main cost components of biofuels are raw material (feedstock and other inputs), capital, transport, operating and maintenance costs. **Figure 28** depicts the average production cost distribution of some biofuels. In the depicted anaerobic digestion case, the raw materials have no costs as the base data consider it to be a treatment of residual processing streams.

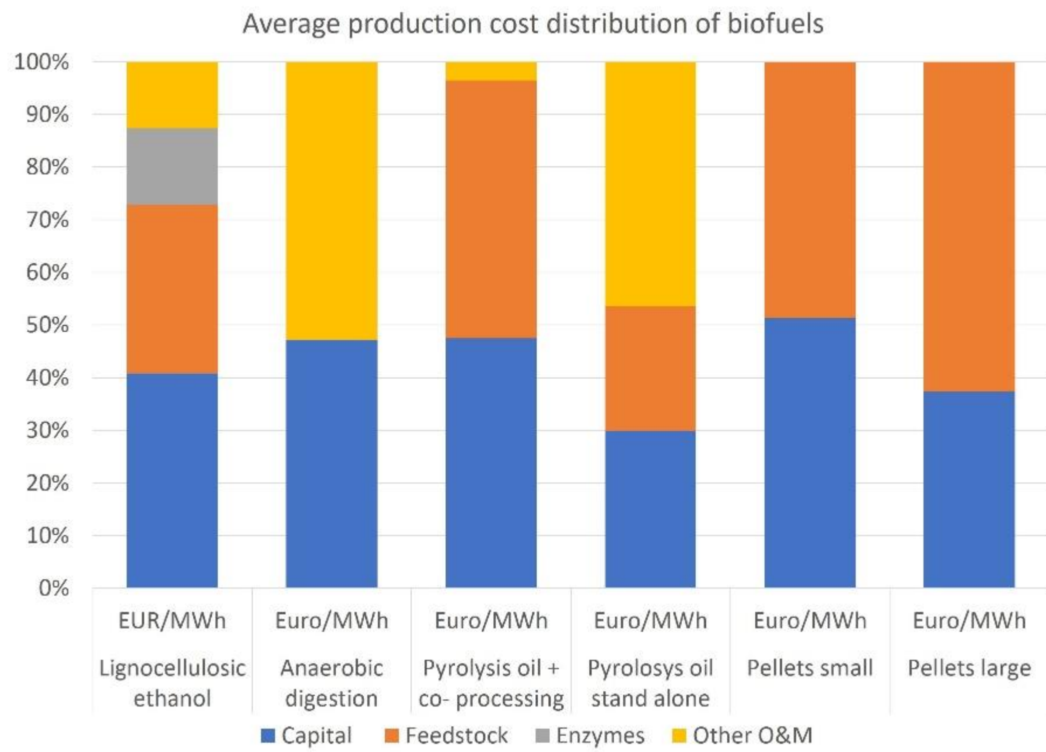


Figure 28. Biofuel production cost distribution (Brown et al., 2020; Visser, Hoefnagels and Junginger, 2020).

Feedstock costs play a major role, with a share ranging 20–60% of biofuel production cost, depending on the pathway. In terms of overall capital cost of biofuel production, these are highly dependent on the process complexity as well as the operation scale (Hamelinck and Faaij, 2006; Patel et al., 2020; Littlewood et al., 2013). The production cost, mainly capital cost, of relatively simple processes, such as solid fuel production (e.g. charcoal, chips and pellets), are less dependent on the economies of scale than more complex processes like those for liquid and gas fuel production (Brown et al., 2020; Visser, Hoefnagels and Junginger, 2020). Therefore, small-, medium- and large-scale systems for solid fuel production have the potential to be economically feasible. In contrast, more advanced technologies (e.g. bioethanol and FT liquids) require large-scale installations and capital investments, as well as large supply chains, for economically feasible business models (Hamelinck and Faaij, 2006; Patel et al., 2020; Littlewood et al., 2013). According to the economies of scale, the capital cost per unit of product is lower for large-scale plants, and the large capital cost of complex technologies can be prohibitive for profitable small-scale business models. **Figure 29** illustrates the effect of plant size on capital costs. The estimates are performed with the exponential estimating method to extrapolate processing plants' cost[11]. The capital costs are estimated based on a large plant producing 50.000 t/year of lignocellulosic ethanol and a capital investment of 120 million euros.

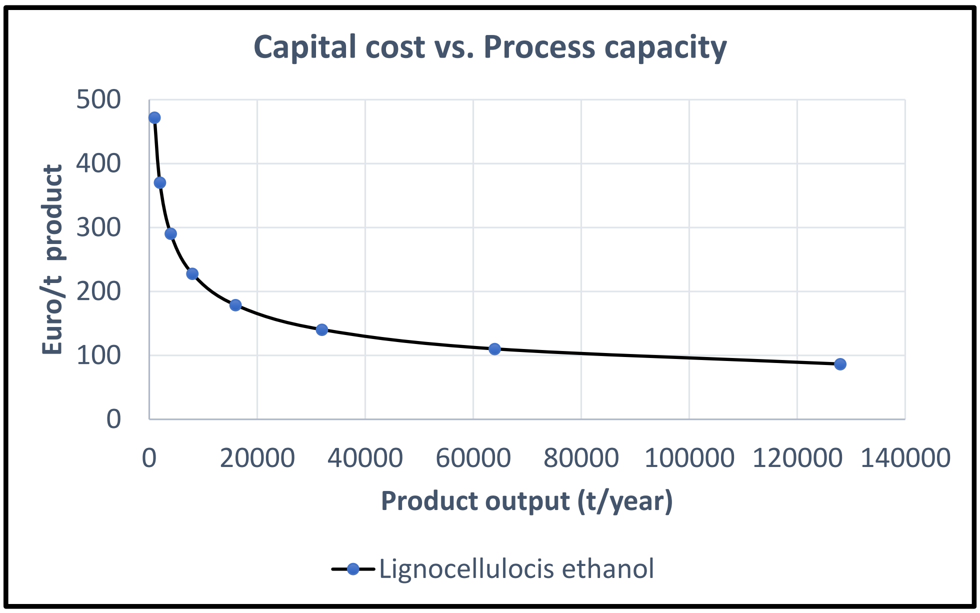


Figure 29. Capital cost vs. production capacity.

The plant capacity also influences the logistics cost (i.e. transport of biomass), which represents an important cost element of biofuel production. A larger factory means the largest feedstock supply areas and, therefore, longer transportation distances. In this context, bamboo exhibits advantages over other biomass crops, due to high crop productivity, which results in lower harvesting area (thus transport distances) required (section 3.1.2). **Figure 30** qualitatively shows the effect of plant capacity on different cost components, such as feedstock transport and capital cost for both biomass and a fossil liquid fuel production.

[11]Used relationship C=Cr*(S/Sr)^n; C – cost at size S; Cr – cost at reference size Sr; n- scale exponent = 0.65

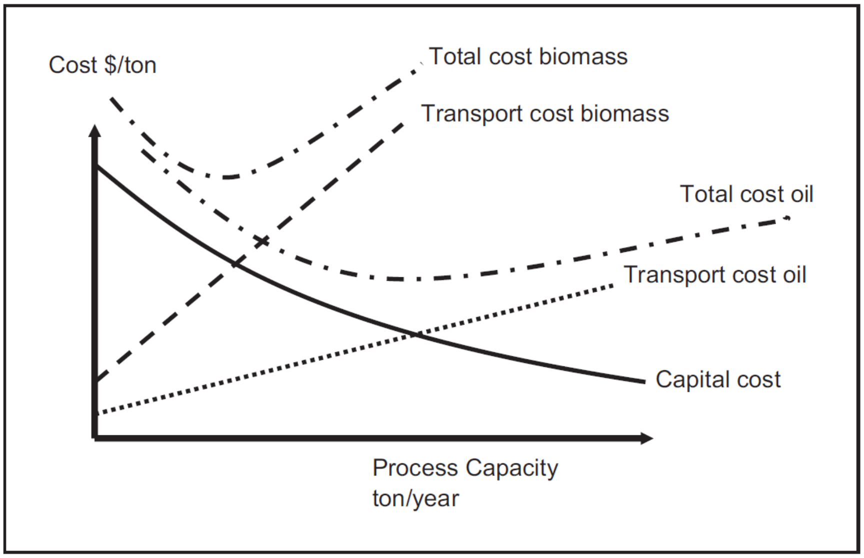


Figure 30. Process capital and transport cost for biocrude oil (Jonker and Harmsen, 2012).

The identified strategies to reduce the costs and improve competitiveness of advanced biofuels include (i) capital cost reduction and (ii) feedstock cost reduction (Brown et al., 2020).

(i) Reducing capital cost of advanced biofuel production is possible through integration with existing refineries. The development of biorefineries is a strategic mechanism for the competitiveness of large-scale biomass value chains. Biorefineries, for the combined production of biofuels and high-quality biomaterials, make optimum use of the raw material potential. The produced biomaterials and biochemicals can be used to expand the value-added chain to be able to offer competitive biofuels on the energy market (Hingsamer and Jungmeier, 2018). The scale of biorefineries is a key challenge, and it is necessary to build on existing infrastructure using the advantage of investments and permits (Ubando, Felix and Chen, 2020).

(ii) In the context of feedstock cost, bamboo is an attractive alternative for advanced biofuel development due to its technical and sustainability characteristics, and the logistic advantages as compared to traditional and alternative feedstocks, such as bioenergy crops and agricultural residues (section 3.3.1). The additional economic benefits of bamboo systems include the possibilities within markets of carbon trading and PES (Grima et al., 2016; Juan and Trinh, 2020; Kiran et al., 2019.). When accounting for the total benefits of bamboo, and depending on the fuel pathway and scale and local conditions, the economy of the complete value chain appears more favourable for bamboo than other alternative biomass resources.

5.1 Cost of bamboo biofuels

Limited information has been documented about the cost of bamboo fuels. Daza Montaňo et al. (2013) reported an overall economic assessment of the import of bamboo pellets from Colombia to the Netherlands, to be used as a coal substitute in the power sector; the estimated potential cost of 18–30 euros/MWh (2012) was found to be competitive with white pellet prices in the EU.

The commercial production of bamboo solid fuels in China is competitive within local markets (Appendix 2). A company produces pellets from bamboo processing residues, at an estimated cost of approximately 25 USD/MWh. Bamboo charcoal cost, in industrial processing in China, is reported to be approximately 40 USD/MWht. For both cases in China, pellets and charcoal, feedstock and transport cost represent approximately 70–80% of the total production cost, followed by electricity (approximately 15–20%) and labour cost, which is 3% in pellet production and 15% in charcoal production (Appendix 2).

Bioethanol production from bamboo is approaching a commercial stage of development in India, with the first biorefinery producing chemicals and ethanol for the local market in a joint venture of biofuel producers and a state-owned Indian oil company (section 4.3.1).

Bamboo biofuel production cost depends on the specific resources (e.g. species and maturity and source of the material), conversion pathway and scale and local conditions (e.g. labour cost, energy, transport cost and policy incentives). *Detailed techno-economic feasibility and sustainability assessments (including LCA) are required to evaluate the total cost and benefits of RE from bamboo, including advanced biofuel production and integrated biorefineries, for both the local and international biofuel market.*

5.2 Residues or bioenergy crop

The development of bamboo supply chains for bioenergy, based either on residual streams or dedicated bioenergy crops, and considering sustainable and selective harvesting practices, have both potential benefits and limitations. **Table 3** presents a qualitative comparison of some relevant aspects among the different alternatives.

Table 3. Potential of residues vs. dedicated bioenergy plantations (Daza Montaňo et al., 2013).

Parameter	**Residue**		**Bioenergy Crop**	**Comments**
	Forest	**Plantation and industries**		
Productivity	+	++	+++	A bioenergy crop/plantation could have higher productivities when best practices of cultivation and management are applied
Current supply potential	++	+	--	Existing area covered/Species
Future potential	++	++	+++	Supply areas
Cost	+	+	++	Main production costs are allocated to the main product
GHG emissions reduction potential	+	+	+++	According to EU methodologies, use of residue accounts emissions from the biomass collection point and doesn't include the crop emissions and carbon stock. While the use of resource from a bioenergy crop includes the high carbon stock of a bamboo system

--Low; + Medium++ High; +++ Very high

The availability and cost of residues depend on the status of the bamboo sector development, as well as the alternative uses and markets of residual streams. In current bamboo processing industries, of the high-value products, residues are approximately 40% of the processed feedstock. The feedstock cost of residues (e.g. sawdust) purchased by pellets and charcoal producers from processing industries in China are approximately 50–90 USD/ t_{dw} (Appendices 1 and 3). Due to the increasing uses of residues in China, price competition is observed, and producers consider it important to develop additional bamboo areas to secure affordable feedstock supply and to not rely on the intermittent supply of residues obtained from other industries.

The current availability of feedstock is limited to regions in which bamboo industries are well established, and other regions, where the bamboo sector is not developed, require strategic approaches to establish and develop competitive biomass supply chains.

As for bioenergy crops, an estimate of potential feedstock cost from a bamboo bioenergy crop could be approximately 50 USD/t_{dw} (at a plant gate) in South America (Daza Montaňo et al., 2013; Korte, 2019). In Indonesia, feedstock from forest is supplied by local communities at a low price of 25 USD/t (Appendix 1).

In terms of GHG emission savings and for the EU market, biofuels obtained from bamboo bioenergy crops have a larger potential than biofuel chains based on residues, due to the accounted high carbon stock of bamboo systems (section 3.3.3). However, in terms of cost, and depending on the local conditions, the production cost of biomass from a dedicated bioenergy crop can be higher than sourcing residual material from forest management and bamboo processing industries.

The feasibility of developing value chains either from residues or from bioenergy crops depends on the local conditions, resource availability and the state of sector development; moreover, multicriteria analysis (techno-economic and sustainability) are required to evaluate alternatives.

6. Strategic integration of bioenergy in the development of bamboo value chains for a circular bioeconomy

6.1 Opportunities

The increasing demand for CO_2 neutral and RE and materials is creating markets that mobilise millions of tons of biomass resources globally, and biomass commodity exchange[12] developments will improve the efficiency of biofuel production. Energy products have a lower market value than non-energy uses, such as materials and chemicals, as depicted in **Figure 31**. However, the market volume of biofuels is very high and offers development and trade possibilities to bamboo-producing countries (van Dam, Elbersen and Daza Montaño, 2018). **Developing bioenergy supply chains can be strategic to give an impulse to the bamboo sector development,** in the short term and in the future, providing incentives for the production of sufficient biomass volumes to access the large global market of biofuel commodities and bamboo products.

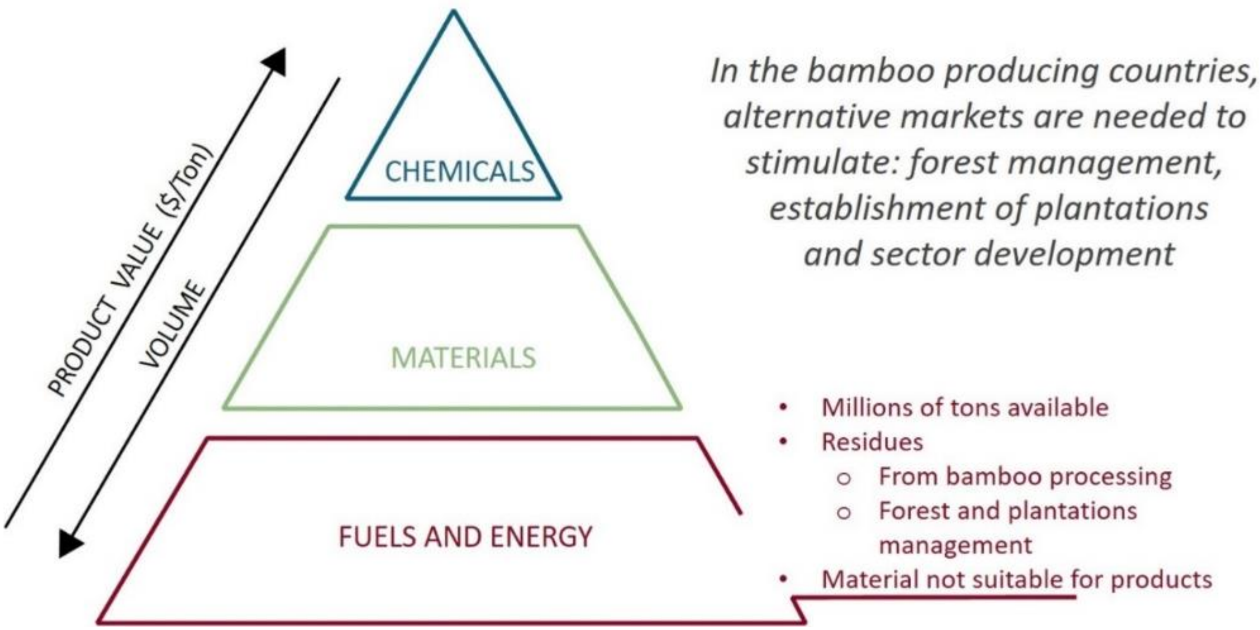


Figure 31. Untapped potential global resource (Daza Montaño, 2020).

Some bamboo producing countries (e.g. Colombia, Brazil, Indonesia, Nigeria and South Africa) are also fuel exporters (e.g. coal and biofuels), and bamboo biofuels offer an opportunity for the development of new supply chains to make their traded fuel portfolio green and diversify it, thereby supporting the ongoing transition from fossil fuels to biofuel trade.

Currently, millions of tons of bamboo resources remain underutilised, and there is a large global potential to establish bamboo plantations, as agro-industrial crops and land restoration alternatives, where bamboo resources can be used for sustainable biofuel production and take a share of the increasing biofuel market (section 2) and within circular bioeconomy development.

The valorisation of bamboo in value-added and low-CO_2 applications directly contributes to circular bioeconomy developments. Bamboo culms, as well as processing side streams, can be converted into a range of value-added products, from bioenergy, biofertilisers to a wide variety of materials (e.g. activated carbon, paper, packaging, composite materials, textiles, construction materials and furniture) and chemicals. Biorefineries, for the combined production of biofuels and high-quality biomaterials, are strategic to improve the competitiveness of biofuels on the energy market.

The industrial production of green chemicals and advanced bamboo-based consumer products will yield significant volumes of by-products that are suitable for energy generation**.** Furthermore, end-of-life bamboo products can be converted into energy, contributing to circular economy development.

6.2 Challenges and the way forward

Bamboo is rarely included in countries' political strategies for socio-economic development, environmental management and to tackle climate change. Some countries (e.g. China, India, Ecuador, Colombia, Peru, Japan, Ethiopia, Ghana, Indonesia, Madagascar, Uganda and Viet Nam) have taken policy measures, while some countries have developed plans and strategies for the bamboo sector development. However, in many countries, the **resources required for the implementation are not allocated**, and hence, the implementation and success of the strategies, programmes and plans are low. Furthermore, **bamboo is often not recognised as an important agricultural and biomass resource for biocommodity production**, and the regulatory framework of some producing countries poses a challenge for the exploitation of bamboo resources at its full potential.

A strategic long-term vision is required for a step-wise development of competitive bamboo value chains within the biobased and circular economy, aiming to produce RE and high-value products, such as flooring, chemicals and materials. **T**he development of the value chain requires multidisciplinary and intersectoral approaches to tackle the legislative restrictions, assess the techno-economic and sustainability issues along the complete value chain and mobilise investment for the chain development.

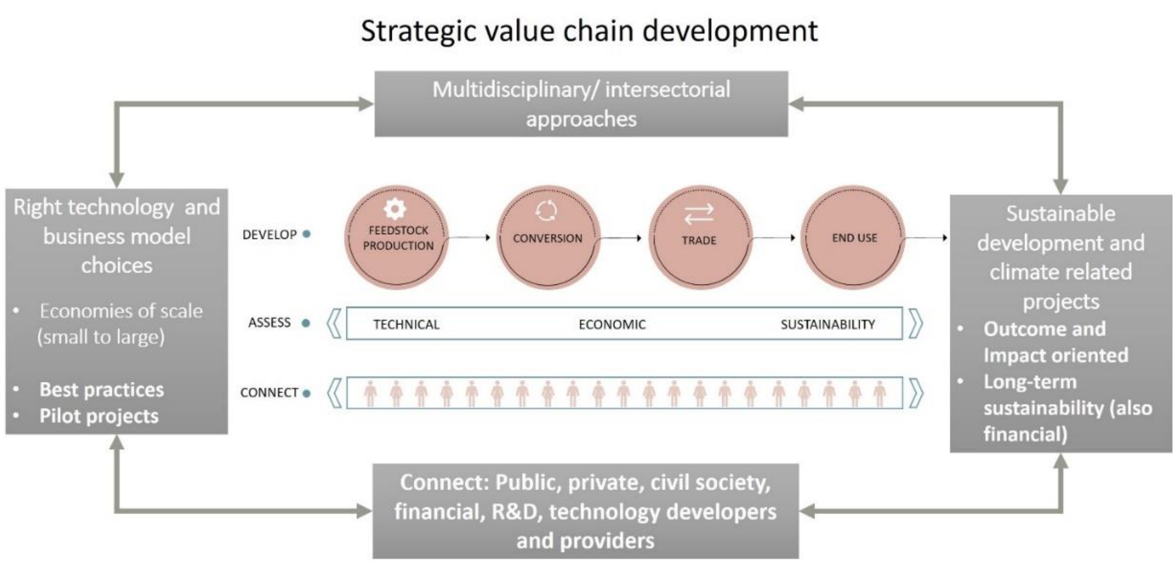


Figure 32. Strategic value chain development.

The following are some key issues for a strategic value chain development (**Figure 32**)

1. Develop bamboo value chains that can supply sufficient volumes of biomass.

A step-wise development of integrated value chains involves initially developing a sufficiently large production volume chain for supply of both local and international bioenergy markets while developing the local capacity to establish competitive processing industries for higher-value application markets. Industrial applications and global commodity trade usually require large-scale production for economically feasible business models. Large quantiles of feedstock supply are required (>20.000 t/year), with often specific high-quality characteristics (e.g. for strip and fibre production or high-end engineered bamboo products). While bioenergy applications are less demanding and require materials with basic characteristics, where lower-quality materials, such as residues from resource management and industrial processing, can be utilised.

The development and transfer of knowledge and technology, as well as local capacity development (pilot and demonstrations), are key to access RE markets (and other biocommodity markets) and to comply with market requirements: quality and sustainability of bamboo products (harvest to end-product), cost and security of supply.

The uptake of bamboo by biomass processors, fuel traders and energy users will provide incentives for supply chain development and trade, for the proper management of existing bamboo resources and for establishing new plantations.

2. Assessment of biomass value chains to develop and adopt proper technologies and business models

Bamboo is a newcomer within the bioenergy commodity trade, which provides an opportunity to implement best practices and lessons learnt from the development of other biomass chains. Detailed techno-economic and sustainability assessments and risk-based approaches are required to evaluate the total cost and benefits of biofuel production from bamboo and to design efficient and sustainable value chains, which are techno-economically viable and sustainable.

3. Mobilise investment, multi-stakeholders and intersectoral partnerships

Due to its multiple uses and potential applications, the development of bamboo value chains offers opportunities to establish strategic partnerships and intersectoral and international cooperation. To mobilise investment for developing sustainable bamboo value chains it is important to remove existing barriers (legislation and techno-economic) and to arrange partnerships of multiple stakeholders from the public and private sectors and civil society.

Therefore, bamboo should be included in national strategies for biocommodity production, for reaching the UN-SDGs and for tackling climate change (within NDC and REDD). Furthermore, the strong cooperation with policy institutions, as well the engagement of the different stakeholders along the complete biomass chain (producers, processors, fuel traders and energy users), is key for the successful development of biomass value chains.

The development of bioenergy value chains can be incentivised in alignment with the SDG agenda in producing countries, through development projects which are impact- and outcome-oriented to allow the long-term sustainability (not only social and environmental but also economic) of project interventions. A strong engagement and cooperation of policy institutions at different levels—as well as the connection of relevant stakeholders along the complete chain, from biomass producers to end users—is required.

Partnerships with the private sector are required, with biofuel processors, existing oil refineries, petrochemical clusters, chemical factories and pulp/sawmills, to produce advanced biofuels, chemicals and materials in integrated business models. Bioenergy is no longer a stand-alone business (Junginger et al., 2019), and integrated value chains, cascading and biorefinery approaches are required for long-term sustainable business models.

The development of bamboo value chains can promote technology development and innovation while integrating local knowledge and creating jobs in producing countries. Partnerships are possible with not only the energy sector but also other sectors, which can support development within their CSR and business innovation strategies, such as the following:

- **Agroindustry, where electricity cogeneration from agricultural residues is established**. Currently, considerable agro-industrial residues (e.g. sugarcane industry and oil palm industry) are used for power co-generation and to dispose of the excess biomass waste. Bamboo can contribute to diversifying the biofuel mix to increase the co-generation capacity of biomass heat and power plants with seasonal input of biomass resources. In this context, when combining the use of residual streams from agroindustry sectors with those of the bamboo sector, the co-generation capacity locally can increase substantially, thus improving not only the economic profitability of the generators but also the reliability and sustainability of the complete bioenergy chain.
- **Energy and emission-intensive industrial sectors (e.g. cement and steel).** Bamboo solid fuels can contribute to diversifying the fuel and raw material portfolio of industries, thus improving the sustainability of related sectors and value chains. Using biomass as a fuel and raw material has the potential to lower the CO_2 emissions from the cement sector (GCCA, 2019; WBCSD, 2011). Bamboo has a high Si content, and the use of agro-waste

ashes, containing considerable Si in amorphous form, holds potential for use as constituents in concrete (Tosti et al., 2021). Replacing a portion of cement raw materials and fuels with bamboo streams can contribute to circular economy developments and achieving targets of CO_2 emission reductions. Furthermore, bamboo systems can be adopted as a restoration alternative by mining industries, within their strategies for quarry rehabilitation and biodiversity management (GCCA, 2020).

Promote R&D with interdisciplinary approaches. Further R&D is required in terms of developing sustainable bamboo production systems suitable strategies and technologies for the logistics, pre-treatment and conversions of bamboo into bioenergy products. Optimising and developing biofuel value chains include the adoption of proper practices and technologies, which can improve the efficiency, cost and sustainability. To this end, multiple disciplines are required.

As bamboo species are numerous and their properties and management practices vary, R&D is required to define priority woody/giant species in producing countries, as well as their specific properties and conversions into fuels. The establishment of bamboo as a commodity requires proper planning and risk-based approaches[13], and the introduction of exotic bamboos in a new area needs preliminary studies to minimise the risks of disturbance of the ecosystem, the forest structure and biodiversity (Buziquia et al., 2019).

Furthermore, sufficient and reliable information from biomass supply areas is a requisite to gain access to international bioenergy commodity markets. The accounting, measuring and monitoring of the sustainability (including LCA) and GHG balances of bamboo systems are required to demonstrate the high potential of bamboo within RE applications.

The long-term development of competitive bamboo value chains requires integrated business models to access markets for bamboo bioenergy and products, as well as carbon markets. The high GHG emission reduction potential of replacing fossil fuels with bamboo fuels, as well as the high carbon storage potential of bamboo forests and plantations, can provide additional economic opportunities within carbon emission trading systems, depending on the carbon markets and

[13] According to REDII, '..operators should take the appropriate steps in order to minimise the risk of using unsustainable forest biomass for the production of bioenergy. To that end, operators should put in place a risk-based approach'.

related incentives. However, though scientific information on bamboo carbon stocks and emissions of bamboo systems exists, integration and accessing benefit from carbon markets are not yet streamlined due to the lack of bamboo-specific carbon methodologies. Therefore, efforts can be made to develop bamboo carbon methodologies and their inclusion at appropriate platforms.

Furthermore, limited information exists on the economics of biofuel production from bamboo as well as bamboo biorefinery concepts. Therefore, research and detailed techno-economic and sustainability analysis, as well as feasibility studies, are required.

The conversion of ***bamboo as sustainable biocommodity*** *for future generations asks for promotion of* ***international cooperation*** *between experts and stakeholders of many disciplines along the* ***supply chain*** (van Dam, 2018)

7. Conclusions

Bamboo is potentially a highly sustainable biomass source and can contribute to domestic and global RE targets, such as those set by the EU within REDII. The development and organisation of sustainable value chains and feedstock diversification are required to effectively deploy biomass supply to growing global bioenergy markets within a circular bioeconomy.

Bamboo bioenergy value chains, for domestic and international markets, have the potential to **comply with market and end users' requirements,** such as (i) security of feedstock supply and scaling-up potential, (ii) technical specifications and (iii) sustainability (economic, social and environmental).

(i) **Bamboo is a resource widely available in the Global South**. If 10% of the estimated global bamboo resources can be economically traded, approximately 50 Mt/year can be produced and play a role in the diversification of the biomass feedstock portfolio. Furthermore, bamboo has a large potential for land restoration and plantation establishment.

(ii) Bamboo can comply with the **technical specifications** for solid biomass fuels, and its properties are superior to those of agricultural residues and similar to those of wood. In addition, bamboo can be converted through biochemical and thermochemical processing into solid, liquid and gaseous fuels. The main advantages of bamboo are the high crop productivities (10–40 t_{dw}/ha/year) and the high biomass densities (300–900 kg/m^3), both highly relevant characteristics for biomass logistics cost and (economic) conversion into bioenergy.

(iii) Bamboo can comply with the **EU sustainability requirements** for biofuels through related recognised forest certification schemes (e.g. FSC and PEFC). The GHG emission savings achieved by replacing fossil fuels with bamboo biofuels can comply with and exceed those required by the EU regulations. Bamboo systems can store a high amount of carbon and produce a feedstock with negative carbon emissions. Establishing new areas with bamboo plantations contributes to carbon sequestration and restoring degraded lands. The carbon-storage potential of bamboo systems can be equivalent, and even double, that of tree plantations. The potential GHG emission reductions of electricity production from bamboo, as compared to coal, have been estimated as 70–300%, depending on the source, ranging from residues to a dedicated bioenergy crop.

Sustainable bamboo value chains can be a strategic contribution to achieving SDG and RE targets of climate change (within NDC and REDD). Bamboo production systems create numerous jobs, and all of the activities in the value chain can be performed and led by women and youth (e.g. establishment of bamboo nurseries and propagation and establishment of plantations, processing, management and marketing), thus providing opportunities for inclusive rural development.

The current commercial status of bamboo conversions into bioenergy mainly relates to solid fuels (e.g. charcoal and pellets), which are commercialised in some countries (e.g. China and Ethiopia). Few applications of gasification exist for rural electrification. Furthermore, power production from bamboo combustion and anaerobic digestion to produce biogas as a transport fuel is at the pilot and demonstration stage, and the commercialisation of bamboo pellets and bioethanol is at the planning stage. The commercial production of bamboo chips for bioenergy applications has not been thoroughly explored and further research is required.

In terms of market opportunities, solid biofuel trade (e.g. chips, pellets and charcoal) is an established and competitive market, while advanced biofuels (e.g. liquid and gas) from lignocellulosic feedstocks are expected to be competitive in the longer term. The large-scale deployment of advanced biofuels largely depends on continuing policy support, including carbon prices, as well as incentives to deploy low-carbon fuels. Charcoal is the most produced solid biofuel globally, and biomass chips are the most traded solid biofuel commodity with growing markets in industrial applications.

Bamboo production chains, which can supply sufficient volumes of biomass for international biocommodity trade, **still need to be developed, and incentives are required**. The uptake of bamboo by biomass processors and energy users will promote the supply chain development and trade, proper management of existing bamboo resources and establishment of new plantations.

8. Recommendations

Bamboo should be included in national policy agendas and strategies to tackle climate change (within NDC and REDD) and to address SDG. Furthermore, bamboo should be recognised as an important agricultural and biomass crop and included in industry strategies to develop sustainable biomass supply chains for bioenergy and biocommodity production.

A long-term vison and a strategic approach are required to develop competitive bamboo supply chains, aiming to produce high-value products, such as housing, flooring, chemicals and materials, food and feed, fertilisers and energy products, in integrated value chains with cascading and biorefinery approaches. Bioenergy production should be part of the development of integrated value chains, as bioenergy products can improve the sector competitiveness through product diversification while creating incentives for sustainable resource establishment and management. A stepwise development of integrated value chains involves initially developing supply chains for large bioenergy and traditional markets, both local and international, while developing the local capacity to establish competitive processing industries for higher-value application markets.

The development of bamboo value chains requires strategic partnerships and intersectoral and international cooperation to remove barriers (legislation and techno-economic), in order to mobilise investment and create access to markets. Partnerships of multiple stakeholders from the public sector, private sector, civil society, research community and academic sector are required. The strong cooperation with policy institutions, as well the engagement of the different stakeholders along the complete biomass chain (producers, processors, fuel traders and energy users), is key for the successful development of biomass value chains.

Partnerships are required not only between stakeholders from the bamboo sector and bioenergy sectors, but also with other industries (e.g. cement and agroindustry), to mobilise investment within industrial strategies of CSR and business innovation.

Partnerships with the research and academic sectors are essential, as multidisciplinary research is required for the detailed assessment (techno-economic and sustainability) and evaluation of the total cost and benefits of biofuel production from bamboo. Further research is required on bamboo biofuel value chains (biomass production, logistics strategies, pre-treatment and conversions technologies), as well as the carbon-sequestration potential and emissions of woody bamboo crop systems, and on the sustainability of associated biofuel value chains. Furthermore, multicriteria analysis, with multidisciplinary research and intersectoral approaches, is required to adopt the proper technologies and design sustainable value chains and bankable business models, as well as to provide sufficient and reliable information from biomass supply areas, which is a requisite to gain access to international biocommodity market.

In the short term, provision of relevant support can be given to bamboo crop production and processing into solid fuels (e.g. charcoal, chips and pellets) for small-, medium-, and large-scale systems and for both local and international markets. Charcoal is the most produced solid biofuel globally; unsustainable charcoal production from forest wood is associated with high GHG emissions, deforestation and environmental degradation, which is highest in the global south. The production of charcoal from bamboo is an opportunity to develop sustainable charcoal value chains from bamboo-producing regions (e.g. Brazil, which is the largest charcoal producer at global scale). Furthermore, wood chips (and pellets) are the most traded fuel globally and their production from bamboo should be further explored and developed.

In the long term, the production of advanced biofuels (e.g. lignocellulosic bioethanol and renewable diesel) is expected to be competitive. Large-scale and biorefinery concepts, as well as partnerships with existing large-scale biomass processors and oil refineries, are required.

The development of bamboo value chains should be incentivised by bamboo-producing countries and international cooperation, through policy agendas and strategies, and with resource allocation for implementation with, for example, the SDG and climate finance mechanisms. Furthermore, local and international cooperation with experts and stakeholders along the supply chain (e.g. fuel traders and biofuel users) is essential to develop robust supply chains and sustainable bamboo biocommodity production for future generations.

References

Akwada, Damenortey R., and Esther T. Akinlabi. 2018. “Bamboo an Alternative Wood to Reducing Tropical Deforestation in Ghana.” In Conference on Infrastructure Development and Investment Strategies for Africa, 1:12.

Alakangas, Eija, Markus Hurskainen, Jaana Laatikainen-Luntama, and Jaana Korhonen. 2016. “Properties of Indigenous Fuels in Finland.” VTT Technology 272.

Aylott, M. J., E. Casella, I. Tubby, N. R. Street, P. Smith, and G. Taylor. 2008. “Yield and Spatial Supply of Bioenergy Poplar and Willow Short-Rotation Coppice in the UK.” New Phytologist 178 (4): 358:370. https://doi.org/10.1111/j.1469-8137.2008.02469.x.

Balduino Junior, Ailton Leonel, Thalles Yurgen Balduino, Gustavo Friederichs, Alexsandro Bayestorff da Cunha, and Martha Andreia Brand. 2016. “Energetic Potential of Bamboo Culms for Industrial and Domestic Use in Southern Brazil.” Ciência Rural 46 (11): 1963:1968. https://doi.org/10.1590/0103-8478cr20160233.

BambooLogic. 2021. “European Bamboo.” 2021.

Banik, Ratan Lal. 2015. “Harvesting Techniques.” In Bamboo: The Plant and Its Uses, edited by Walter Liese and Michael Köhl, 193:226. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-14133-6_7.

Bastin, Jean Francois, Yelena Finegold, Claude Garcia, Danilo Mollicone, Marcelo Rezende, Devin Routh, Constantin M. Zohner, and Thomas W. Crowther. 2019. “The Global Tree Restoration Potential.” Science 365: 76:79. https://doi.org/10.1126/science.aax0848.

Beld, Bert van de. 2018. “Fast Pyrolysis Based Production of Biochemicals & Biomaterials. Biomass Technology Group (BTG).” In 5th Biorizon Annual Event on Bio Aromatics 15 November 2018 / ’s Hertogenbosch, Netherlands.

Berndes, Göran, Annette Cowie, and Luc Pelkmans. 2020. “The Use of Forest Biomass for Climate Change Mitigation: Dispelling Some Misconceptions.” IEA Bioenergy Task 45. https://www.ieabioenergy.com/blog/publications/the-use-of-forest-biomass-for-climate-change-mitigation-dispelling-some-misconceptions/.

Boissiere, M., Beyessa, M., Atmadja, S. 2019. “Guiding Principles for Sustainable Bamboo Forest Management Planning: Benishangul-Gumuz Regional State (BGRS).” FAO. Rome.

Brand, Martha Andreia, Ailton Leonel Balduino Junior, Daniela Leticia Nones, and Angela Zakostelsky Neves Gaa. 2019. “Potential of Bamboo Species for the Production of Briquettes.” Pesquisa Agropecuaria Tropical 49: 1:7. https://doi.org/10.1590/1983-

40632019v4954178.

Brassilbiomassa.com.br. 2020. “Brasil Biomassa Pellets Business.” 2020. https://www.brasilbiomassa.com.br/?lang=en.

Brown, Adam, Lars Waldheim, Ingvar Landälv, Jack Saddler, Mahmood Ebadian, James D. McMillan, Antonio Bonomi, and Bruno Klein. 2020. “Advanced Biofuels – Potential for Cost Reduction.” IEA Bionenergy: Task 41.

BTG Biomass Technology Group BV. 2013. “Charcoal Production from Alternative Feedstocks.” NL Agency, NL Energy and Climate Change.

Buziquia, Sarah Tanganeli, Paulo Victor Freitas Lopes, Aleska Kaufmann Almeida, and Isabel Kaufmann de Almeida. 2019. “Impacts of Bamboo Spreading: A Review.” Biodiversity and Conservation 28: 3695:3711. https://doi.org/10.1007/s10531-019-01875-9.

Camargo García, Juan Carlos, and Thang Long Trinh. 2020. “Assessment of Ecosystem Services from Bamboo-Dominated Natural Forests in the Coffee Region, Colombia.” Inbar. https://www.inbar.int/resources/inbar_publications/assessment-of-ecosystem-services-from-bamboo-dominated-natural-forests-in-the-coffee-region-colombia/.

Camargo, Juan Carlos, José Alexander Rodríguez, and Angela María Arango. 2011. “Crecimiento y Fijación de Carbono En Una Plantación de Guadua En La Zona Cafetera de Colombia.” Recursos Naturales y Ambiente 61: 86:94.

Ceccherini, Guido, Gregory Duveiller, Giacomo Grassi, Guido Lemoine, Valerio Avitabile, Roberto Pilli, and Alessandro Cescatti. 2020. “Abrupt Increase in Harvested Forest Area over Europe after 2015.” Nature 583: 72:96. https://doi.org/10.1038/s41586-020-2438-y.

Chakrabarti, H.C. 2018. “Gasification of Bamboo and Its Waste. As a Feedstock in Updraft Gasifier.” Akshay Urja June: 32:35. https://mnre.gov.in/file-manager/akshay-urja/june-2018/Images/32-35.pdf.

Chang, Chia Chi, Chi Pai Chen, Cheng Shiun Yang, Yen Hau Chen, Michael Huang, Ching Yuan Chang, Je Lueng Shie, et al. 2016. “Conversion of Waste Bamboo Chopsticks to Bio-Oil via Catalytic Hydrothermal Liquefaction Using K2CO3.” Sustainable Environment Research 26: 262:267. https://doi.org/10.1016/j.serj.2016.08.002.

Chempolis. 2020. “Chempolis.” 2020. https://chempolis.com/references/.

Chen, Wei Hsin, Shih Hsien Liu, Tarng Tzuen Juang, Chi Ming Tsai, and Yi Qing Zhuang. 2015. “Characterization of Solid and Liquid Products from Bamboo Torrefaction.” Applied Energy 160: 829:835. https://doi.org/10.1016/j.apenergy.2015.03.022.

Chidumayo, Emmanuel N., and Davison J. Gumbo. 2013. "The Environmental Impacts of Charcoal Production in Tropical Ecosystems of the World: A Synthesis." Energy for Sustainable Development 17 (2): 86–94. https://doi.org/10.1016/j.esd.2012.07.004.

Chin, Kit Ling, Shamsudin Ibrahim, Khalid Rehman Hakeem, Paik San H'ng, Seng Hua Lee, and Mohd Azmi Mohd Lila. 2017. "Bioenergy Production from Bamboo: Potential Source from Malaysia's Perspective." BioResources 12 (3): 6844:6867. https://doi.org/10.15376/biores.12.3.6844-6867.

Cosentino, Salvatore L., Danilo Scordia, Giorgio Testa, Andrea Monti, Efthymia Alexopoulou, and Myrsini Christou. 2018. "The Importance of Perennial Grasses as a Feedstock for Bioenergy and Bioproducts." In Perennial Grasses for Bioenergy and Bioproducts. https://doi.org/10.1016/b978-0-12-812900-5.00001-1.

Cunningham;Michelle, Uffelen; Luke Van, and Chambers;Mark. 2019. "Global Economy The Changing Global Market for Australian Coal." Bulletin – September 2019. 2019. https://www.rba.gov.au/publications/bulletin/2019/sep/the-changing-global-market-for-australian-coal.html.

DAIICHI JITSUGYO CO., LTD. 2019. "Biomass-Based Power Generation through Bamboo." 2019. https://www.djkasiagroup.com/news/detail.php?seq=10.

Dam, Jan E.G. van. 2018. "Bamboo Innovations for Sustainable Biocommodity Development." In Global Bamboo and Rattan Congress (BARC). Beijing, China.

Dam, Jan E.G. van, H. Wolter Elbersen, and Claudia M. Daza Montaño. 2018. "Bamboo Production for Industrial Utilization." In Perennial Grasses for Bioenergy and Bioproducts. https://doi.org/10.1016/b978-0-12-812900-5.00006-0.

Dam, Jan E.G. Van, Barbara De Klerk-Engels, Paul C. Struik, and Rudy Rabbinge. 2005. "Securing Renewable Resource Supplies for Changing Market Demands in a Bio-Based Economy." Industrial Crops and Products 21 (1): 129–44. https://doi.org/10.1016/j.indcrop.2004.02.003.

Dam, Jan E.G. Van, Koen Meesters, H. Wolter Elbersen, Bert Annevelink, and Harriette L. Bos. 2019. "Bioresources and Biocommodities for the Global Bioeconomy." In Lignocellulose for Future Bioeconomy, 287:300. https://doi.org/10.1016/B978-0-12-816354-2.00015-3.

Daza-Montaño, C. M, J R Pels, L E Fryda, and Robin Zwart. 2012. "Evaluation of Torrefied Bamboo for Sustainable Bioenergy Production." In 9th World Bamboo Congress. Antwerp, Belgium.

Daza Montaňo, C.M., R. Zwart, J.C. Camargo, R. Diaz-Chavez, X. Londoňo, L. Fryda, A. Janssen, et al. 2013. "Torrefied Bamboo for the Import of Sustainable Biomass from Colombia. Project Report. ECN-E--15-020."

Daza Montaño, Claudia M. 2020. "Retos y Oportunidades Del Uso Del Bambú Como Energía Renovable. Bamboo: Challenges and Potential for Renewable Energy." Webinar. INBAR. 2020. https://www.inbar.int/es/8-bambu-webinar-inbar-el-bambu-para-la-bioenergia.

Dolom, Priscila C, Aresna B Palacpac, Hanna Leen, L Capinpin, Noel L Tolentino, Ma Magdalena, B Villanueva, et al. 2019. "An Enabling Policy for a More Vibrant Philippine Bamboo Industry." Ecosystems and Development Journal 9 (1&2): 37–44. www.edjournal.cfnr-uplb.org.

Drawdown.org. 2019. "Bamboo Production." Https://Www.Drawdown.Org/Solutions/Land-Use/Bamboo. 2019. https://www.drawdown.org/solutions/land-use/bamboo.

Düking, Raimund, Johan Gielis, and Walter Liese. 2011. "Carbon Flux and Carbon Stock in a Bamboo Stand and Their Relevance for Mitigating Climate Change." Bamboo Science and Culture 24 (1): 1–6.

Durai, J, and T T Long. 2019. "Manual for Sustainable Managemenet of Clumping Bamboo Forest." INBAR, no. 41. https://www.inbar.int/resources/search/?resource-type=all&keyword=harvesting.

E4tech. 2018. "Report on Market and Industrial Development Intelligence for Sustainable Advanced Biofuels. Final Report." https://platformduurzamebiobrandstoffen.nl/wp-content/uploads/2020/02/JRC_Final_Report_Public.pdf.

EPC. 2021. "European Wood Pellet Consumption." 2021. https://epc.bioenergyeurope.org/about-pellets/pellets-statistics/european-consumption/.

FAO. 2020a. "Global Forest Resources Assessment 2020. Main Report." Global Forest Resources Assessment 2020. Rome. https://doi.org/10.4060/ca9825en.

FAO. 2020b. "Sustainable Charcoal Production for Food Security and Forest Landscape Restoration." http://www.fao.org/3/ca7967en/ca7967en.pdf.

FAO. 2021. "Forestry Production and Trade." FAOSTAT. http://www.fao.org/faostat/en/#data/FO.

Fei, Benhua, Zhijia Liu, Zehui Jiang, Zhiyong Cai, Xing'e Liu, and Yan Yu. 2013. "Mechanical Properties of Moso Bamboo Treated with Chemical Agents." *Wood and Fiber Science* 45 (1): 34–41.

Ferreira, Evandro, Risto Kalliola, and Kalle Ruokolainen. 2020. "Bamboo, Climate Change and Forest Use: A Critical Combination for Southwestern Amazonian Forests?" *Ambio* 49: 1353–

63. https://doi.org/10.1007/s13280-019-01299-3.

Fritsche;, Uwe R., Christiane Hennig, J. Richard Hess;, Ric Hoefnagels;, Patrick Lamers;, Chenlin Li;, Olle Olsson;, et al. 2019. "Margin Potential for a Long- Term Sustainable Wood Pellet Supply Chain. IEA Bioenergy Task 40." https://www.ieabioenergy.com/blog/publications/new-publication-margin-potential-for-a-long-term-sustainable-wood-pellet-supply-chain/.

Fryda, Lydia, Claudia Daza, Jan Pels, Arno Janssen, and Robin Zwart. 2014. "Lab-Scale Co-Firing of Virgin and Torrefied Bamboo Species Guadua Angustifolia Kunth as a Fuel Substitute in Coal Fired Power Plants." *Biomass and Bioenergy* 65: 28–41. https://doi.org/10.1016/j.biombioe.2014.03.044.

Funke, Alex; Dahmen, Nicolas. 2020. "Direct Thermochemical Liquefaction Characteristics , Processes and Technologies Characteristics , Processes and Technologies. IEA Bioenergy: Task 34." https://doi.org/10.5445/IR/1000120883.

Fusco, L. De, F. Defoort, R. Rajczyk, H. Jeanmart, J. Blondeau, and F. Contino. 2016. "Ash Characterization of Four Residual Wood Fuels in a 100 KWth Circulating Fluidized Bed Reactor Including the Use of Kaolin and Halloysite Additives." *Energy and Fuels* 30 (10): 8304–15. https://doi.org/10.1021/acs.energyfuels.6b01784.

Gangwar, Tarun, and Dominik Schillinger. 2019. "Microimaging-Informed Continuum Micromechanics Accurately Predicts Macroscopic Stiffness and Strength Properties of Hierarchical Plant Culm Materials." *Mechanics of Materials* 130: 39–57. https://doi.org/10.1016/j.mechmat.2019.01.009.

Gauli;, Kalyan, Jayaraman Durai;, and Nellie Odour. 2018. "Value Chain Analysis and Market Assessment of Bamboo Products in Kenya." INBAR. https://www.inbar.int/resources/inbar_publications/kenya-value-chain-analysis-and-market-assessments-of-bamboo-products/.

Gauthier, G., I. Avagianos, C. Calderón, and B. Vaskyte. 2020. "Bioenergy Europe. Statistical Report 2020." https://bioenergyeurope.org/article/268-pellet.html.

Gawande, Abhishek R. n.d. "The Wicked Problem of Sustainable Bamboo." *Economic & Political Weekly* 56 (12): 10. https://www.epw.in/engage/article/wicked-problem-sustainable-bamboo-management.

GCCA. 2019. "GCCA Sustainability Guidelines for Co-Processing Fuels and Raw Materials in Cement Manufacturing." Global Cement and Concrete Association GCCA.

GCCA. 2020. “GCCA Sustainability Guidelines for Quarry Rehabilitation and Biodiversity Management May 2020.” Global Cement and Concrete Association GCCA.

Grima, Nelson, Simron J. Singh, Barbara Smetschka, and Lisa Ringhofer. 2016. “Payment for Ecosystem Services (PES) in Latin America: Analysing the Performance of 40 Case Studies.” *Ecosystem Services* 17: 24–32. https://doi.org/10.1016/j.ecoser.2015.11.010.

Hamelinck, Carlo N., and André P.C. Faaij. 2006. “Outlook for Advanced Biofuels.” *Energy Policy* 34: 3268–83. https://doi.org/10.1016/j.enpol.2005.06.012.

He, Ming Xiong, Jing Li Wang, Han Qin, Zong Xia Shui, Qi Li Zhu, Bo Wu, Fu Rong Tan, et al. 2014. “Bamboo: A New Source of Carbohydrate for Biorefinery.” *Carbohydrate Polymers* 111: 645–54. https://doi.org/10.1016/j.carbpol.2014.05.025.

Henderson, Jill. 2018. “America’s Native Bamboo.” 2018. https://www.ecofarmingdaily.com/grow-crops/grow-fruits-vegetables/fruit-and-vegetable-planting/americas-native-bamboo/.

Henke, Jan. 2018. “Feedstock Classification , Its Implications and Double Counting in EU Member States.” ISCC. https://www.iscc-system.org/wp-content/uploads/2018/01/Feedstock-Classification-its-Implications-and-Double-Counting-in-EU-Member-States.pdf.

Hingsamer, Maria, and Gerfried Jungmeier. 2018. “Biorefineries.” In *The Role of Bioenergy in the Emerging Bioeconomy: Resources, Technologies, Sustainability and Policy*. https://doi.org/10.1016/B978-0-12-813056-8.00005-4.

Hong, Chuntao, Jia Fang, Aiwu Jin, Jianguo Cai, Haipeng Guo, Junxia Ren, Qianjun Shao, and Bingsong Zheng. 2011. “Comparative Growth, Biomass Production and Fuel Properties Among Different Perennial Plants, Bamboo and Miscanthus.” *Botanical Review* 77 (3): 197–207. https://doi.org/10.1007/s12229-011-9076-x.

IEA. 2019a. “Ensure Sustainability.” Tracking Transport. 2019. https://www.iea.org/reports/tracking-transport-2019/transport-biofuels.

IEA. 2019b. “Renewables 2019 – Analysis - IEA.” *International Energy Agency*, 204. https://www.iea.org/reports/renewables-2019.

IEA. 2020a. “IEA (2020), Coal Information: Overview.” IEA, Paris. 2020. https://www.iea.org/reports/coal-information-overview.

IEA. 2020b. “Key-World-Energy-Statistics-2020/Prices.” 2020. https://www.iea.org/reports/key-world-energy-statistics-2020/prices.

INBAR. 2015a. “Inbar Position Paper. Bamboo, Rattan and the UN Framework Convention on Climate Change.” *INBAR*. https://www.inbar.int/resources/inbar_publications/inbar-position-paper-bamboo-rattan-the-convention-on-climate-change/.

INBAR. 2015b. “Inbar Position Paper. Bamboo Rattan and the SDGs.” *International Network for Bamboo & Rattan*. https://resource.inbar.int/download/showdownload.php?lang=cn&id=167790.

INBAR. 2017. “Dutch-Sino-East Africa Bamboo Development Programme.” INBAR. https://www.inbar.int/project/dutch-sino-east-africa-bamboo-development-project/.

INBAR. 2019a. “Bamboo and Climate Change: Fact Sheet.” INBAR. https://www.inbar.int/resources/inbar_publications/bamboo-and-climate-change-fact-sheet/.

INBAR. 2019b. “Bamboo as a Source of Bioenergy: Fact Sheet.” *INBAR*. https://www.inbar.int/resources/inbar_publications/bamboo-as-a-source-of-bioenergy-fact-sheet/.

INBAR. 2019c. “Understanding Bamboo’s Ecosystem Services.” Understanding Bamboo’s Ecosystem Services. 2019. https://www.inbar.int/understanding-bamboos-ecosystem-services/.

Jayaraman, Durai;, Fiker; Assefa, Seyoum; Assefa, Fu; Jinhe, Tesfaye; Hunde, Wondimangegn; Bekele, Zerihun; Tsigaye, Selim; Reza, and Biruk Kebede. 2018. “Value Chain Analysis and Market Assessment of Bamboo Products in Ethiopia.” INBAR. https://www.inbar.int/resources/inbar_publications/ethiopia-value-chain-analysis-and-market-assessments-of-bamboo-products/.

Jeffery, Simon, Diego Abalos, Marija Prodana, Ana Catarina Bastos, Jan Willem Van Groenigen, Bruce A. Hungate, and Frank Verheijen. 2017. “Biochar Boosts Tropical but Not Temperate Crop Yields.” *Environmental Research Letters* 12 (053001): 6.

Jiang Hua, X, and Y XiaoSheng. 2001. “Transfer of Technology Model (TOTEM).” INBAR.

Johnson, Eric. 2019. “Process Technologies and Projects for BiOLPG.” *Energies* 12 (250): 29. https://doi.org/10.3390/en12020250.

Jonker, Gerald, and Jan Harmsen. 2012. “Creating Design Solutions.” In *Engineering for Sustainability*, 61–81. https://doi.org/10.1016/b978-0-444-53846-8.00004-4.

Jung, Su Hwa, Bo Sung Kang, and Joo Sik Kim. 2008. “Production of Bio-Oil from Rice Straw and Bamboo Sawdust under Various Reaction Conditions in a Fast Pyrolysis Plant Equipped with a Fluidized Bed and a Char Separation System.” *Journal of Analytical and Applied Pyrolysis* 82: 240–47. https://doi.org/10.1016/j.jaap.2008.04.001.

Junginger, Hans Martin, Thuy Mai-Moulin, Vassilis Daioglou, Uwe Fritsche, Ruben Guisson, Christiane Hennig, Daniela Thrän, et al. 2019. "The Future of Biomass and Bioenergy Deployment and Trade: A Synthesis of 15 Years IEA Bioenergy Task 40 on Sustainable Bioenergy Trade." *Biofuels, Bioproducts and Biorefining* 13: 247–66.

Kadivar, Marzieh, Christian Gauss, Gonzalo Mármol, Adriana Dominique de Sá, Carlos Fioroni, Khosrow Ghavami, and Holmer Savastano. 2019. "The Influence of the Initial Moisture Content on Densification Process of D. Asper Bamboo: Physical-Chemical and Bending Characterization." *Construction and Building Materials* 229 (116896): 12. https://doi.org/10.1016/j.conbuildmat.2019.116896.

Kantarelis, Efthymios, Junli Liu, Weihong Yang, and Wlodzimierz Blasiak. 2010. "Sustainable Valorization of Bamboo via High-Temperature Steam Pyrolysis for Energy Production and Added Value Materials." *Energy and Fuels* 24: 6142–50. https://doi.org/10.1021/ef100875g.

Kiel, Jaap. 2019. "Overview of Biomass Gasification for Energy Products." In *European Biomass Conference & Exhibition EUBCE 2019, Lisbon Portugal, 28 May 2019*.

Kiran, Paudyal, Bhandari Anil, Adhikari Shankar, Birhane Emiru, Sharma Sunil, Darcha Girmay, Samsudin Yusuf B., Thang Long Trinh, and Raj Paudyal Bijaya. 2019. "Framework for Assessing Ecosystem Services from Bamboo Forests." CIFOR. https://www.cifor.org/knowledge/publication/7433/.

Kolawole, F.O., A.M. Rees, G.A. Etuk-Udo, Shola Odusunya, and W.O. Soboyejo. 2015. "Effects of Pre-Treatment on Lignocellulosic Butanol as a Bio-Fuel Produced from Bamboo Using Clostridium Acetobutylicum." *Advanced Materials Research* 1132: 295–312. https://doi.org/10.4028/www.scientific.net/amr.1132.295.

Korte, Guilherme. 2019. "Personal Communication Guilherme Korte. President at Brazilian Bamboo Producers Association."

Kumar, Sanjeev, Lohit K.S. Gujjala, and Rintu Banerjee. 2017. "Simultaneous Pretreatment and Saccharification of Bamboo for Biobutanol Production." *Industrial Crops and Products* 101: 21–28. https://doi.org/10.1016/j.indcrop.2017.02.028.

Lewis, Simon L., Edward T.A. Mitchard, Colin Prentice, Mark Maslin, and Ben Poulter. 2019. "Comment on 'The Global Tree Restoration Potential.'" *Science* 366 (6463). https://doi.org/10.1126/science.aaz0388.

Li, X. B., T. F. Shupe, G. F. Peter, C. Y. Hse, and T. L. Eberhardt. 2007. "Chemical Changes with Maturation of the Bamboo Species Phyllostachys Pubescens." *Journal of Tropical Forest Science* 19 (1): 6–12.

Liese, W. 1985. “Anatomy and Properties of Bamboo.” *Bamboo Workshop Hangzhou*, 196–393. http://www.inbar.int/publication/PDF/INBAR_PR_03_1.pdf.

Liese, Walter. 2009. “Bamboo as Carbon Sink-Fact or Fiction?*.” *Journal of Bamboo and Rattan* 8 (3–4): 103–14.

Liese, Walter, and Thi Kim Hong Tang. 2015a. “Preservation and Drying of Bamboo.” In *Bamboo: The Plant and Its Uses*. https://doi.org/10.1007/978-3-319-14133-6_9.

Liese, Walter, and Thi Kim Hong Tang. 2015b. “Properties of the Bamboo Culm.” In *Bamboo: The Plant and Its Uses*, 227–56. https://doi.org/10.1007/978-3-319-14133-6_8.

Lin, Jessie, Saurabh Gupta, Tim K. Loos, and Regina Birner. 2019. “Opportunities and Challenges in the Ethiopian Bamboo Sector: A Market Analysis of the Bamboo-Based Value Web.” *Sustainability* 11 (6): 1644. https://doi.org/10.3390/su11061644.

Littlewood, Jade, Lei Wang, Colin Turnbull, and Richard J. Murphy. 2013. “Techno-Economic Potential of Bioethanol from Bamboo in China.” *Biotechnology for Biofuels* 6 (173): 13. https://doi.org/10.1186/1754-6834-6-173.

Liu, Yi Hung, and Tian Ming Yen. 2021. “Assessing Aboveground Carbon Storage Capacity in Bamboo Plantations with Various Species Related to Its Affecting Factors across Taiwan.” *Forest Ecology and Management* 481 (August 2020): 7. https://doi.org/10.1016/j.foreco.2020.118745.

Liu, Zhijia, Wanhe Hu, Zehui Jiang, Bingbing Mi, and Benhua Fei. 2016. “Investigating Combustion Behaviors of Bamboo, Torrefied Bamboo, Coal and Their Respective Blends by Thermogravimetric Analysis.” *Renewable Energy* 87: 346–52. https://doi.org/10.1016/j.renene.2015.10.039.

Lobovikov, Maxim, Yiping Lou, Dieter Schoene, and Raya Widenoja. 2009. “The Poor Man’s Carbon Sink. Bamboo in Climate Change and Poverty Alleviation.” https://agris.fao.org/agris-search/search.do?recordID=XF2006442295.

Lugt, Pablo Van der, Trinh ThangLong, and Charlotte King. 2018. “Carbon Sequestration and Carbon Emissions Reduction through Bamboo Forests and Products,” 28. https://www.inbar.int/resources/inbar_publications/carbon-sequestration-and-carbon-emissions-reduction-through-bamboo-forests-and-products/.

Ma, Zhongqing, Yu Zhang, Yunfang Shen, Junhao Wang, Youyou Yang, Wenbiao Zhang, and Shurong Wang. 2019. “Oxygen Migration Characteristics during Bamboo Torrefaction Process Based on the Properties of Torrefied Solid, Gaseous, and Liquid Products.” *Biomass* *and Bioenergy* 128 (105300): 11. https://doi.org/10.1016/j.biombioe.2019.105300.

Mai-Moulin, Thuy, Lotte Visser, Kevin R. Fingerman, Wolter Elbersen, Berien Elbersen, Gert Jan Nabuurs, Uwe R. Fritsche, et al. 2019. "Sourcing Overseas Biomass for EU Ambitions: Assessing Net Sustainable Export Potential from Various Sourcing Countries." *Biofuels, Bioproducts and Biorefining* 13: 293–324. https://doi.org/10.1002/bbb.1853.

Malico, Isabel, Ricardo Nepomuceno Pereira, Ana Cristina Gonçalves, and Adélia M.O. Sousa. 2019. "Current Status and Future Perspectives for Energy Production from Solid Biomass in the European Industry." *Renewable and Sustainable Energy Reviews* 112: 960–77. https://doi.org/10.1016/j.rser.2019.06.022.

Mizuta, Kei, Toshitatsu Matsumoto, Yasuo Hatate, Keiichi Nishihara, and Tomoki Nakanishi. 2004. "Removal of Nitrate-Nitrogen from Drinking Water Using Bamboo Powder Charcoal." *Bioresource Technology* 95: 255–57. https://doi.org/10.1016/j.biortech.2004.02.015.

Nabukalu, Catherine, and Reto Gieré. 2019. "Charcoal as an Energy Resource: Global Trade, Production and Socioeconomic Practices Observed in Uganda." *Resources* 8 (183): 27. https://doi.org/10.3390/RESOURCES8040183.

Nuamah, A., A. Malmgren, G. Riley, and E. Lester. 2012. "Biomass Co-Firing." In *Comprehensive Renewable Energy*, 5:55–73. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-087872-0.00506-0.

Nzihou, Ange, Brian Stanmore, and Patrick Sharrock. 2013. "A Review of Catalysts for the Gasification of Biomass Char, with Some Reference to Coal." *Energy* 58: 305–17. https://doi.org/10.1016/j.energy.2013.05.057.

O' Connell, Adrian Parker;, Matteo; Prussi, Monica; Padella, Aikaterini; Konti, and Laura Lonza. 2019. "Sustainable Advanced Biofuels. Technology Market Report." https://doi.org/10.2760/487802.

Obernberger, Ingwald, Friedrich Biedermann, Walter Widmann, and Rudolf Riedl. 1997. "Concentrations of Inorganic Elements in Biomass Fuels and Recovery in the Different Ash Fractions." *Biomass and Bioenergy* 12 (3): 211–24. https://doi.org/10.1016/S0961-9534(96)00051-7.

Patel, Beena, Akash Patel, Bharat Gami, and Pankaj Patel. 2020. "Energy Balance, GHG Emission and Economy for Cultivation of High Biomass Verities of Bamboo, Sorghum and Pearl Millet as Energy Crops at Marginal Ecologies of Gujarat State in India." *Renewable Energy* 148: 816–23. https://doi.org/10.1016/j.renene.2019.10.167.

Pavlenko, Nikita. 2018. "Failure to Launch: Why Advanced Biorefineries Are So Slow to Ramp Up Production." 2018. https://theicct.org/blog/staff/failure-to-launch-biorefineries-slow-ramp-up.

Proskurina, Svetlana. 2018. "International Trade in Biomass for Energy Production: The Local and Global Context." Lappeenranta University of Technology. https://lutpub.lut.fi/handle/10024/158444.

Prosperity Bamboo. 2021. "Prosperity Bamboo." 2021. https://www.prosperitybamboo.com/.

Rocha, Elém Patrícia Alves, Ekaterina Sermyagina, Esa Vakkilainen, Jorge Luiz Colodette, Idalmo Montenegro de Oliveira, and Marcelo Cardoso. 2017. "Kinetics of Pyrolysis of Some Biomasses Widely Available in Brazil." *Journal of Thermal Analysis and Calorimetry* 130: 1445–54. https://doi.org/10.1007/s10973-017-6138-2.

Rousset, Patrick, Clarissa Aguiar, Nicole Labbé, and Jean Michel Commandré. 2011. "Enhancing the Combustible Properties of Bamboo by Torrefaction." *Bioresource Technology* 102: 8225–31. https://doi.org/10.1016/j.biortech.2011.05.093.

Runge, Troy M., and Scott Paul. 2015. "Desilication of Bamboo for Pulp Production." *Tappi Journal* 14 (11): 743–49. https://doi.org/10.32964/tj14.11.743.

Salakka, Jaakko. 2014. "Identifying Appropriate Small Scale Harvesting Technologies for Commercial Scale Bamboo Fuel." Karelia University Of Applied Sciences.

Sánchez, Javier, María Dolores Curt, Nicolas Robert, and Jesús Fernández. 2018. "Biomass Resources." In *The Role of Bioenergy in the Emerging Bioeconomy: Resources, Technologies, Sustainability and Policy*, 25–111. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813056-8.00002-9.

Sathitsuksanoh, Noppadon, Zhiguang Zhu, and Y. H Percival Zhang. 2012. "Cellulose Solvent- and Organic Solvent-Based Lignocellulose Fractionation Enabled Efficient Sugar Release from a Variety of Lignocellulosic Feedstocks." *Bioresource Technology* 117: 228–33. https://doi.org/10.1016/j.biortech.2012.04.088.

SBP. 2020. "Sustainable Biomass Program." 2020. https://sbp-cert.org/about-us/.

Schneider, D., M. Escala, K. Supawittayayothin, and N. Tippayawong. 2011. "Characterization of Biochar from Hydrothermal Carbonization of Bamboo." *International Journal of Energy and Environment* 2 (4): 647–52.

Scurlock, J. M.O., D. C. Dayton, and B. Hames. 2000. "Bamboo: An Overlooked Biomass Resource?" *Biomass and Bioenergy* 19: 229–44. https://doi.org/10.1016/S0961-9534(00)00038-6.

Searchinger, Timothy D., Tim Beringer, Bjart Holtsmark, Daniel M. Kammen, Eric F. Lambin, Wolfgang Lucht, Peter Raven, and Jean Pascal van Ypersele. 2018. "Europe's Renewable Energy Directive Poised to Harm Global Forests." *Nature Communications* 9 (3741): 4. https://doi.org/10.1038/s41467-018-06175-4.

Shanmughavel, P., and K. Francis. 2002. "The Dynamics of Biomass and Nutrients in Bamboo (Bambusa Bambos) Plantations." *Journal of Bamboo and Rattan* 1 (2): 157–70. https://doi.org/10.1163/156915902760181621.

Sharma, Roshan, Jaya Wahono, and Himlal Baral. 2018. "Bamboo as an Alternative Bioenergy Crop and Powerful Ally for Land Restoration in Indonesia." *Sustainability* 10 (4367): 1–10. https://doi.org/10.3390/su10124367.

Shojaeiarani, Jamileh, Dilpreet S. Bajwa, and Sreekala G. Bajwa. 2019. "Properties of Densified Solid Biofuels in Relation to Chemical Composition, Moisture Content, and Bulk Density of the Biomass." *BioResources* 14 (2): 4996–5015. https://doi.org/10.15376/biores.14.2.Shojaeiarani.

Slupska, Margaret, and Dave Bushong. 2019. "Lessons from Commercialization of Cellulosic Ethanol – A POET Perspective." *Biofuels, Bioproducts and Biorefining* 13: 857–59. https://doi.org/10.1002/bbb.2033.

Sweygers, N., M. Somers, and L. Appels. 2018. "Optimization of Hydrothermal Conversion of Bamboo (Phyllostachys Aureosulcata) to Levulinic Acid via Response Surface Methodology." *Journal of Environmental Management* 219: 95–102. https://doi.org/10.1016/j.jenvman.2018.04.105.

Tambe, Sandeep, Suprava Patnaik, Anup P. Upadhyay, Advait Edgaonkar, Rekha Singhal, Jigyasa Bisaria, Pankaj Srivastava, et al. 2020. "Evidence-Based Policy for Bamboo Development in India: From 'Supply Push' to 'Demand Pull.'" *Forest Policy and Economics* 116 (February): 102187. https://doi.org/10.1016/j.forpol.2020.102187.

Temmerman, M;, F. Van Belle, J. Delcarte, J Gielis, and V. Brias. 2005. "Bamboo as a Source of Bioenergy. Technical Paper." *Centre Wallon de Recherches Agronomiques*. https://doi.org/10.13140/RG.2.1.5049.5608.

The Mainichi. 2019. "Bamboo Burned as Biomass Fuel in Southwestern Japan Experiment." 2019. https://mainichi.jp/english/articles/20191102/p2a/00m/0na/021000c.

Tonn, Bettina, Ulrich Thumm, Iris Lewandowski, and Wilhelm Claupein. 2012. "Leaching of Biomass from Semi-Natural Grasslands - Effects on Chemical Composition and Ash High-

Temperature Behaviour." *Biomass and Bioenergy* 36: 390–403. https://doi.org/10.1016/j.biombioe.2011.11.014.

Tosti, Lorenzo, André van Zomeren, Jan R. Pels, and Rob N.J. Comans. 2021. "Evaluating Biomass Ash Properties as Influenced by Feedstock and Thermal Conversion Technology towards Cement Clinker Production with a Lower Carbon Footprint." *Waste and Biomass Valorization* 12: 4703–19. https://doi.org/10.1007/s12649-020-01339-0.

Ubando, Aristotle T., Charles B. Felix, and Wei Hsin Chen. 2020. "Biorefineries in Circular Bioeconomy: A Comprehensive Review." *Bioresource Technology* 299: 122585. https://doi.org/10.1016/j.biortech.2019.122585.

Vilela, C. F.Mourao, and P. Abelha. 2019. "Pneumatic Transport of Torrefied Biomass in Dilute and Dense Phase." In *27th European Biomass Conference and Exhibition Proceedings*, 624–29. Lisbon, Portugal. https://doi.org/10.5071/27thEUBCE2019-2DO.7.3.

Visser, L., R. Hoefnagels, and M. Junginger. 2020. "Wood Pellet Supply Chain Costs – A Review and Cost Optimization Analysis." *Renewable and Sustainable Energy Reviews* 118: 109506. https://doi.org/10.1016/j.rser.2019.109506.

Vorontsova, Maria S.;, L. G.; Clark, John Dransfield, Rafael Govaerts, Tim Wikinson, and William J. Baker. 2016. "World Atlas of Bamboos Rattans." Beijing, China.: INBAR.

Wahono, Jaya. 2019. "Personal Communication with Jaya Wahono. CEO Clean Power Indonesia."

Wang, Hankun; Chen, Hong; Zhang, Rong; Liu, Xinge; Jayaraman, Durai. 2019. "Properties of East African Bamboo." *INBAR Working Paper No. 80*.

Wang, Liang, Johan E. Hustad, Øyvind Skreiberg, Geir Skjevrak, and Morten Grønli. 2012. "A Critical Review on Additives to Reduce Ash Related Operation Problems in Biomass Combustion Applications." *Energy Procedia* 20: 20–29. https://doi.org/10.1016/j.egypro.2012.03.004.

Wang, Wei, Qi Yang, Shuangshuang Zheng, and Donglei Wu. 2013. "Anaerobic Membrane Bioreactor (AnMBR) for Bamboo Industry Wastewater Treatment." *Bioresource Technology* 149: 292–300. https://doi.org/https://doi.org/10.1016/j.biortech.2013.09.068.

WBA. 2019. "Global Bioenergy Statistics 2019 World Bioenergy Association," 58. https://worldbioenergy.org/uploads/191129 WBA GBS 2019_HQ.pdf.

WBCSD. 2011. "The Cement Sustainable Initiative. Climate Actions" 2011 (4th of October). http://www.wbcsd.org/templates/TemplateWBCSD5/layout.asp?type=p&MenuId=MTQ5MQ&doOpen=1&ClickMenu=LeftMenu.

Wegst, Ulrike G.K., Hao Bai, Eduardo Saiz, Antoni P. Tomsia, and Robert O. Ritchie. 2015. "Bioinspired Structural Materials." *Nature Materials* 14: 23–36. https://doi.org/10.1038/nmat4089.

Wei, Jin, and Xuan Taotao. 2020. "Bamboo Briquette Charcoal and Biomass Pellet Production Units in Zhejiang, China. Bamboo for Smallholder Income and Energy Security." July 2020/INBAR Webinar Session 2.4.

Wei, Yi, Chaoyue Shen, Jiale Xie, and Quan Bu. 2020. "Study on Reaction Mechanism of Superior Bamboo Biochar Catalyst Production by Molten Alkali Carbonates Pyrolysis and Its Application for Cellulose Hydrolysis." *Science of the Total Environment* 712: 136435. https://doi.org/10.1016/j.scitotenv.2019.136435.

Welfle, Andrew. 2017. "Balancing Growing Global Bioenergy Resource Demands - Brazil's Biomass Potential and the Availability of Resource for Trade." *Biomass and Bioenergy* 105: 83–95. https://doi.org/10.1016/j.biombioe.2017.06.011.

Wi, Seung Gon, Dae Seok Lee, Quynh Anh Nguyen, and Hyeun Jong Bae. 2017. "Evaluation of Biomass Quality in Short-Rotation Bamboo (Phyllostachys Pubescens) for Bioenergy Products." *Biotechnology for Biofuels* 10 (127): 11. https://doi.org/10.1186/s13068-017-0818-9.

Wijeyekoon, Suren, Kirk Torr, Hilary Corkran, and Paul Bennett. 2020. "Commercial Status of Direct Thermochemical Liquefaction Technologies Technologies. IEA Bioenergy: Task 34."

Wild, Paul De. 2015. "Pyrolysis of Bamboo Vulgaris for Fuels , Chemicals and Energy." In *International Biomass Conference & Expo*. Minneapolis, MIN.

Wu, Donglei, Wei Wang, Shaojun Chen, Zhizhong Yang, Guangming Tian, Shams Ali Baig, and Qaisar Mahmood. 2013. "Advanced Bamboo Industry Wastewater Treatment through Nanofiltration Membrane Technology." *Desalination and Water Treatment* 51 (16–18): 3454–62. https://doi.org/10.1080/19443994.2012.749327.

Xiao, Xiao, Jing Bian, Ming Fei Li, Hui Xu, Bin Xiao, and Run Cang Sun. 2014. "Enhanced Enzymatic Hydrolysis of Bamboo (Dendrocalamus Giganteus Munro) Culm by Hydrothermal Pretreatment." *Bioresource Technology* 159: 41–47. https://doi.org/10.1016/j.biortech.2014.02.096.

Xu, Lin, Xu Deng, Jiayang Ying, Guomo Zhou, and Yongjun Shi. 2020. "Silicate Fertilizer Application Reduces Soil Greenhouse Gas Emissions in a Moso Bamboo Forest." *Science of the Total Environment* 747: 141380. https://doi.org/10.1016/j.scitotenv.2020.141380.

Xu, Ning, Aiyong He, Jiaxing Xu, and Fengxue Xin. 2020. “Bioconversion of Organosolv-Treated Bamboo into Biobutanol Integrated with on-Site Hydrolytic Enzyme Production.” *Biofuels, Bioproducts and Biorefining* 14: 117–126. https://doi.org/10.1002/bbb.2065.

Yan, Wei, Sandy Perez, and Kuichuan Sheng. 2017. “Upgrading Fuel Quality of Moso Bamboo via Low Temperature Thermochemical Treatments: Dry Torrefaction and Hydrothermal Carbonization.” *Fuel* 196: 473–80. https://doi.org/https://doi.org/10.1016/j.fuel.2017.02.015.

Yang, Wei, Hui Wang, Meng Zhang, Jiayu Zhu, Jie Zhou, and Shengji Wu. 2016. “Fuel Properties and Combustion Kinetics of Hydrochar Prepared by Hydrothermal Carbonization of Bamboo.” *Bioresource Technology* 205: 199–204. https://doi.org/10.1016/j.biortech.2016.01.068.

Yiping, Lou, Yanxia; Li, Kathleen Buckingham, and Zhou Guomo. 2010. “Bamboo and Climate Change Mitigation Bamboo: A Comparative Analysis of Carbon Sequestration. INBAR Technical Report No. 32,” no. 32: 47.

Yuan, Zhaoyang, Yangbing Wen, Nuwan Sella Kapu, Rodger Beatson, and D. Mark Martinez. 2017. “A Biorefinery Scheme to Fractionate Bamboo into High-Grade Dissolving Pulp and Ethanol.” *Biotechnology for Biofuels* 10 (38): 1–16. https://doi.org/10.1186/s13068-017-0723-2.

Yuen, Jia Qi, Tak Fung, and Alan D. Ziegler. 2017. “Carbon Stocks in Bamboo Ecosystems Worldwide: Estimates and Uncertainties.” *Forest Ecology and Management* 393: 113–38. https://doi.org/10.1016/j.foreco.2017.01.017.

Zachariah, E J, B Sabulal, D N K Nair, A J Johnson, and C S P Kumar. 2016. “Carbon Dioxide Emission from Bamboo Culms.” *Plant Biology* 18 (3): 400–405. https://doi.org/10.1111/plb.12435.

Zemnukhova, L., U. Kharchenko, and I. Beleneva. 2015. “Biomass Derived Silica Containing Products for Removal of Microorganisms from Water.” *International Journal of Environmental Science and Technology* 12: 1495–1502. https://doi.org/10.1007/s13762-014-0529-8.

Zhan, Tianyi, Fengze Sun, Chao Lyu, Qian He, Kang Xu, Yaoli Zhang, Liping Cai, Zhenhua Huang, and Jianxiong Lyu. 2020. “Moisture Diffusion Properties of Graded Hierarchical Structure of Bamboo: Longitudinal and Radial Variations.” *Construction and Building Materials* 259: 119641. https://doi.org/10.1016/j.conbuildmat.2020.119641.

Zhang, Yongchao, Menghua Qin, Wenyang Xu, Yingjuan Fu, Zhaojiang Wang, Zongquan Li, Stefan Willför, Chunlin Xu, and Qingxi Hou. 2018. “Structural Changes of Bamboo-Derived Lignin in an Integrated Process of Autohydrolysis and Formic Acid Inducing Rapid

Delignification." *Industrial Crops and Products* 115 (February): 194–201. https://doi.org/10.1016/j.indcrop.2018.02.025.

Zheng, Xiao, Shuyan Lin, Huajun Fu, Yawen Wan, and Yulong Ding. 2020. "The Bamboo Flowering Cycle Sheds Light on Flowering Diversity." *Frontiers in Plant Science* 11 (381): 14. https://doi.org/10.3389/fpls.2020.00381.

Zhu, Zhaohua, and Wei Jin. 2018. *Sustainable Bamboo Development*. https://doi.org/10.1079/9781786394019.0000.

Zion Market Research. 2020. "Global Bamboos Market - By End-User (Construction, Wood and Furniture, Paper and Pulp, Textile, Medical, Agriculture, Food Products), and By Region: Latest Industry Insights, Comprehensive Analysis and Forecast 2019 - 2026." https://www.zionmarketresearch.com/report/bamboos-market.

Appendix: CASE STUDIES

Appendix 1. Rural electrification in Indonesia

CPI develops community-based biomass gasification power plants, and together with the Indonesian government, runs bamboo gasification demonstration projects for rural electrification in Indonesia. This project is the first of its kind in Indonesia and Asia pacific (Wahono, 2019).

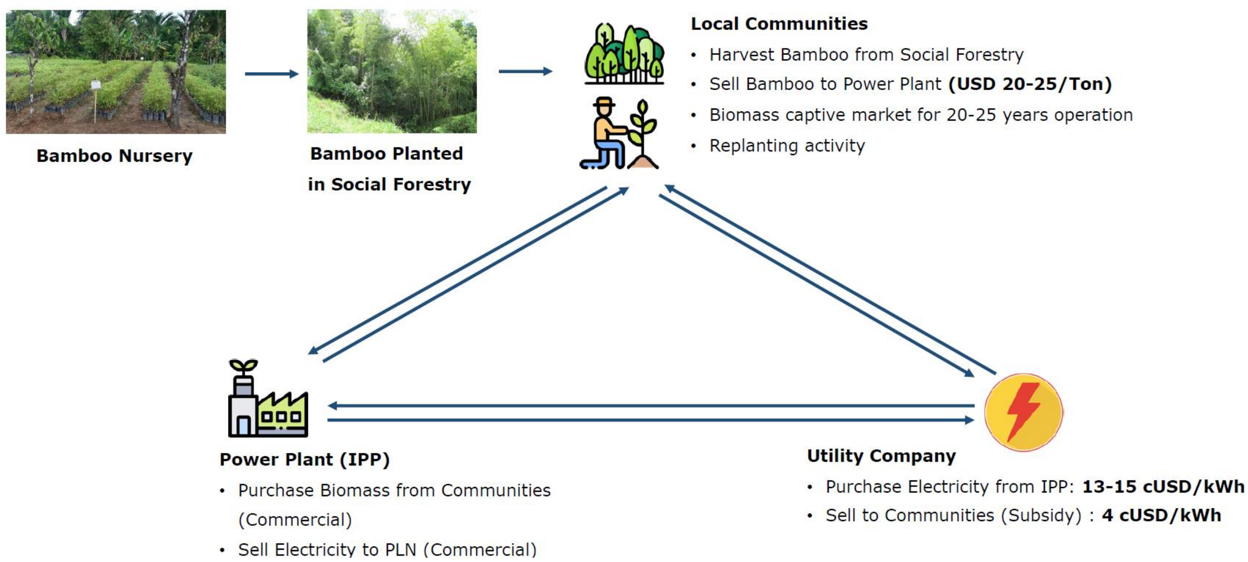


Figure 33. CPI system.

The company utilises local biomass sources, such as bamboo, forest residues and municipal solid waste. The company purchases biomass from local communities and sells electricity to a utility company, which distributes electricity to the entire area. This scheme allows the electrification of isolated rural areas and the creation of jobs for the local communities, which is estimated to be up to 400 jobs/MW capacity. In addition to the electricity output, CPI also produces biochar as a by-product and uses it as a fertiliser in the surrounding area. The plans include the production of charcoal as cooking fuel.

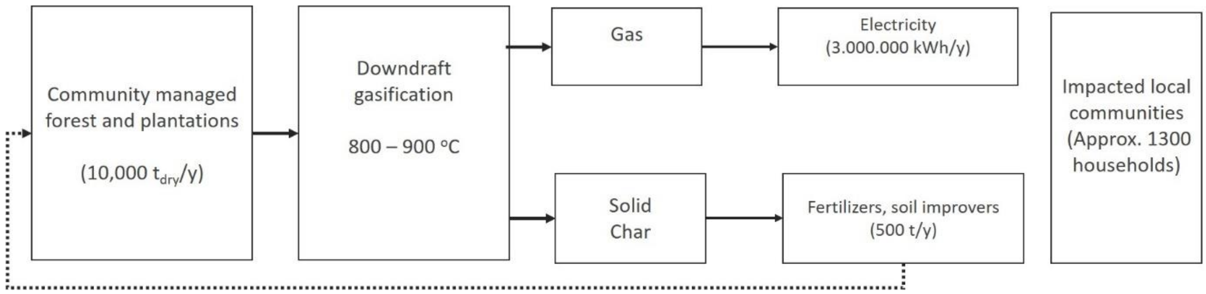


Figure 34. Block diagram of CPI.

Biomass supply: Community existing forest, and forest residues (bamboo and woody biomass). The processed bamboo species include *Dendrocalamus asper, Bambusa blumeana and Bambusa balcooa*. The average properties of the bamboo feedstock are listed in Table 4.

Figure 35. Biomass warehouse CPI

Table 4. Feedstock properties

Average feedstock input and properties		**Units**
Bamboo	10000	t_{dw}/year
Maturity	3–4	Years old
Another biomass	2000	t_{dw}/year
Particle size of the raw bamboo feedstock	Chips Diameter: 25–50 mm; Length: 60–75 mm	mm
Moisture	30–40	wt%
Bulk density	300–400	kg/m^3
Particle density	400–500	kg/m^3
Higher heating value	18	MJ/kg
Ash	3.5–4.5	% dry weight
Cost		
Price	18	USD/t $_{dw}$
Transport	2	USD/t $_{dw}$
Transport distance	0–5	km

Technology

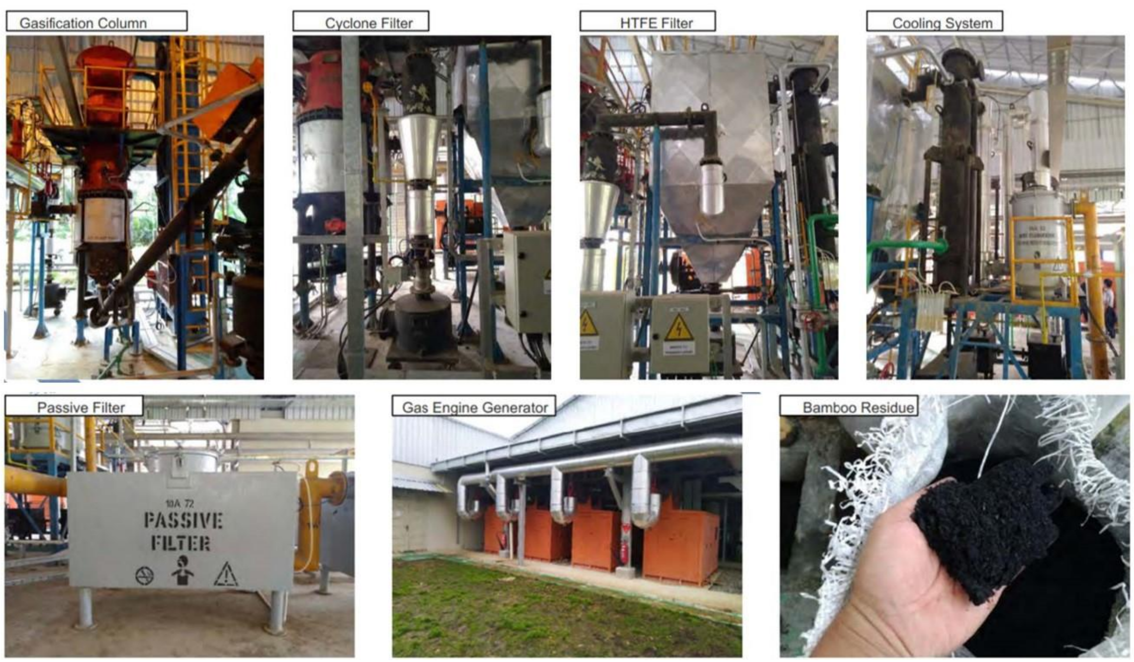


Figure 36. Main equipment CPI

The main pieces of equipment are downdraft gasifier, gas cooling system and gas engine. The gasification operation temperature is approximately 900^{o}C and the obtained volumetric syngas composition is, on average, 20% H_2, 17% CO and 4% CH_4. The char yield is approximately 10 wt% and the oil is cracked and evaporated inside the gasifier.

The main specifications and related investment cost are listed in Table 5.

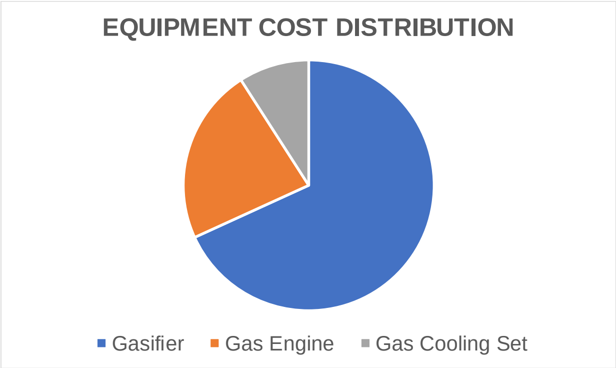
Table 5. Technology specifications and investment costs

Equipment	**Details**	**Unit**
Downdraft gasifier **(3 installed)**, gas cooling, gas engine	100–300	kW
Gasifier operating conditions	800–900	ºC
Side streams (char, oil, tar)	The char yield is approximately 10 wt% and the oil is cracked and evaporated inside the gasifier.	
Gas composition	20% H2, 17% CO, 4% CH_4	% vol
Total electricity output	3.000.000	kWh/year
By products. Char	500	t/year
Investment cost		
Installed equipment cost	**2.200.000**	**USD**
Total capital investment	**3.000.000**	**USD**

Production Cost

The cost of equipment and the estimated total production cost distribution are shown in Figure 37. According to the equipment cost distribution, the gasifier contributes the most to the equipment cost. In terms of total production cost, feedstock costs are approximately 50% of total cost, followed by capital cost[14]. The estimated production of the generated power is approximately 120–130 USD/MWh_e. Given the electricity price as sold to communities at 40 USD/MWh, this **project is economically feasible due to the subsidised business model.**

[14] Capital cost is estimated assuming a linear depreciation in 20 years.



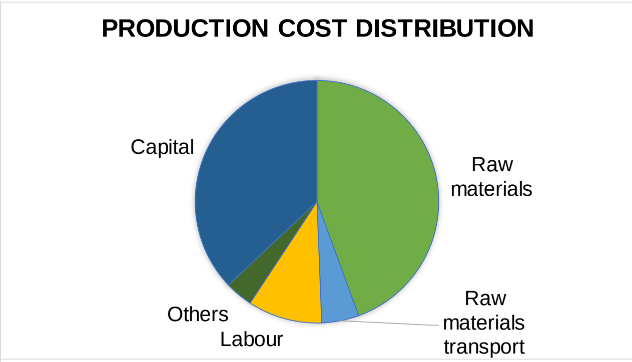


Figure 37. Production cost distribution of gasification and rural electrification in Indonesia

Labour and gender

In terms of job creation, the system provides 100 jobs, from which approximately 50% are women involved mainly in activities related to feedstock collection.

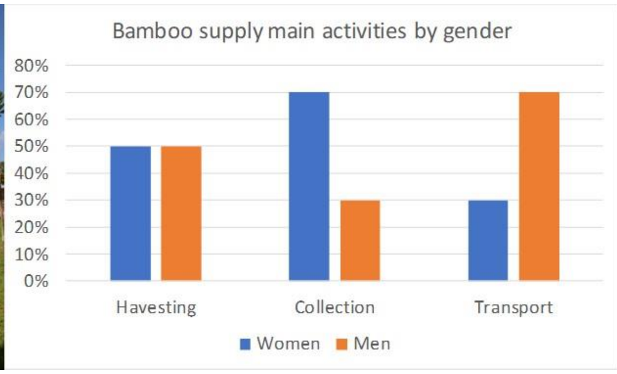


Figure 38. Labour and gender CPI

LESSONS LEARNT AND CHALLENGES

Supply chain

The main requirement for a successful supply chain is the management of the forest and plantations by local communities and at sourcing areas close to the conversion facilities. This allows for a relatively low price of bamboo feedstock.

One of the challenges identified for feedstock collection is the identification of suitable areas for harvesting in the local forest. Therefore, areas and forest mapping activities are essential.

Process

A redundant supply chain is crucial; therefore, the improvement and development of a suitable large storage of biomass is required.

The gasification technology is reported to work properly and be favourable for small-scale capacity (100 kW to 5 MW) applications and suitable to process multiple biomass streams.

Cost and sustainability

The economic feasibility of the business model relies on a subsidised price of the produced electricity.

Appendix 2. Pellet production in China

The company **Zhejiang Anji Bamboo Energy Biomass Energy Plant** produces bamboo pellets from bamboo sawdust. The feedstock is supplied from bamboo pre-processing factories in the area, usually bamboo strip-forming plants, commonly known as shredding plants. The pellet plant consumes approximately 25% of the total sawdust generated in Anji County. The company started trial production and development in 2003.

The plant has one production line and two pelletisers with an annual production capacity of 25,000 t. The pellets are used as boiler fuel and coal replacement, and the current market is dominated by domestic sales. Pellets are sold mainly in bulk, in ‘tonne bags’, with a volume of approximately 1 m^3 per bag.

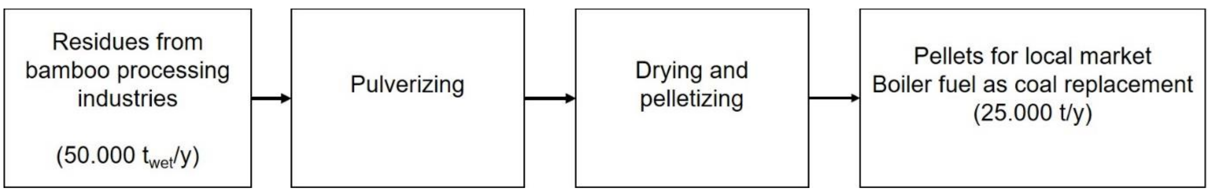


Figure 39. Block diagram. Pellet plant Zhejiang Anji, China

Biomass supply

Figure 40. Bamboo sawdust feedstock (J. Wei and Taotao, 2020)

The main properties and prices of both feedstock and product are shown in Table 6.

Table 6. Feedstock and product flows and properties

Average feedstock input and properties		**Units**
Bamboo	50.000	t_{wet} /year
Maturity	3 – 4	Years old
Another biomass		
Particle size of the raw bamboo feedstock	Powder & Chips (Diameter 6–8 mm, maximum length 30 mm)	mm
Moisture	<50	wt%
Bulk density	300	kg/m^3
Particle density	600	kg/m^3
Lower heating value	19	MJ/kg
Ash	2	% wt dry
Cost		
Feedstock price	90	USD/t_{dw}
Transport	7	USD/t_{dw}
Transport distance	20	km
Average product output and properties		**Units**
Pellets	25,000	t/year
Bulk density	700	kg/m^3
Particle density	600	kg/m^3
Lower heating value	19	MJ/kg
Ash	2	% wt dry
Product sales price	140–170	USD/t

Technology

The drying and pelleting technology was purchased from Jiangsu Chint Company and has been developed independently for bamboo feedstock.

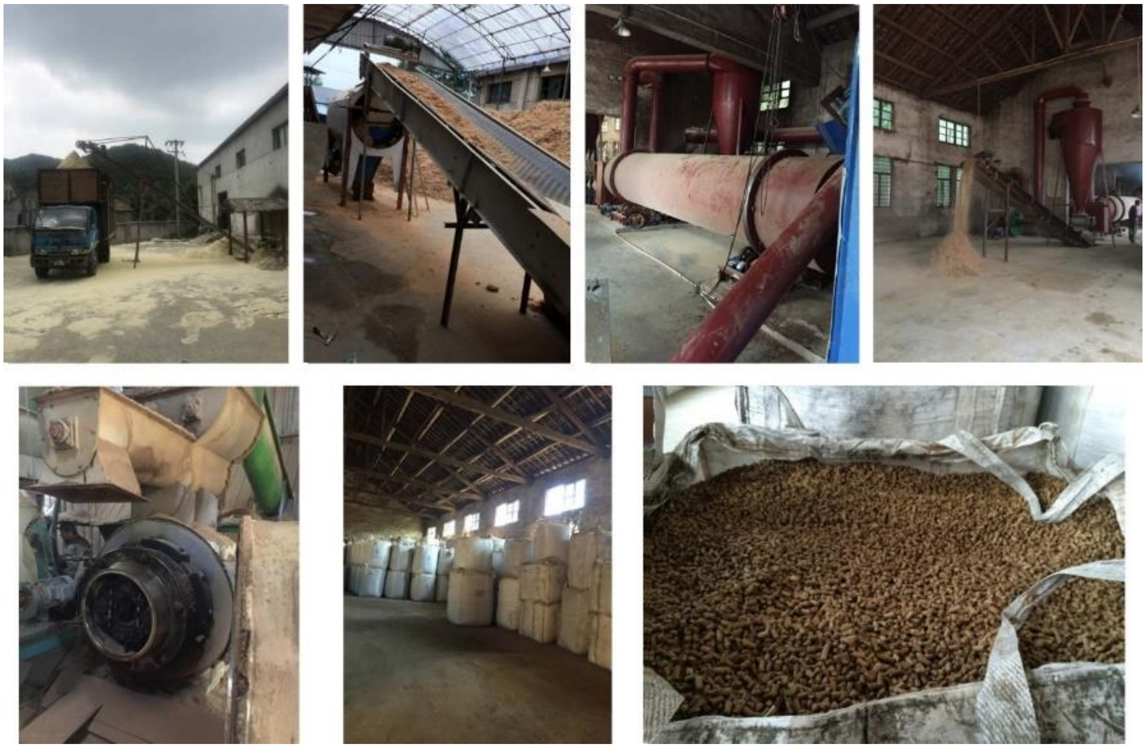


Figure 41. Technology and product (J. Wei and Taotao, 2020)

Table 7 presents the investment cost and estimated total production cost.

Table 7. Investment cost and estimated production costs

Equipment	**Cost**	**Unit**
Crushers	50.000	USD
Dryers	100.000	USD
Pelletiser (Integrated*3)	750.000	USD
Cooling	10.000	USD
Packaging	10.000	USD
Control cabinets	20.000	USD
Conveyors	20.000	USD
Other auxiliary equipment	100.000	USD
Investment cost		
Installed equipment cost	1.060.000	USD
Total capital investment	1.500.000	USD
Estimated production cost	**115–130**	**USD/t**
Estimated production cost	**20–25**	**USD/MWh**

The estimated average pellet production cost is approximately 115 USD/t, which is equivalent to 20 USD/MWh. The bamboo feedstock and transport costs represent approximately 80% of total cost, followed by the electricity cost, which is approximately 16% of the total production cost. Electricity use is approximately 150 kWh/t product.

Figure 42 depicts the average production cost and the installed equipment cost distribution.

Cost distribution

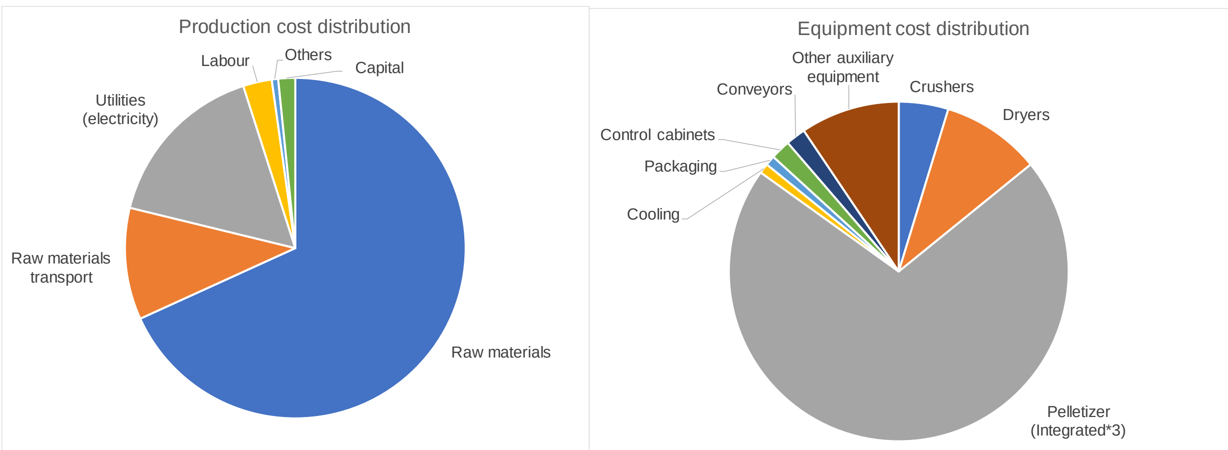


Figure 42. Production cost distribution of a pellet plant in China.

Labour and gender

The plant has 16 FTE employees, of which 50% are women, whose main activities are related to end product selection and packing.

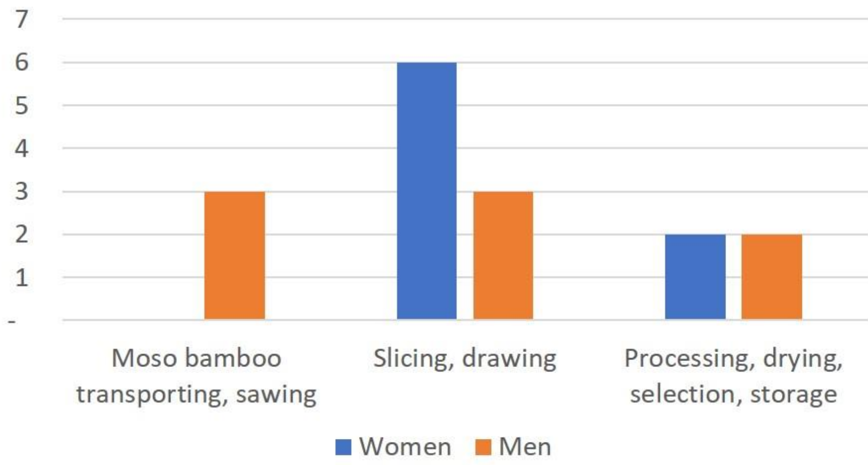


Figure 43. Labour and gender

Lessons learnt and challenges

Supply chain

The security of the feedstock supply depends exclusively on saw dust residues obtained from processing industries. The company utilises approximately 25% of the total feedstock availability in the region, and feedstock use competition and the high feedstock price are considered challenges.

Process

In terms of technology, the common equipment for wood pellets are proved to not be suitable for bamboo processing. After extensive testing, only the equipment of Jiangsu Chint Company was found suitable. Small granulators with a capacity below 2 t/h were not efficient, and the development of larger-capacity pelletisers, such as 5 t/h, appeared as a technology required by the company.

The required skill levels of operators mainly relate to a non-technical level. However, for a successful operation, it is essential to account for skilled mechanics.

Due to high export cost and current production capacity, the current market is still domestic and mainly for users who replace coal as boiler fuel. Nevertheless, export of pellets can be considered by the company.

Cost and sustainability

The company considers that the additional production areas for bamboo should be planned in a unified manner and an industrial chain should be established. The company wishes to establish cooperation with investors, public institutions and social organisations.

Appendix 3. Charcoal briquette production in China

The company **Anhui Guangde Juneng Carbon Industry Co., Ltd.**, in Guangde, China, has been producing bamboo charcoal since the late 1980s. The company has experienced earth kilns, brick kilns, track kilns and the current hoisting kilns, and is currently developing dry distillation kilns. The technology is completely self-developed, and experts and scholars from universities, colleges and research institutions work together to overcome the technical problems. Furthermore, government support has been provided. The raw material supply chain mainly relies on the MOSO bamboo processing industry. The market situation is favourable, and buyers directly select the goods.

The company produces 3.000 t/year of charcoal from bamboo processing residues and from MOSO bamboo plantations. The main market of the produced charcoal is for local applications in the BBQ markets.

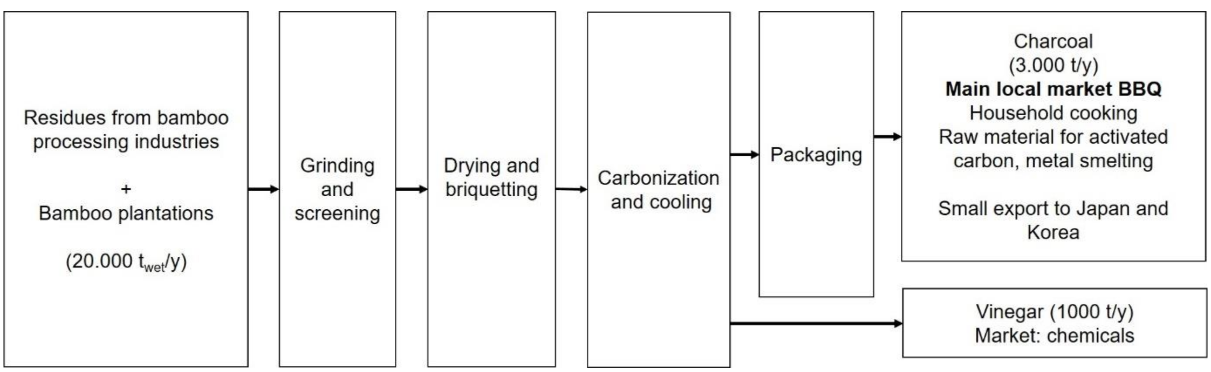


Figure 44. Block diagram. Charcoal briquette plant in Guande, China

The feedstock bamboo is chipped, crushed, dried, subjected to rod-making, carbonised, cooled, selected and packaged in packs of 10–15 kg. The carbonisation temperature is 600°C and one carbonisation cycle comprises eight days. Water use is about 2.8–3 t/t product. Electricity use is approximately 450 kWh/t product. The produced gas is fuelled for heat production in the drying step and the tar and vinegar produced is commercialised for chemical production. Furthermore, emission control and environmental protection facilities are installed. Table 8 presents the properties and prices of the feedstocks and products.

Table 8. Feedstock and product flows and properties

Average feedstock input and properties		**Units**
Bamboo	20.000	t_{dw} /year
Maturity	5–8	Years old
Another biomass		
Particle size of the raw bamboo feedstock	Chips, full bamboo pole	
Moisture	<50	wt%
Bulk density	300–400	kg/m^3
Particle density	300–400	kg/m^3
Lower heating value	19	MJ/kg
Ash	2	% wt dry
Cost		
Price	72	USD/t_{dw}
Transport	8.5	USD/t_{wet}
Transport distance	60	km
Average product output and properties		**Units**
Charcoal briquettes	3.000	t/year
Moisture	5–6	% wt
Bulk density	600	kg/m^3
Particle density	1100–1300	kg/m^3
Lower heating value	25	MJ/kg
Ash	2	% wt dry
Product price. Charcoal briquette (screw type)	500–700	USD/t
Vinegar-tar mixture	1000	t/year

Equipment and production cost

The plant area is 4000 m^2, and the steel structure is 8.5 m high. The plant involves one electric weighbridge, 5 t of travelling crane and one 450 kv transformer. The required equipment and total investment of the plant are listed in Table 9, and the total production cost distribution is depicted in Figure 45.

Table 9. Equipment and capital cost of the charcoal plant

Equipment	**Units**
Flow plus air mixer dryer 7.5 KW	1 set
Rod making machine 260 KW	12 sets
Heavy duty pulveriser 37 KW	1 set
Centrifugal stainless-steel fan 30 KW	
Conveying wheel 13 KW	6 sets
Conveying rod and short rod machine 13 KW	1 set

Environmental protection equipment, dust removal (air compressor), electrostatic dust removal	1 set
Hoisting kiln (pyrolysis furnace), 2 x 3 x 2.3 m^3 (height)	50 kilns (with covers, hoods)
Other ancillary equipment, workshop tools, 1 forklift truck each	
Installed equipment cost	**850.000 USD**
Total capital investment	**1.850.000 USD**

The estimated production cost for charcoal briquettes is approximately 490 USD/t, which is equivalent to 40 USD/MWh. The bamboo feedstock and transport costs represent approximately 70% of the total cost, followed by the electricity cost and labour cost, each representing approximately 13% of the total production costs.

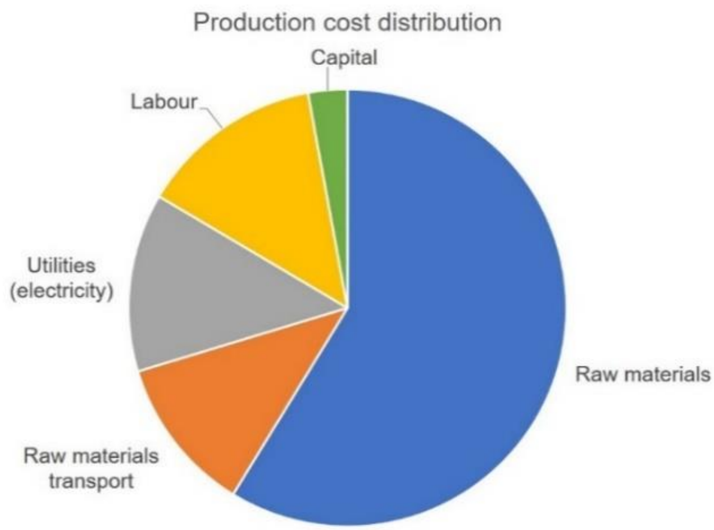


Figure 45. Production cost distribution of the charcoal plant in China

Labour and gender

The plant has 21 employees, of which approximately 40% are women. Activities such product sorting and packing are mainly performed by women. The required skills of the employees are depicted in Figure 46.

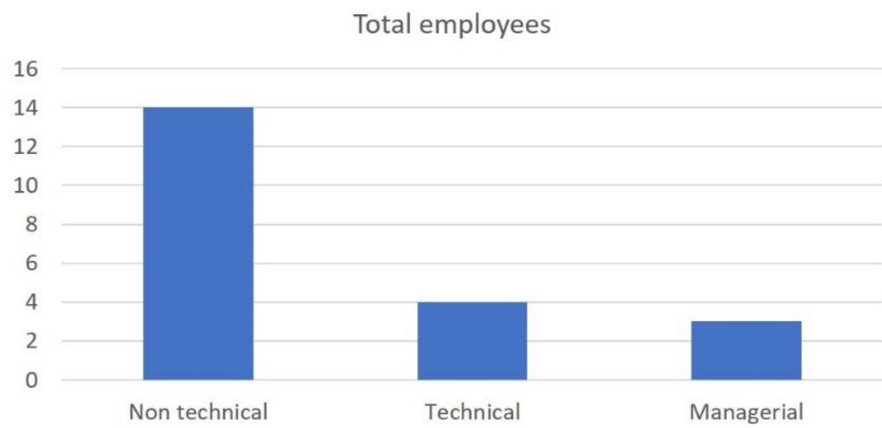


Figure 46. Required skills of employees in a charcoal plant in China

Lessons learnt and challenges

Supply chain

The feedstock supply highly depends on the residues MOSO's bamboo processing industry, and the feedstock availability is not continuous. Furthermore, feedstock competing use and prices are seen, due to the installation of other plants that also process bamboo residues.

Process

The continuous improvement in the charcoal kiln technology in terms of energy efficiency and reduction in electricity cost is key to maintaining the competitiveness of charcoal production.

Additional areas for bamboo production need to be developed. In terms of technology and value chain development, the company advocates a strong cooperation with universities, colleges and research institutes.

INTERNATIONAL BAMBOO AND RATTAN ORGANISATION

www.inbar.int

@INBAROfficial