Bioenergy Production from Bamboo: Potential Source from Malaysia's Perspective

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Global energy sectors are facing the crucial challenge of sustainability and diversification of energy resources. Seeking renewable resources with a sustainable supply is therefore a matter of the utmost concern. In this respect, bamboo, a renewable lignocellulosic material and non-food biomass, has great potential to be utilized to produce energy. Several studies have been conducted on a wide range of bamboo species and the results have shown that bamboo could potentially be used as a suitable fuel because it shares desirable fuel characteristics present in other woody biomass. Bamboo can be used as an energy source by converting it into solid, liquid, and gaseous fuels. However, to utilize bamboo as a high promise energy crop resource for biofuels, a secure and stable supply is required. Therefore, additional information on the availability, cultivation, and harvesting operations of bamboo is vital to ensure the practicability of the idea. The objective of this review is to highlight the potential of bamboo as an alternative source of bioenergy production, particularly in a Malaysian context, with emphasis on the concepts, pretreatment, and conversion technologies.

Keywords: Bamboo; Bioenergy; Biofuel; Malaysia; Energy crisis

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INTRODUCTION

The rapid depletion of fossil fuels and the need to protect the global environment from climate change have resulted in the urgent seeking of alternative sources of fuels to meet an increasing energy demand. The need for energy, which was 540 quadrillion British thermal units (Btu) in 2012, is expected to increase worldwide to 815 quadrillion Btu by 2040 (International Energy Outlook 2015), including in Malaysia, where rapid economic growth is expected. Developing countries, such as Malaysia, presently rely on non-renewable fuels as the main source of energy, with all major power stations still utilizing fossil fuels, such as oil, gas, and coal, to generate electricity (Chin *et al.* 2013a). The dependence on fossil fuels has to be gradually replaced with a cleaner and more sustainable source of energy.

At the moment, the crucial challenge faced by the energy sector in Malaysia is the issue of a sustainable energy supply and diversified energy resources. Utilizing fossil fuels have two major disadvantages: they are non-renewable resources and are recognized as major drivers of climate change.

Such global environmental problems can have disastrous ramifications on the socioeconomic development in Malaysia. Furthermore, Malaysia is also a signatory to the UN Convention on Climate Change and the Kyoto Protocol, which have committed the country to move forward to reduce greenhouse gas emissions (Rahman and Lee 2006). Thus, the Malaysian Government is committed to search for other forms of alternative energy sources with an emphasis on renewable energy. In this respect, biomass remains the only sustainable source of carbon that can be utilized to produce renewable fuels. It is also the oldest source of energy known to humans.

The feedstock used for biofuels has been categorized into three major groups, cellulose biomass, sugar and starchy crops, and oil-producing plants (Uriarte 2010). Interest is currently focused on the first group, also known as second-generation biofuel. This is because the second and third groups have conflicts with food production for human and animal consumption (Kullander 2009). Furthermore, the conversion of raw oil from starchy crops and oil-producing plants is too expensive and is less competitive compared to fossil fuels. Therefore, to meet the target for global sustainable energy production, biomass was deemed an appropriate alternative.

Biomass energy can be defined as the energy from plant-based organic matter used for heat, electricity, and transportation fuel. Using biomass to provide energy services is one of the most versatile options to increase the proportion of renewable energy in the global energy system. Currently, biomass energy is the most widely used form of renewable energy in the world. This biomass energy can be in liquid, gas, or solid forms. Biomass can be converted to energy in three different ways: chemical conversion, thermal conversion, and biochemical conversion. Attention has been focused not only on the conversion processes, but also on the issue of sustainability of the feedstock supply, although it was recognized that the conversion of cellulose to liquid fuel is a challenging process, which demands better technologies (Sánchez and Montoya 2013; O'Keefe *et al*. 2014).

Biomass sources from grasses and herbaceous plants are preferred because of their fast growing nature and greater biomass production. Comprehensive reviews have been published by O'Keefe *et al*. (2014) and Kerckhoffs and Renquist (2013) on potential grasses and herbaceous plants in Europe and New Zealand that can be used as feedstock for biofuel production. Bamboo is a member of the grass family (Poaceae) and has great potential for use as feedstock for biofuel production. While most of the scientific studies on bamboo as a biofuel feedstock are from China and Japan, there is little research focused on tropical bamboo species (Hakeem *et al*. 2015). Littlewood *et al*. (2013) examined the potential of bioethanol production from two local bamboo species in China (*Phyllostachys dulcis* and *P. viridiglaucescens*) and found that the sugar content of the bamboo species is high, *i.e.* about 62% of the dry matter.

Malaysia is now enhancing its forest plantation program, and bamboo is one of the potential non-timber species to be commercially planted (Hakeem *et al*. 2015). While the utilization of lignocellulosic materials from bamboo for other uses have been well documented, a review of the majority of research specific to the bioenergy production from bamboo has not been presented to date. Considering this fact, the present review is highly pertinent to highlight the potential of bamboo as an alternative source of bioenergy production, particularly in Malaysia.

BIOENERGY PRODUCTION FROM BAMBOO

Solid Biofuel

More than 90% of the world's main energy supply is produced by direct combustion. This is the most commonly used and established technology, for the purpose of providing heat and energy services, such as materials processing including food preparation, electricity, transportation, ventilation, cooling, and space heating. During combustion, biomass fuel is combusted with oxygen from the air to produce heat. The initial stage of combustion involves the development of combustible vapours from the biomass solid biofuel that burn as flames. The residue, in the form of charcoal, is burned in a forced air supply to provide more heat (Overend 2009). The hot combustion gases are sometimes directly utilized for product drying, but more often than not, they are sent through a heat exchanger to produce hot air, water, or steam. Burning the biomass materials in a chamber to produce heat in the form of released hot gas is one of the simplest methods to obtain energy. A biomass boiler can be used to convert the heat into steam, and turbines for electricity generation can be rotated by said steam.

Sadiku *et al*. (2016) reported that the chemical composition of *Bambusa vulgaris* was in the range 4 to 7% for extractives, 61 to 78% for cellulose, and 39 to 46% for lignin. Engler *et al*. (2012) showed that both of the tested bamboo species, *Bambusa emeiensis* and *Phyllostachys pubescens*, are potentially suitable to be used as a fuel in biomass-fed combustion plants. Bamboo shares desirable fuel characteristics with other woody biomass, with the exception of ash fusibility. The study also reported that *B. emeiensis* showed the most favourable results when harvested after 5 years, when the calorific value was highest and the ash and chloride content were comparatively low. For *P. pubescens*, a harvesting time for energy purposes was suggested of between 2 and 3 years. Overall, the mean gross calorific value for *P. pubescens* and *B. emeiensis* were 19.44 MJ/kg and 18.32 MJ/kg, respectively (Dayton *et al*. 1995). The gross calorific value ranges from 1810.90 cal/kg to 4160.60 cal/kg with an average of 3157.80 for *Bambusa vulgaris* aged between 2 to 4 years (Sadiku *et al.* 2016).

Fang and Jia (2012) studied the ash melting characteristics of bamboo, Bermuda grass, corn straw, and red pine. The study reported that a serious sintering phenomenon occurred when the bamboo was ashed at 815 °C. The ash melting temperature for bamboo was the lowest among the four biomasses. The ash composition and physical and chemical properties of the biomass were determining factors that affected the fouling, slagging, and corrosion processes in the direct combustion of biomass, and its ash fusion characteristics (Dayton *et al*. 1995). The proportions of the element (K, Si, Ca, Mg, *etc*.) levels relative to each other were more important than the absolute levels of certain elements in relation to the ash melting characteristics (Chin *et al*. 2015b). Although representing only a minor proportion by weight, ash appeared to be a major determinant in the combustion behavior of lignocellulosic material. Bamboo shares a number of desirable fuel characteristics with certain other bioenergy feedstocks, such as low ash content and alkali index. Its heating value is lower than many woody biomass feedstocks but higher than most agricultural residues, grasses and straws.

Torrefaction was proposed by Rousset *et al.* (2011) to improve the energy characteristics of bamboo. The study reported that torrefied bamboo had an increased heating value. At 280 °C, the heating value in the torrefied bamboo increased 27% compared to the untreated material. During the torrefaction process of subjecting lignocellulosic materials to temperatures between 200 °C and 300 °C, the cell walls degraded and the nature of the resulting product was between that of lignocellulose and charcoal (Chin *et al*. 2013b). Hernández-Mena *et al*. (2014) studied the effect of slow pyrolysis on the biochar properties of bamboo (*Dendrocalamus giganteus* Munro). The process was conducted in a fixed bed reactor at temperatures ranging from 300 °C to 600 °C with a 10 °C/min heating rate. The char produced at 500 °C contained approximately 68% of the energy content in the raw material with a Higher Heating Value (HHV) above 30 MJ/kg, which was as high as the HHV of anthracite. Bamboo torrefied under carbon dioxide atmosphere at 240 to 340 °C, obtained solid products with mass yield 41 to 97%, energy yield 63 to 99%, and HHV 18.78 to 28.51 MJ/kg (Li *et al.* 2015a). Bamboo is extremely high in lignin content (29 to 46%), and this makes it a desirable species for solid biofuel production, as a high lignin content in the torrefied biomass results in a higher HHV (Chin *et al*. 2013b). Co-firing with bamboo by replacing up to 30% of the coal requirements has been shown to be economical and is a promising environmentally friendly technology (Chao *et al*. 2008). Kwong *et al*. (2007) described the co-combustion performance of coal with rice husks and bamboo. Preliminary experiments indicated a reduction in carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) emissions for a mixture with a 10% to 30% bamboo blending ratio.

Liquid Fuel

Conversion of lignocellulose to saccharides and bioethanol

In the process of bioethanol production, hydrolyzing of the lignocellulosic material to fermentable sugars faces a bottleneck situation due to the limitations set on the digestibility of lignocellulose by many physico-chemical, compositional, and structural factors (Chin *et al*. 2010, 2011). Thus, pretreatment is a vital step in the production of fermentable sugars due to the recalcitrance characteristics of the feedstock. Pretreatment is mainly aimed at breaking down the lignin structure and disruption of the crystalline structure of cellulose, thus increasing the accessibility of glucans and xylans to enzymatic attack (Mosier *et al*. 2005).

Pretreatment and hydrolysis processes

The biological approach to biofuels utilizing lignocellulosic biomass, such as bamboo, is currently more of a challenge than the utilization of starchy material, where starch is readily hydrolysed to glucose enzymatically. A variety of pretreatment methods have been developed to reduce the recalcitrance of lignocellulosic biomass for improved access to sugar. The methods proposed in the literature include biological and chemical pretreatments to selectively degrade hemicellulose or lignin. A summary of pretreatment and hydrolysis conditions found in the literature for bamboo can be found in Table 1.

The pretreatment of bamboo at low temperatures with a sodium hydroxide/urea solution, followed by extractions of the dissolved lignin and hemicelluloses were conducted by Li *et al*. (2010). They utilized a cold sodium hydroxide/urea based pretreatment in which the sample was mixed with a 7% NaOH/12% urea solution at -12 °C for 10 min. The relative content of lignin in the cellulosic rich fractions decreased to less than 14% compared to the original sample, which contained 23%. The partial removal of lignin in the Li *et al*. (2010) study decreased the barrier to hydrolysis considerably, and thus, enhanced the hydrolysing efficiency.

Table 1. Summary of Pretreatment and Hydrolysis Methods for Bamboo

Bamboo Species	Pretreatment Conditions	Hydrolysis Conditions	Yield	References
Bambusa vulgaris	Dilute acid 200 °C, 1% H_2SO_4 concentration for 4 h	Enzymatic saccharification Cellulase and ß-glucosidase 50 °C, 121 rpm for 72 h	153.1 mg/g glucose/g initial dry sample	Kolawole *et al.* 2016
Bambusa pervariabilis	Steam Explosion Step 1 Saturated steam at 2.0 MPa for 4 min	Enzymatic saccharification Cellulolytic enzyme 50 °C, 200 rpm for 24 h	62.5% conversion yield (based on conversion of cellulose to glucose)	Li *et al*. 2015b
	Delignification with $NaClO_2$ $NaClO_2$ at 80 °C for 1 h	Enzymatic saccharification Cellulolytic enzyme 50 °C, 200 rpm for 24 h	93.1% conversion yield (based on conversion of cellulose to glucose)	
	Unpretreated bamboo	Enzymatic saccharification Cellulolytic enzyme 50 °C, 200 rpm for 48 h	2.5% conversion yield (based on conversion of cellulose to glucose)	
Dendrocalamus sp.	Dilute acid 120 °C, 5% H_2SO_4 concentration for 90 min	Enzymatic saccharification Cellulolytic enzyme, 50 °C, 200 rpm for 48 h	319 mg/g of reducing sugar	Sindhu *et al*. 2014
Neosinocalamus affinis	NaOH/urea 7% NaOH/12% urea solutions at -12 °C and subsequent neutral solvent extractions	Acid hydrolysis 72 wt.% H_2SO_4, at 25 °C for 45 min followed by a high temperature hydrolysis at 105 °C for 2.5 h by dilution to 3% H_2SO_4	58% of glucose (mainly from cellulose) and 26% of xylose (from hemicellulose)	Li *et al*. 2010
	Non-pretreated bamboo	Acid hydrolysis 72 wt.% H_2SO_4, at 25 °C for 45 min followed by a high temperature hydrolysis at 105 °C for 2.5 h by dilution to 3% H_2SO_4	51% of glucose (mainly from cellulose) and 23% of xylose (from hemicellulose)	
Phyllostachys pubescens	Steam explosion/NaOH 20 atm and 5 min steam explosion followed by 10 wt.% NaOH treatment at 121 °C for 60 min	Enzymatic saccharification Cellulolytic enzyme, 45 °C, 140 rpm for 48 h	456 mg glucose/g initial dry sample and 460 mg reducing sugar/g initial dry sample	Yamashita *et al*. 2010
	Alkaline peroxide 1% (v/v) H_2O_2 and 1 wt.% sodium hydroxide	Enzymatic saccharification Cellulolytic enzyme, 45 °C, 140 rpm for 48 h	399 mg glucose/g initial dry sample and 568 mg reducing sugar/g initial dry sample	
	Unpretreated bamboo	Enzymatic saccharification Cellulolytic enzyme, 45 °C, 140 rpm for 48 h	63 mg glucose/g initial dry sample and 88 mg reducing sugar/g initial dry sample	
Phyllostachys heterocycla	-	Acid hydrolysis 5% sulfuric acid and 9% sodium sulphite at 180 °C for 30 min	89.3% conversion yield (based on conversion of cellulose to glucose)	Li *et al*. 2014

Phyllostachys heterocycla	Organosolv and alkali Step 1 2% w/w H_2SO_4 in 75% w/w ethanol, 160 °C for 30 min Step 2 NaOH (10% and 20% w/w) or $Ca(OH)_2$ (10% w/w) at 50 °C for 70 h	Enzymatic Cellulolytic enzyme, 50 °C, 220 rpm, pH 4.8 for 48 h	33.4% glucose yields from the raw bamboo (calculated based on 41.3% cellulose content in raw bamboo)	Li *et al*. 2012a
	Unpretreated bamboo	Enzymatic saccharification Cellulolytic enzyme, 50 °C, 220 rpm for 48 h	2.4% glucose yields from the raw bamboo (calculated based on 41.3% cellulose content in raw bamboo)	
Phyllostachys heterocycla	Microwave-KOH 40 min, 12% KOH concentration in the microwave oven at a power level of 400 W (≈ 180 °C)	Enzymatic saccharification Cellulolytic enzyme, 50 °C, 220 rpm for 48 h	20.87% glucose and 63.06% xylose of resulting biomass	Li *et al*. 2012b
	Unpretreated bamboo	Enzymatic saccharification Cellulolytic enzyme, 50 °C, 220 rpm for 48 h	2.41% glucose and 2.94% xylose of resulting biomass	
Phyllostachys pubescence	White rot fungi Pretreated with *E. taxodii* 2538 at 25 °C for 120 d	Enzymatic saccharification Cellulolytic enzyme, 50 °C, 220 rpm for 120 h	332.9 mg fermentable sugar/g substrate	Zhang *et al*. 2007a
	Unpretreated bamboo	Enzymatic saccharification Cellulolytic enzyme, 50 °C, 220 rpm for 120 h	38 mg fermentable sugar/g substrate	
Phyllostachys pubescence	White rot fungi Pretreated with *Coriolus versicolor* at 25 °C for 120 d	Enzymatic saccharification Cellulase from *Aspergillus niger*, 48 °C, 200 rpm for 48 h	223.2 mg/g of reducing sugar	Zhang *et al*. 2007b
	Unpretreated bamboo	Enzymatic saccharification Cellulase from *Aspergillus niger*, 48 °C, 200 rpm for 48 h	95.9 mg/g of reducing sugar	
Not stated	Concentrated acid 75 wt.% H_2SO_4 at at 50 °C for 30 min (solubilisation step)	Acid hydrolysis 27 wt.% H_2SO_4, stirred at 80 °C for 60 min	97.7 g/L concentration of glucose and 23.6 g/L concentration of xylose	Sun *et al*. 2011

Yamashita *et al.* (2010) reported the use of an enzymatic saccharification method to obtain 399 mg glucose/g of the initial dry sample and 568 mg reducing sugar/g of the initial dry sample from bamboo. Glucose yield of 0.15 g/g was obtained from dilute acid pretreated and enzymatic hydrolysed bamboo (Kolawole *et al.* 2016). A substantial amount of glucose and reducing sugar, 456 mg/g of initial dry sample and 460 mg/g of initial dry sample, respectively, were obtained from the steam explosion pretreatment, followed by a sodium hydroxide treatment (Li *et al.* 2015b). Sindhu *et al.* (2014) looked at the effect of the dilute acid pretreatment on the lignin chemistry for *Dendrocalamus* sp. Between the different mineral acids and organic acids used for pretreatment, H_2SO_4 resulted in the highest amount of reducing sugar (0.22 g/g), which was followed by HCl (0.17 g/g), acetic acid (0.14 g/g), and formic acid (0.13 g/g). The maximum amount of reducing sugar of 0.319 g/g was produced with a 5% (w/w) H_2SO_4 concentration, 10% (w/w) biomass loading, and a 90 min pretreatment time in a laboratory autoclave. When 2-year moso bamboo (*Phyllostachys edulis*) was treated at 180 °C for 30 min with a solution containing 5% sulfuric acid and 9% sodium sulfite, the conversion of cellulose to glucose during hydrolysis was as high as 89.3% (Li *et al.* 2014).

Li *et al*. (2012a) reported on the method using a two-stage organosolv and alkali pretreatment, which successfully removed around 96.5% (NaOH) and 85.7% ($Ca(OH)_2$) lignin. It was discovered that the crystallinity of the two-stage organosolv pretreated bamboo was diminished compared to the untreated bamboo, which indicated a breakdown of the crystalline cellulose zone, and also, a gain in the amorphous zone. Some studies have shown indications that bamboo encompasses several non-structural sugars, such as starch, sucrose, glucose, and fructose (Hirano *et al*. 2003; Okahisa *et al*. 2005). Shimokawa *et al*. (2009) found that immature bamboo contains a greater quantity of non-structural sugars than mature bamboo, which leads to a higher saccharification yield from immature bamboo compared to mature bamboo.

Fermentation

Through the hydrolysis process of bamboo, the content of both pentoses and hexoses, should hydrolysation of both hemicellulose and cellulose occur, can be determined within the hydrolysates produced. Taking the lignocellulose source into account, the hydrolysate typically consists of glucose, xylose, mannose, arabinose, rhamnose, fucose, and galactose (Saha 2003). The dominant sugars in the mixture are glucose and xylose. The commonly used microbes in ethanol fermentation, such as *Zymomonas mobilis* and *Saccharomyces cerevisiae*, are unable to ferment xylose, but they are capable of the efficient fermentation of glucose into ethanol. Examples of yeasts known to be involved in xylose fermentation into ethanol are *Pachysolen tannophilus*, *Pichia stipitis*, and *Candida shehate* (Wang *et al*. 1980; Schneider *et al*. 1981).

Sindhu *et al*. (2014) reported that with sequential separate hydrolysis and fermentation (SHF), a maximum ethanol concentration of 1.758% (v/v) was obtained after 72 h fermentation of the bamboo hydrolysate (obtained from enzymatic saccharification of dilute acid pretreated bamboo) by *S. cerevisiae*. Sindhu *et al*. (2014) also noted a 41.69% overall efficiency of the process, which was calculated based on the theoretical ethanol yield from glucose. Li *et al*. (2015b) reported a higher ethanol yield of 88.1% to 96.2% of the corresponding theoretical ethanol yield after 24 h fermentation of enzymatic hydrolysates of steam explosion pretreated bamboo with *S. cerevisiae*. Conversion of immature shoots of *Phyllostachys bambusoides* and *P. pubescens* yielded 169 g/kg and 139 g/kg of ethanol, respectively using simultaneous saccharification and fermentation (SSF) process with 12 FPU/g enzymes and *S. cerevisiae* (Shimokawa *et al*. 2009). This was 98% and 81%, respectively, of the theoretical yields based on the hexose conversion. A substantial amount of xylose was observed within the solution after the SSF processes. The net ethanol production can be doubled, provided that the xylose from immature bamboo shoots could be fermented to ethanol as well. A study was conducted by Li *et al*. (2014) that compared the ethanol conversion yields of SHF and SSF. The results indicated that a higher ethanol yield was obtained from SHF of sulphite- and sulphuric acid-treated bamboo than SSF. The use of recombinant *Z. mobilis* to ferment total reducing sugars in the enzymatic hydrolysate of pretreated bamboo was reported by He *et al*. (2013) and yielded 55.82% ethanol within 24 h at 30 °C. The ethanol yields from bamboo were higher compared to corn stover (37.13%) using the SSF techniques.

Biocrude oil

Previous studies have focused on the potential of using pyrolysis to convert bamboo to biocrude oil. A summary of the pyrolysis conditions and quality of biocrude oil produced from bamboo found in the literature can be found in Table 2.

Table 2. Summary of Pyrolysis Conditions and Quality of Biocrude Oil from Bamboo

Conditions	Reactor Type	Biocrude Oil Composition (%)				Yield (%)	HHV (MJ/kg)	References
		C	H	N	O			
405 °C, 5.4 g/min feed rate	Fluidized bed	41.39	7.03	2.01	49.6	72	17.4	Jung *et al*. 2008
460 °C, 3.6 kg/h feed rate	Fluidized bed	27.41	8.72	0.45	63.4	55	14.0	Lin *et al*. 2013
797 °C with a steam flow of 7.85 ± 0.2 g/min	Batch type fixed bed	74.44	9.55	NS	16.0	33.5	NA	Kantarelis *et al*. 2010
700 °C, heating rate 5 °C/min	Slow pyrolysis	69.3	6.1	1.6	22.7	39.2	NS	Chen *et al*. 2014

Jung *et al*. (2008) reported pyrolysis oil yields from *P. bambusoides* greater than 70% with a HHV of 17.4 MJ/kg using a bubbling fluidized bed with a char separation system. The reaction was conducted at 405 °C. Jung *et al*. (2008) observed the differences in biocrude oils acquired from various lignocellulosic biomasses and discovered that bamboo biocrude oils possessed less aromatic hydrocarbons and nitrogen containing compounds than the alfalfa stem biocrude oils. It was also discovered that the levoglucosan levels in the bamboo biocrude oils were five times lower than that of the rice straw biocrude oil. Lin *et al*. (2013) looked at the potential use of thorny bamboo and long-branch bamboo from southern Taiwan as feedstock to produce biocrude oil. Lin *et al*. (2013) found that the main compounds in the biocrude oils from thorny bamboo were phenols, carboxylic acids, ketones, and a few furans. Biocrude oils from *Pinus indicus* were mainly comprised of levoglucosan, furfural, phenol, aldehydes, and vanillin (Luo *et al*. 2004), which was similar to the composition of biocrude oil produced from spruce (Adam *et al*. 2005). Also, the major compounds of biocrude oils from rice straw were acetic acids, formic acids, ketones, and aldehydes, and those from most hardwoods were aldehydes, ketones, and esters (Sipilä *et al*. 1998). This indicates that biocrude oils are a complex mixture with all kinds of oxygenated organics, such as esters, ethers, aldehydes, ketones, phenols, carboxylic acids, and alcohols.

The effect of the heating rate on slow pyrolysis behaviour and physio-chemical properties of moso bamboo for biocrude oil production was studied by Chen *et al*. (2014). The study discovered that changes in the heating rate resulted in large variations in the properties of the biocrude oil obtained. Chen *et al*. (2014) found that increasing the heating rate caused the biocrude oil yield to decrease, but resulted in an improvement to the phenolics production, while reducing the amount of water in the biocrude oil. Chen *et al*. (2014) also observed that with rapid bamboo pyrolysis, the small-molecule substances in the biocrude oil were lower than with slow bamboo pyrolysis. This was possibly due to the secondary decomposition of volatiles being more efficient in slow pyrolysis with a lengthy residence time of volatiles in the pyrolysis furnace (Muhammad *et al*. 2012; Ren *et al*. 2013; Chin *et al*. 2015a). Thus, different testing methods for pyrolysis resulted in different effects on the products from bamboo pyrolysis. Bio-oil and non-condensable gas contained 50–60% of carbon and energy content when the pyrolysis temperature was >400 °C (Chen *et al.* 2015).

The method to obtain biocrude oil from high-temperature steam pyrolysis was studied by Kantarelis *et al*. (2010). The study obtained bamboo biocrude oil with a low O/C ratio and a HHV of 33.54 MJ/kg. Upon comparison of the data obtained by Kantarelis *et al*. (2010) with data from other literature (Jung *et al*. 2008; Lin *et al*. 2013), it was seen that the oil produced from high-temperature steam pyrolysis had a higher carbon and hydrogen content and lower oxygen content. Dong and Xiong (2014) studied the pyrolysis kinetics of moso bamboo, which was conducted in a conventional thermogravimetric analyzer and a microwave thermogravimetric analyzer. The results showed that the activation energy required for conventional pyrolysis was much higher than that for microwave pyrolysis (24.5 kJ/mol) at a similar heating rate of 160 °C/min. Based on the low activation energy obtained under microwave irradiation, Dong and Xiong (2014) suggested microwave heating as a promising method for biomass pyrolysis.

Qi *et al*. (2006) examined the influence of the final pyrolysis temperature of different bamboo species samples on the pyrolysis products. This study involved a fixed bed reactor and temperatures ranging from 573 °C to 873 °C. The resulting average biocrude oil yields ranged from 22.6% to 37%. The results showed that different bamboo species samples had different optimum temperatures for the formation of certain constituents or the maximum biocrude oil yield. For example, it was found that pyrolysis conducted at 773 °C and 823 °C produced the highest biocrude oil yield from *Neosinocalamus affinis* (34.1%) and *P*. *pubescens* (37%), respectively.

The same study by Qi *et al*. (2006) also observed the pyrolysis of bamboo using NaY-type zeolite as a catalyst. The bamboo species used in the study were *Bambusa rigida*, *P*. *pubescens*, *Neosinocalamus affinis*, and *Dendrocalamus latiflorus*. After catalysis, the liquid yield for all the samples noticeably increased from the range of 19.7 wt.% to 53.3 wt.% to the range of 64.1 wt.% to 68.8 wt.%.

Gaseous Fuel

In addition to converting bamboo biomass to solid or liquid fuels, there are alternative methods of utilizing bamboo as an energy source by converting the lignocellulosic biomass to gaseous fuels. This gas is then able to be combusted for the production of heat and steam, and it can be utilized in internal combustion engines or gas turbines, which results in the production of electricity, as well as mechanical energy. The methods of conversion fall into two broad categories, thermochemical and microbial conversion. Microbial conversion uses anaerobic digestion, it proceeds at milder temperatures, and has milder reaction rates (consumes little or no energy) than thermochemical conversion. Thermochemical conversion, such as gasification or pyrolysis, is characterized by faster conversion rates and higher temperatures, which can convert the organic fraction of biomass into a gas mixture with fuel value. These processes may yield more energy, but the net yield is reduced by the energy consumed in the process.

Combustible gas from thermochemical conversion

The thermochemical conversion processes include gasification and pyrolysis. Gasification is a conversion process that occurs at high pressures and temperatures in oxygen reduced conditions to produce fuel gases. Pyrolysis is similar to gasification, but with the absence of oxygen. Chen *et al*. (2014) examined the effect of the pyrolysis heating rate on the yields of bamboo products. Thermal energy is generated from a separate reaction chamber using the biogas that is produced during the pyrolysis reaction. Steam and electricity could then be produced by this thermal energy. By increasing the heating rate, the biogas yield increased from 29.7% at 5 °C/min to 42.9% at 30 °C/min. The non-condensable gas contained methane (CH_4) (11% to 15%), CO_2 (34% to 36%), CO (18% to 22%), hydrogen (H_2) (23% to 28%), and a small amount of hydrocarbons (C_nH_m). Ren *et al*. (2013) also reported that the main peaks of the IR spectrum for the biogas were CH_4, CO_2, CO, H_2O, acids, aldehydes, aromatics, ethers, and alcohols. Jung *et al*. (2008) stated that the HHV of the product gas increased with respect to the pyrolysis temperature, and the maximum HHV of the biogas was approximately 9 MJ/kg.

The use of steam as a medium in the gasification of bamboo powder has been studied by Kantarelis *et al*. (2010). The study reported that between 797 K and 865 K, 15% to 20% CO and 10% to 20% H_2 was obtained. An increased steam to biomass ratio resulted in an increase of the overall gas yield with increased yields of CO_2 and H_2, and reductions of CO and CH_4. Thus, the heating value of the gas was decreased. Wongsiriamnuay *et al*. (2013) performed a study to determine the effects of the reactor temperature (400 °C, 500 °C, and 600 °C) and gasifying medium (air and air/steam) on the product gas composition and heating value. The results showed that at 400 °C with air/steam gasification, there was a carbon conversion efficiency of 98.5%, maximum hydrogen content of 16.5% v/v, and tar conversion of 80%. The presence of a catalyst was found to promote the tar reforming reaction, thus providing an improvement to the heating value, carbon conversion efficiency, and gas yield, which was due to increases in H_2, CO, and CH_4. Wongsiriamnuay *et al*. (2013) also compared their study with other literature and the authors stated that the gas yields and carbon conversion efficiencies acquired from bamboo gasification were very similar to other biomass materials, but higher than cellulose.

Combustible gas from anaerobic digestion

Anaerobic digestion is a natural biological decomposition process in the absence of oxygen and produces a biogas that can be used to generate electricity and heat. The main end product of these processes is called biogas, which is the result of microbial degradation of carbon-containing compounds. The biogas produced in anaerobic digestion is mainly CH_4, CO_2, and a small amount of hydrogen (Nurliyana *et al*. 2015). Biohydrogen production from lignocellulosic biomass *via* dark fermentation by hydrogen-producing anaerobic microorganisms is attracting increasing attention (Lay *et al*. 2010; Hallenbeck and Ghosh 2012) due to the low pollutant emissions and high-value products associated with this approach. Hydrogen has a high energy content by mass basis (lower heating value of 120 MJ/kg) compared to that of CH_4 (50 MJ/kg), while the energy content by volume basis (10.8 MJ/Nm^3) is less than one third of CH_4 (35.9 MJ/Nm^3) (Balat 2008). Biogas can be employed as a fuel for engines, gas turbines, cells, boilers, and industrial heaters, and as a feedstock for chemical manufacture.

Kobayashi *et al*. (2004) reported that methane could not be produced from raw bamboo, but methane production can be enhanced through steam explosion. The maximum quantity of methane produced (215 mL), was obtained from 1 g of exploded bamboo (*Phyllostachys heterocycla*) at a steam pressure of 3.53 MPa and a steaming time of 5 min. Shen *et al*. (2014) looked at the influence of different pretreatments for the enhancement of the biochemical methane potential of bamboo. The results showed that all of the pretreatments enhanced the Chemical Oxygen Demand (COD) solubilization, though it was more pronounced with the alkaline and acid pretreatments. As reported by Shen *et al*. (2014) the best pretreatment in terms of methane yield was the alkaline pretreatment that resulted in a surplus of up to 88% methane yield compared to the raw or untreated sample.

Wu *et al*. (2014) modified *Klebsiella oxytoca* HP1 *via* metabolic engineering to improve the efficiency of hydrogen production from xylose, and reduce or eliminate the inhibitory effect of glucose. In the cited work, dark fermentation was performed using bamboo powder hydrolysates to test their efficiency in xylose utilization and hydrogen production. Hydrogen production from bamboo stalk hydrolysate was remarkably enhanced with the overexpression of xylulokinase and xylose isomerase in *K. oxytoca* HP1 in terms of total hydrogen yield, hydrogen yield per mole substrate, and hydrogen production rate. Also reported by Wu *et al*. (2014), the hydrogen yields from 1 g of pre-processed bamboo powder with the overexpression of xylulokinase and xylose were 78.8 mL-H_2/g and 83.7 mL-H_2/g, respectively.

MALAYSIAN PERSPECTIVE

Energy Crisis in Malaysia

A worldwide energy race is anticipated, both in the global superpowers and in developing countries, like Malaysia, which is looking forward to rapid economic growth. The high demand from the industrial and domestic sectors has contributed to the rapid growth of the energy demand. To grow towards a high-income economy, the country requires even more energy. An average Gross Domestic Product (GDP) growth of 6.5% has persisted for nearly half a century in Malaysia since its independence and has earned Malaysia one of the best economic records in Asia. Due to the high demand from both commercial and domestic sectors, a surge of 4.3% in electricity consumption was anticipated in 2016 in tandem with its GDP growth. Figure 1 shows the energy consumption in Malaysia by sector for 2016. By 2020, an estimated 10.8 GW of new generation capacity will be needed, given that 7.7 GW of existing capacity are due for sequestration. With an economic growth and the growing population exceeding 27.5 million, various concerns are constantly being raised by the government regarding the issue of increasing energy demand.

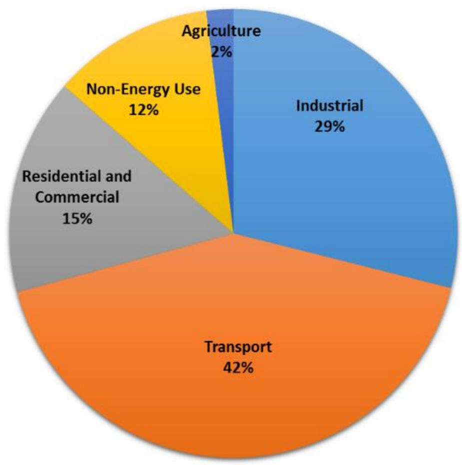

Fig. 1. Energy consumption in Malaysia by sector for 2014 (International Energy Agency 2016)

In the 8th Malaysia Plan (2001 through 2005), renewable energy was prioritized by the Malaysian government as the fifth source of fuel. This was stated in the Five Fuel Diversification Policy that succeeded the Four Fuel Diversification Policy from 1999 (Tenth Malaysia Plan 2010). During that time, an estimated RM 5 billion could be saved over a period of 5 years on the premise that 5% of renewable energy was to be utilized in the energy mix (Mariyappan 2000). In line with this objective, many efforts were undertaken to encourage the utilization of renewable resources, such as mini-hydro, biogas, solar, and lignocellulosic biomass, for energy generation (Ölz and Beerepoot 2010).

The Fifth Fuel Policy was continually given priority in the 9th and 10th Malaysia Plans (2006 through 2015), which provided a more conducive environment to support projects involving renewable energy. In addition, the 10th Malaysia Plan (2011 through 2015) announced a target of 985 MW, or 5.5% of grid-connected renewable electricity generation by 2015 (Ölz and Beerepoot 2010). In 2011, the Malaysian government launched the National Renewable Energy Policy 2011 after analyzing issues that resulted from the previous policies. The aim of the National Renewable Energy Policy 2011 was to improve the utilization of renewable resources to help in securing an electricity supply for a national level and for the development of sustainable socio-economics (Tenth Malaysia Plan 2010; Eleventh Malaysia Plan 2015).

Tenaga Nasional Berhad (TNB), with the largest generation capacity, is the largest electricity utility company in the country. Figure 2 shows the fuel sources in Malaysia power stations in 2014. Fossil fuels, such as oil, gas, and coal, are still in use by most of the major power stations in Malaysia to produce electricity. The Malaysian energy sector had been relying heavily on a single source of energy, which was oil, during the international oil crisis and when there were large leaps in oil prices in 1973 and 1979

(Rahman and Lee 2006). The government had advocated for the diversification of energy resources in the face of a possible prolonged energy crisis to reduce the sole dependence on oil. The alternative energy resources available at that time were coal and natural gas (Thaddeus 2002). The company TNB is heavily reliant on subsidised gas from Petronas for fuelling its power plants in Peninsular Malaysia, and there is a lack of cheaper gas, which results in no options other than to use more expensive alternatives for fuel. Coal is now one of the most common fuel sources in Malaysia power stations. Approximately 70% to 80% of TNB's coal requirements are purchased from third parties (National Energy Balance 2015). In turn, this has resulted in a high fuel cost for TNB as the use of coal has increased over time. Due to the high energy demand, the energy production from fossil fuels would be a contribution to the degradation of local environments.

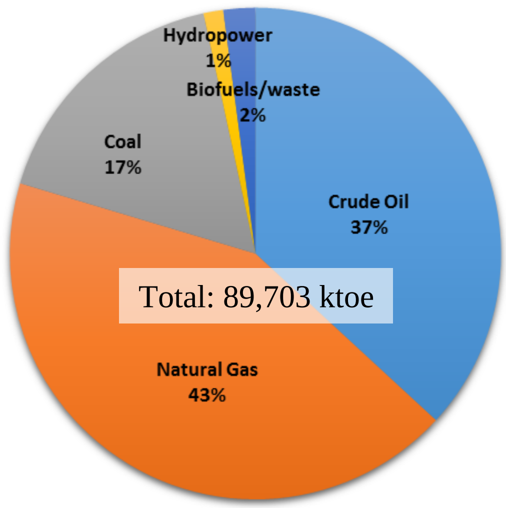

Fig. 2. Energy inputs in Malaysia power stations for 2014 (IEA 2016)

The Renewable Energy Policy and Action Plan aims at achieving 4,000 MW of installed renewable energy capacity by 2030, a target that raises the total capacity installed to 17%, from less than 1% today (National Biomass Strategy 2013). Five individual types of renewable energy are involved in the plan: solid waste, biomass, biogas, solar photovoltaic (PV), and small hydro. For biogas alone, the target is 410 MW installed capacity by 2030, which is only achievable through the conversion of most mills to utilize biogas, which was previously mandated *via* Entry Point Projects (EPP) 5 of the Economic Transformation Programme with a deadline of 2020. Bioenergy is a renewable energy derived from biomass. In Malaysia, the target is for biomass to energy conversion to reach 1,340 MW by 2030 (National Biomass Strategy 2013). Due to the efficiency of the plants constructed, the interim target of 800 MW in 2020 will require 6 to 9 million tons of biomass for this purpose. To meet this production target, biomass utilization with sufficient continuous supply sources in Malaysia seems to be a huge challenge.

Availability of Lignocellulosic Sources for Bioenergy Production in Malaysia

Lignocellulosic biomass can be obtained from many sources, either in the form of waste from the agricultural and forestry industry or specially cultivated energy crops, such as herbaceous plants, *e.g.* bamboo. The availability of these materials tends to be interrelated with activities of other major economic sectors, which include forestry, farming, paper, food processing, and building materials (Faaij 2006). Therefore, biomass for energy covers a wide range of materials that can be classified into five basic categories: (i) Energy crops that are grown specifically for energy applications, (ii) Virgin wood from all types of forestry, arboricultural, and industry related activities, (iii) Food waste during preparation and processing, and post-consumer waste, (iv) Agricultural residues from agricultural operations, and (v) Industrial waste and co-products from manufacturing and industrial processes (Mitchell and Connor 2004).

The usage of lignocellulosic biomass as energy resources depends on many factors, including a continuous supply of biomass, drying, storage, and production technology available. Of these factors, a sufficient continuous supply of resources poses a serious challenge for biomass utilization in Malaysia. The variability in chemical composition across individual varieties and environmental growth conditions is another characteristic to consider in selecting raw materials for suitable conversion processes. In Malaysia, the potential lignocellulosic feedstock for bioenergy consists of (i) Veneer mill and sawmill residues, (ii) Wood from existing plantations established for proposed pulp mills, veneer, or sawlogs, (iii) New plantations on pulpwood regimes established primarily for producing biomass, (iv) Harvest residues produced as a by-product from the logging of existing plantations, (v) Biomass produced as a by-product of the palm oil industry, and (vi) New woody and non-woody short rotation plantations, such as grasses, canes, and bamboo (National Biomass Strategy 2013). The feedstock volumes that are potentially available in Malaysia are shown in Table 3. The most promising feedstock is forest residues and dedicated short-rotation crops.

Table 3. Potential Feedstock for Pellets, Biofuels, and Bio-based Chemicals (National Biomass Strategy 2013)

Item	Potential Volume (BDMt/annum)
Mill residues	300,000
Export woodchips	200,000
Existing plantations – no pulp mill	1,000,000
Existing plantations – pulp mill proceeds	670,000
New plantations	450,000
Harvest residues	400,000
Arundo donax (16,700 gross ha)	400,000
Bamboo (17,000 gross ha)	200,000

Lignocellulosic biomass is an indigenous energy source, and the availability of these materials tends to be intertwined with activity of the major economic sectors of the respective country. Undoubtedly, residues from processing mills is a great choice as a source for biomass fuel production due to its current abundance. Nonetheless, the capacity of the biomass supply has to meet the demands from consumers and power stations. Residues from processing mills is a by-product whose availability largely depends on the primary production of the industry. Sawmill and veneer mill residues are also available in a substantial amount, but there are competing uses from existing users (for particleboard, MDF, and export woodchip), and these may cause an unsustainable amount for bioenergy production and increasing cost. Additionally, these lignocellulosic biomass from processing mills, combined with extraneous materials (residues may contain major amounts of bark, leaves, needles, dirt, rocks, and traces of chemicals from adhesives and preservatives) may not be suitable for certain biofuel production with stringent standard specification requirements and can cause substantial production inefficiencies. If fuel from lignocellulosic biomass is intended to be used as a commercial fuel, there is a need to look for alternative sustainable feedstock resources, such as energy crops, to support the bioenergy production.

Increasing the lignocellulosic biomass yield can be achieved *via* energy crops. The ideal energy crop possesses characteristics that include high yield, low production costs, low nutrient requirements, and a composition with low amounts of contaminants (McKendry 2002). Various studies on the long-term contribution of biomass to the future global energy supply have highlighted dedicated energy crops as a major potential solution for increasing this supply (Smeets *et al*. 2007; Berndes *et al*. 2003). These crops are fast-growing plants or trees that are harvested specifically for energy production. Ideally, these would allow for fuel to be grown, thus reducing the dependence on fossil fuels and vulnerability to disruption in the energy supply. Bamboo is among the fastest-growing plants in the world. Certain species of the 45 different genera of bamboo were reported as the fastest growing plant in the world, and have been found to grow 91 cm/d or at a rate of 0.00003 km/h. These desired characteristics depend highly on the local climate, soil conditions, and access to water. Above-ground biomass of *Thyrsostachys siamensis* in Thailand (14° N; elevation 60 m; mean annual temperature and rainfall, 28° C and 950 mm) varied from 11 to 54 t/ha, with a mean value of 32 t/ha, and mean stand height ranged from 5.5 to 9.9 m (Suwannapinunt, 1983). In Malaysia, bamboo has the entire year to grow, and it would be expected to outgrow bamboo in temperate climates on an annual basis, even if their instantaneous growth rates are not as high. In this framework bamboo provides a lot of opportunities. Unlike *Arundo donax*, bamboo is a hardy plant which a range of ecological advantages, and as a material it can be supplied in a sustainable way to different industries. Although bamboos are grasses, they possess the remarkable ability to sequester carbon through photosynthesis and to lock carbon in the fibrous root system which is an important aspect of the forest ecosystem and the carbon sink (Sijimol *et al.* 2016). The use of bamboo as raw material for industry or bioenergy is a completely different approach compared to high end uses such as handicrafts, utensils and bamboo parquet. Considering competing material interests from other industries in which the bottom parts of the bamboo are usually used, the top and middle parts could be of interest for the bioenergy sector. How to implement this into an efficient concept of silviculture treatment and biomass supply might be part of additional research.

Availability and Production of Bamboo in Malaysia

Bamboo in Malaysia undergoes sympodial growth. It is estimated there are 50 bamboo species in Peninsular Malaysia, which are from the seven genera of *Bambusa*, *Dendrocalamus*, *Dinochloa*, *Racemobamboos*, *Schizostachyum*, *Thyrsostachys*, and *Gigantochloa*. The most common species extracted are *Gigantochloa scortechinii, G. levis, G. ligulata, Dendrocalamus asper, Bambusa blumeana, Schizostachyum grande*, and *S. zollingeri*. The extent of area covered by bamboo in Malaysia was estimated to be approximately 0.67 million ha in 2010, or approximately 3.8% of the total bamboo area in

Asia (Kuehl 2015). There is potentially 200,000 BDMt/annum (Bone Dry Metric Ton per Annum) of bamboo biomass available in Malaysia (National Biomass Strategy 2013). The total biomass of monopodial bamboo was estimated between 9 ton/ha to 30 ton/ha, and 10 ton/ha to 37 ton/ha was estimated for sympodial bamboo species (Kuehl 2015).

In natural stands of *Gigantochloa scortechinii* in Kedah, Malaysia the average number of culms per clump was 19 and the basal area in the 1 ha research trial plot was 12.32 m^2 (Azmy 1991). The shoots grew faster during the day time and the maximum height was 12.5 m after 10 weeks. A single application of 2 kg of compound fertilizer NPK (15:15:15), increased the sprouting of shoots by 30% annually (Azmy 1992). Table 4 shows annual standing crop production of the common bamboo species in Malaysia.

Table 4. Annual Standing Crop Production of the Common Bamboo Species Available in Malaysia.

Bamboo Species	Weight of dry weight culm (kg)	Standing crop production of dry weight culms (t ha^{-1} yr^{-1})	Location of bamboo stand	References
Gigantochloa scortechini	16.6	72	Malaysia	Othman, 1992
Gigantochloa levis	12.5	116	Philippines	Suzuki and Jacalne 1986
Dendrocalamus asper	59.4	267	Philippines	Philippine Council for Agriculture 2009
Bambusa blumeana	27.6	120	Philippines	Dransfield and Widjaja 1995
Schizostachyum grande	4.25	20	Malaysia	Mohamed *et al.* 1991
Schizostachyum zollingeri	8.6	28	Malaysia	Dransfield and Widjaja 1995

Dendrocalamus asper has the highest standing crop production of dry weight culms of 267 t ha^{-1} yr^{-1} among the common bamboo species available in Malaysia. During harvesting, mature culms of bamboo are selectively harvested. Clear-cutting of bamboo is rarely practiced in clump-growing bamboo, known as sympodial-type bamboo, as commonly found in Malaysia. The clear-felling of sympodial bamboo stands is a common silvicultural practice in removing dead culms following mass flowering events and retaining sprouts of young shoots that will form in the next crop. Because flowering is very irregular and occurs over a long period of time, the practice of clear-felling as a silviculture practice is rarely performed. Clear-felling of old culms of bamboo to reduce congestion was reported being practiced in certain parts of India (Banik 2015). Azmy (1992) reported that a 40% felling intensity increased the number of culms produced. The bamboo is cut to a certain length to facilitate carrying the product out from the forest to the nearest road, before being transported to the mill. Different bamboo harvesting practices in different countries in the region have been well documented by Banik (2015).

Bamboo is commonly cultivated in rural areas for daily use by local communities and in urban areas as ornamental plants. In Peninsular Malaysia, the major products from bamboo are furniture, chopsticks, musical instruments, toothpicks, picture frames, handicrafts, and ornamental plants. Additionally, bamboo is also used for landscaping gardens in public and private areas. In recent years, there has been an increasing emphasis on extending the usage of bamboo for bioenergy (Kantarelis *et al*. 2010; Wongsiriamnuay 2013; Chen *et al*. 2014; Dong *et al*. 2014; Li *et al*. 2015b). New processing techniques with major technological breakthroughs can lead to the increased use of bamboo to generate electricity, heat, or liquid fuels for motor vehicles that have substantially lower environmental impacts than traditional fossil fuels.

CONCLUSIONS AND FUTURE PROSPECTS

This paper reviewed the use of bamboo as a potential feedstock due to its high biomass production and availability of knowledge and technology to promote bamboo on a commercial plantation scale. Different routes were outlined for the processing of bamboo into solid, liquid, and gas fuels. For the biochemical platform, sugar conversion and products yield are summarized using the reported literature data. A different scenario of producing fuels using the thermochemical route has also been presented. With the help of this review one can understand what has been accomplished so far in this field and identify other barriers which can be overcome in the near future for commercially producing biofuels from bamboo in a lignocellulosic biorefinery.

The establishment of commercial plantations is fundamental to the sustainability of the resource supply. Despite the fact that many studies have been conducted, there is a need to look into the relationship between the quality of biofuel and the maturity of bamboo culms. A limited study conducted using freshly cut samples showed that there is a direct relationship between the two, but more conclusive evidence is required through testing of bigger samples collected from different locations and different storage periods. It is noted that the chemical compositions of bamboo may be affected by different storage times and different cultivation techniques, which warrants further investigation. The effects of varying the parameters in hydrolysis, fermentation processes, and thermo-chemical conversion to produce various forms of biofuel have also been studied, but more studies specific to local bamboo species in Malaysia should be conducted.

Lignocellulosic biomass recalcitrance to saccharification is one of the major obstacles to cost-efficient production of biofuels and value-added biochemicals from bamboo. The recalcitrance of bamboo has been well documented for its resistance in releasing sugars. Additional research into the ultrastructure of the components of the cell walls in the various bamboo cultivars would be very useful in increasing the future yield of saccharides and ethanol from bamboo. In tandem with increasing biomass yields, a focus should be placed on plant breeding research pertaining to the modification of the chemical composition of bamboo with the aim of reducing recalcitrance to improve bioconversion. Advancements in agronomy, genetics, and conversion processes will undoubtedly help to increase the feasibility of biofuel production from bamboo. Environmental, social, and economic components with regard to acquiring larger areas for bamboo supply also need to be addressed.

Many developed countries have changed to alternative sources of energy that are more environmentally friendly. However, Malaysia has yet to adopt the technology, in spite of the abundant supply of biomass material suitable for biofuel production and have in place the appropriate policies on alternative energy. With a greater commitment to address any shortcomings in utilizing bamboo biomass for biofuel production, Malaysia could be in a better position to be on par with developed nations in the use of biomass as an alternative source of energy. Alternatively, bioenergy might provide a market for utilization of waste materials from thinning/harvesting of bamboo stands grown for other purposes.

The economics of bamboo biofuel production in Malaysia require thorough evaluation, both for single-use and multiple-product scenarios. Large-scale trials are needed in order to develop recommendations for cost-effective establishment and stand management. Solid biofuel for combustion has the largest potential to contribute to Malaysia energy demands and even more to the economy. This is due to the technologies for producing solid biofuel and generating energy out of solid biofuel for heat, electricity or both are mature, offering efficient and reliable processes. Besides, bamboo is quite high in lignin content, and this makes it a desirable species as an energy crop for solid biofuel production. Over the past few years, the development of products from biomass through the pyrolysis technique has been intensively researched. Three form of biofuel are always produced during pyrolysis; gas (syngas), liquid fuel (bio-oil) and solid fuel (char). However, the proportions can be varied over a wide range by adjustment of the process parameters. Through pyrolysis rather than combustion, biomass can lead to carbon negative liquid, gaseous and solid fuels. The main objective of a sustainable biorefinery system is to produce multiple products using combination of technologies. So there is a need to integrate process operation, reactor and catalyst design to improve the effectiveness of different processes used for bamboo biofuels production in a typical biorefinery system.

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