Bamboo for Biomass Energy Production

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Energy consumption in human society has increased as more energy supplies are required to meet the needs of the world's growing population. However, there is a major concern about fulfilling energy demand while reducing reliance on fossil fuels. Bamboo-based biomass has great potential for use as a raw material for the production of biofuels and bioenergy. Bamboo possesses excellent fuel qualities that can be converted into solid, liquid, and gaseous biofuels. Hence, the cultivation and harvesting operations must be performed efficiently to ensure that the availability of this biomass is sufficient to meet the demand for biofuel production. Several studies have shown that the micropropagation technique has increased bamboo production and that proper bamboo plantation management can benefit both the environment and society. Nevertheless, there are several challenges in bamboo cultivation and biofuel production, such as environmental impact from land management and economic risk from the industrial supply chain. Bamboo-producing countries, including Malaysia, have initiated several policies to propose strategies for sustaining the bamboo industry.

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INTRODUCTION

Modern applications, such as the use of air conditioners, chargers, and even aircraft, contribute to the consumption of energy. This energy is generated by utilizing physical or chemical resources. Current society consumes and depletes the planet's resources faster than they can be replenished (Crețu *et al*. 2019). Energy consumption has increased from 8,589 million tonnes oil equivalent (Mtoe) in 1995 to 13,150 Mtoe in 2015 (Dong *et al*. 2020). This situation arises as more energy resources are required to meet the needs of the world's growing global population (Rodionova *et al*. 2017). The current global population is 7.7 billion people, with a potential increase up to 11 billion by 2100 (McBride 2021).

Energy is fundamental for human activities, and the primary sources of energy used by humans are fossil fuels. Fossil fuels are chemical elements formed millions of years ago in the earth's crust as rich organic compounds and are able to supply 80% of the world's energy, as they can generate a vast amount of energy once burned (Morales Pedraza 2019; Rezania *et al*. 2020). These fuels continue to exist as the largest reservoirs for societal energy, and it is estimated that fossil fuels utilization will increase by approximately 18% from 2015 to 2035 (Senjyu and Howlader 2016; Yildiz 2018).

However, the availability of fossil fuels has begun to dwindle, raising public concern (Zhao and Ci 2018). Fossil fuels are not sustainable and can have adverse environmental effects such as global warming and air pollution. The combustion of fossil fuels results in the release of greenhouse gases and pollutants (Shindell and Smith 2019). This situation has caused public ailments, such as asthma and allergies, which have had and will continue to have an impact on society's health if the problem is not addressed (Eguiluz-Gracia *et al*. 2020). Therefore, a much greener alternative must be considered, and the use of biofuels as a substitute for fossil fuels can overcome this problem.

Biofuels are more environmentally friendly and cost-saving renewable energy, and thus a suitable substitute for fossil fuels (Sekoai *et al*. 2019). However, the cost of biofuel is estimated to be 2 to 7 times that of conventional fuel. But, the price of conventional fuel is projected to rise to 88.25 $/barrel in 2025, and may reach 99.39 $/barrel in 2030 (Hong *et al*. 2019).

Plant biomass is a renewable energy source that can meet up to 14% of the world's energy demands (Sindhu *et al*. 2019). Because of its excellent qualities, bamboo-based biomass can be used as a raw material for the production of biofuels and bioenergy (Singh *et al*. 2017). Despite the presence of other crops, bamboo plants can grow rapidly in any degraded area (Sharma *et al*. 2018). Bamboo possesses a rhizome-dependent system that enables the bamboo to grow fast (Goh and Zulkornain 2019). Bamboo can be harvested when the crops reach maturity, which takes about 5 to 12 years, without having to remove the clump every year for the next 30 to 50 years. Thus, bamboo biomass is a sustainable resource that can be used as a feedstock for biofuel and bioenergy production.

BAMBOO BIOMASS AND ITS CHEMICAL PROPERTIES

Bamboo Lignocellulose as Raw Materials

Plant life is one of the most abundant biological resources that can be used as raw materials (Vavilala *et al*. 2019). It can be transformed into various types of refined and improved products that include chemicals and biofuels (Ning *et al*. 2021). The three main components of biomass are cellulose, hemicellulose, and lignin (Chen *et al*. 2018). The biomass structure is made up of 30 to 50% cellulose, 20 to 40% hemicelluloses, 10 to 20% lignin, and an appropriate amount of carbohydrates (*i.e.* holocellulose, the sum of cellulose plus hemicelluloses) (Karagoz *et al*. 2019).

Urban grasses and herbaceous crops are commonly used as sources of lignocellulosic biomass due to their ability to generate higher content of biomass feedstock and short growth period (Chin *et al*. 2017). Furthermore, grass releases a large amount of oxygen that can increase the yield of biomass production (Pandey *et al*. 2018). Bamboo itself is a perennial woody grass that belongs to the Gramineae family and Bambuseae subfamily. Even though bamboo is included under the grass family, many of the larger bamboos have tree-like features. Due to its high lignocellulosic content and fast growth rate, bamboo holds great potential as a raw material for biomass production (Luo *et al*. 2018). The lignocellulosic components vary due to developmental stage, species, and management system of the bamboo.

Bamboo biomass is also an ideal raw material for bioethanol production due to its high cellulose content and low lignin level (Kumar *et al*. 2017). There are over 1575 species of bamboo with 116 genera discovered around the world. The lignocellulosic contents also vary within each bamboo species. It was reported that *Bambusa vulgaris* contains 61% to 78% of cellulose and 39% to 46% of lignin components while *Melocanna baccifera*, recorded 52.8% cellulose and 25.2% lignin (Sadiku *et al*. 2016; Tripathi *et al*. 2018).

Quality of Bamboo as Biofuel

The quality of the fuel is highly dependent on the raw material used (Tsoutsos *et al*. 2019). Hence, it is crucial to select feedstock that possesses excellent fuel characteristics that are fit for generating bioenergy. Fuel quality parameters, such as ash content, fixed carbon, calorific value, and volatile matter content, will determine the operational attributes and performance of the fuel. Ash is a by-product that is comprised of inorganic materials from the burning of fuel (Čubars and Poiša 2017). The ash compositions consist of major elements that are more than 10,000 mg/kg, minor elements ranging from 1000 mg/kg to 10,000 mg/kg, and trace elements that are less than 1000 mg/kg. The amount for ash content is usually in between 0.03% to 0.07% by weight (Sarkar 2015). A higher amount of ash can also cause difficulties during the automation of biomass combustion activity. Thus, it is crucial to choose the right source of biomass to become the feedstock.

Bamboo can be utilized as a plant biomass for biofuels production due to its fuel characteristics (Sharma *et al*. 2018). There are several bamboo species that possess fuel quality properties and can be used as biomass crops. *Bambusa emeiensis*, a clumping bamboo, was reported to produce low amounts of ash content (Chin *et al*. 2017). *Bambusa vulgaris*, *Bambusa tuldoides*, *Dendrocalamus giganteus*, and *Gigantochloa angustifolia* have lower ash contents compared to the biomass of rice husk and coconut fiber (Marafon *et al*. 2019).

Other fuel properties include volatile matter content and heating value. In the case of coal, the volatile matter refers to the gases that are comprised of sulfur, long-chain aliphatic carbon atoms, or aromatic hydrocarbons that are dispersed as the fuel is burnt at 950 °C in an oxygen-free environment (Ozbayoglu 2018). The heating value, also known as the gross calorific value, refers to the quantity of heat formed on combusting a unit volume of gas (Rena *et al*. 2019). Both parameters correlate to one another, whereby the heating value of the fuel will rise as the volatile content increases (Lisý *et al*. 2020). This becomes a drawback because the internal combustion engine can experience difficulties as more volatile matters are present in the fuel (Kumar and Anand 2019). The optimum percentage of volatile content in biomass for energy production was reported between 75% and 85% (Rusch *et al*. 2021). As for bamboo, the volatile matter content was demonstrated to range from 72% to 80% (Park *et al*. 2019). Hence, this shows that bamboo plants are suitable for biofuel production.

The moisture content of biomass is another crucial parameter for fuel analysis. Moisture content refers to the amount of water present inside the biomass (Sánchez *et al*. 2018). The combustion process can be influenced by this parameter, as the performance of the equipment and the net heating value will decrease as the moisture content in the fuel rises (Anisimov *et al*. 2016). Bamboo generally has lower moisture content relative to other biomass, but this is dependent on the age of the bamboo culms. Younger culms have a higher amount of moisture content (Gebremariam and Assefa 2018). It was reported that the moisture content for *Bambusa beecheyana* culms decreased from 71.2% to 59.4% after a year's growth (Vanghele *et al*. 2021). Therefore, much older bamboo culms have better potential for energy production.

Micropropagation of Bamboo for Sustainable Biomass Production

Substitution of fossil fuel with a bioenergy product is a great initiative to address the climate crisis. To generate bioenergy production, biomass can be used as a feedstock. The biomass from agriculture products is biodegradable, low in price, and sustainable (Ramlee *et al.* 2019). However, the availability of this biomass must be sufficient to fulfil the demand for biofuel production. Thus, the process of cultivation and harvesting operations must be done efficiently.

Practicing conventional methods in the mass production of planting materials in agriculture can be time-consuming. Hence, the use of the micropropagation approach can address this problem. This technique has been widely utilized in the agriculture and forestry sectors for large-scale production of high-quality plant materials that are free from any infections, which is necessary for biomass production (Oseni *et al*. 2018; Chawla *et al*. 2020).

Cultivation of bamboo plants using the micropropagation technique has been extensively used to increase its production. About 54 bamboo species have been successfully cultivated using this technique. These include *Dendrocalamus asper*, *Bambusa polymorpha*, *Arundinaria auriculata*, *Cephalostachyum pergracile*, and *Dendrocalamus giganteus* (Prutpongse and Gavinlertvatana 1992). Among the successful explant materials used were zygotic and somatic embryos and nodal buds (Tripathy *et al*. 2020).

The growth and development of the bamboo *in vitro* cultures were greatly affected by the type of media used. Murashige and Skoog (1962) medium showed significant results in buds proliferation and multiplication in contrast to Schenk and Hildebrandt's (1972) medium, Gamborg *et al.*'s (1968) B5 medium, Nitsch and Nitsch's (1969) medium, and the woody plant medium used by Lloyd and McCown (1980).

The application of plant growth regulators (PGRs) can also influence the growth of plants. Plant growth regulators, also known as plant exogenous hormones, can increase the number of cultures (Ankalabasappa *et al*. 2021). The PGRs that are widely used for bamboo cultures include 6–benzyl aminopurine (BAP), naphthalene acetic acid (NAA), indole 3-butyric acid (IBA), indole acetic acid (IAA), zeatin (ZN), kinetin (KN), and thidiazuron (TDZ), as summarized in Table 1.

Contamination is one of the biggest concerns for propagating bamboo through the micropropagation technique. Upon cutting the bamboo nodes, the intercellular space of the explants is exposed, allowing bacterial and fungal spores to invade (Ray and Ali 2018). Nevertheless, contaminants can be eliminated by using the surface sterilization technique. This technique can be performed using a sterilizing agent at an optimum concentration within a specific duration. Bavistin is a fungicide that is able to control fungal contamination in bamboo. It was reported that the *Bambusa balcooa in vitro* cultures were able to maintain sterility up to 21 days upon using bavistin for 10 min as part of the surface sterilization methods (Chavan *et al*. 2021). Apart from that, mercuric chloride ($HgCl_2$) is also widely used for bamboo surface sterilization. It was reported that a 20 min treatment of 0.1% $HgCl_2$ on *Dendrocalamus hamiltonii* was able to achieve 77.8% aseptic buds and 72% bud break (Jha and Das 2021). However, the gastrointestinal tract tissue can experience extreme irritation once $HgCl_2$ is ingested (Gupta *et al*. 2018). Thus, it is important to handle this corrosive chemical with caution. Nevertheless, there are other disinfectants that are able to sterilize the bamboo explant but with a much safer approach. Sodium hypochlorite (NaOCl) is a sterilizing agent that comes with an economical cost, yet it is still effective and safe (Pittard 2017). *Oxytenanthera abyssinica* seeds were able to achieve up to 98.76% clean cultures using 5% NaOCl with the addition of Tween-20 as a wetting agent, for 25 min (Daba *et al*. 2019).

Table 1. Successful Micropropagation of Bamboo Species Using Plant Growth Regulators

Species	Explant	Basal Medium	Plant Growth Regulators	Purpose	Reference
Bambusa balcooa	Node segments with auxiliary bud	Full MS	3 mg/L of BAP	Shoot multiplication	Thapa *et al*. (2018)
Bambusa maculata	Shoot tip	Full MS	1 mg/L of BAP + 0.5 mg/L IBA	Shoot induction	Larekeng *et al*. (2020)
Bambusa vulgaris	Inter-node	Full MS	3 mg/L of IAA + 0.3 mg/L of BAP	Shoot induction and root formation	Kaladhar *et al*. (2017)
Bambusa vulgaris	Shoot tip	Full MS	0.5 mg/L of NAA	Shoot induction	Hiswan *et al*. (2020)
Dendrocalamus asper	Nodes from the mature bamboo branches at age ± 6-month-old	¾ MS	3 mg/L of TDZ	Shoot multiplication	Gusmiaty *et al*. (2020)
Drepranostachyum falcatum	Node segments with single axillary buds	Full MS	4.5 mg/L of BAP	Axillary bud induction and proliferation	Saini *et al*. (2016)
Pseudoxytenanthera ritcheyi	Nodes	Full MS	0.22 mg/L of TDZ	Axillary bud proliferation	Sankar and Muralidharan (2017)
Pseudoxytenanthera stocksii	Nodes	Full MS	4.0 mg/L of BAP and 0.25 mg/L of naphthalene acetic acid (NAA)	Shoot multiplication	Rajput *et al.* (2019)
Thyrsostachys siamensis	Nodes	Full MS	2.5 mg/L of 2,4-dichlorophenoxyacetic acid	Callus formation	Obsuwan *et al*. (2019)

Bamboo as an Alternative Bioenergy Crop

The advancement of energy production in using biomass for feedstocks has increased over the years as awareness of the negative impacts of utilizing fossil fuels has increased (Bajpai 2020). Bioenergy refers to the utilisation of biological materials for energy purposes. There are two biological methods to convert biomass which include thermochemical and biochemical conversions.

Thermochemical conversion

Currently, thermochemical techniques for agricultural biomass conversion to energy appear promising and practicable. This technique offers high productivity with a broad range of biomasses that can be converted into numerous products. Moreover, it involves a complete use of the biomasses without having secondary waste as an after-product and it does not require a pre-treatment step in the conversion process.

Bioenergy is by far the most significant renewable contributor to the transportation and heating industries. It also plays a vital role in the power generating sectors for a few countries which includes Germany, France, Sweden, and Austria. Most countries are powering towards a low-carbon future by implementing bioenergy, owing to the fact that utilising bioenergy can protect the environment, contributes to the low-carbon energy systems while sequestering atmospheric carbon, and offers socioeconomic advantages.

While the study of thermochemical conversion method utilizing wood and coal dates back to the late 17^{th} century, the growth of such pathways implementing lignocellulosic biomass feedstock only began in the 1970s, as the first and second oil crises occurred (Mussatto *et al*. 2022). This method implements the breakdown of biomass structure in an oxygen or oxygen-free environment at high temperature (Wang 2018). Combustion, gasification, pyrolysis, and liquefaction are the main approaches for thermochemical conversion.

As for direct combustion, it is a technique whereby the biomass is burned within the range 1000 to 2000 °C in the open air. As for bamboo, the bamboo will firstly be dried and then often utilized as firewood to produce heat and electrical energy (Sharma *et al.* 2018). However, this technique is not efficient, as it can cause air pollution leading to a health problem.

Thus, the pyrolysis technique is a much-preferred approach for thermochemical conversion. For converting biomass material, pyrolysis is recognized as an effective method that is inexpensive and easy to use. Pyrolysis is a technique that involves the thermochemical breakdown of the carbonaceous organic at a high temperature without oxygen (Kumar *et al*. 2018). The products of the pyrolysis process would be biogas, biochar, and bio-oil. To produce vapors and a carbon-rich residue during pyrolysis, the heat required is between 207 to 434 kJ/kg (Garba 2020). The bamboo biomass feedstock can be subjected to both conventional and catalytic pyrolysis. It was reported that implementing zeolite or red mud as catalyst can decrease the liquid field yet increase the quality of bio-oil (Ly *et al.* 2020). The higher heating value for bamboo-based bio-oil increases to 27.97 and 27.03 MJ/kg while using HZSM-5 and red mud, respectively. Examples of bamboo species that had been subjected to pyrolysis treatment were *Bambusa rigida*, *P. pubescens*, *Neosinocalamus affinis*, and *Dendrocalamus latiflorus* (Chin *et al*. 2017).

As for gasification, it is a technique that used to turn solid biomass into flammable gas (Dincer and Ishaq 2022). The biomass will be burned partially at a regulated quantity of oxygen at high pressure and temperature, which is higher than 700 °C to create biogas. The biogas produced is used for generating electricity and bioethanol production. However, gasification agents such as air, oxygen, steam and carbon dioxide (CO_2) are required to react with the heavier hydrocarbons and solid char to produce carbon monoxide and hydrogen molecules as end products. It was reported that *Bambusa balcooa* Roxb, *Chimonobambusa callosa* Munro, *Bambusa bambos*, *Oxytenanthera albociliata* Munro, and *Dendrocalamus longispathus* are suitable for use as feedstock for gasification (Pattanayak *et al*. 2020).

Biochemical conversion

Biochemical conversion is technique whereby the biomass undergoes degradation using microbial enzymes (Sam and Barik 2019). This technique utilizes low energy consumption, as it is conducted at lower temperatures, which is made possible by the presence of microbes. The biochemical conversion technique creates a platform for the production of fuels and chemicals in the form of biogas, hydrogen, ethanol, butanol, acetone, and a variety of organic acids. There are two main pathways of biochemical conversion, and these are anaerobic digestion and fermentation. As for anaerobic digestion, it involves the use of different microbial species to degrade organic matter (Achinas *et al*. 2020). It is one of the most economical and sustainable technologies for lignocellulosic matter to recover energy in the form of biofuels. The end result for the anaerobic digestion is biogas, which largely consists of methane (CH_4), CO_2, and a slight amount of hydrogen. Nevertheless, the anaerobic digestion process can encounter instability due to the fluctuation of features and flow rates of the biomass (Ren *et al*. 2020). Adding hydrochar has been shown to increase biochemical processes and microbial growth, boosting buffer capacity and enabling direct interspecies electron transfer, which leads to an increase of CH_4 production (Cavali *et al*. 2022). Hydrochar is a carbon-based material created through hydrothermal carbonization (HTC) at temperatures ranging from 180 to 250 °C. Bamboo can aid as hydrochar to improve biochemical reactions during anaerobic digestion. It was reported that adding 4 g/ L of hydrochar from moso bamboo increased the CH_4 and biogas yields by 18% and 19%, respectively (Choe *et al*. 2021).

In fermentation, the biomass is converted into alcohol or acid, in an oxygen-free environment to produce a nutrient-rich residue (Gautam *et al*. 2019). Fermentation is carried out at atmospheric pressure and ambient temperature in the presence of bacteria. Many countries have utilised fermentation for the mass scale production of ethanol. There are two procedures for converting lignocellulosic biomass into biofuel that include the hydrolysis of cellulose to obtain reducing sugar followed by the fermentation of the sugars into biofuels (Patra *et al*. 2022). Implementing pre-treatment techniques such as alkali, acid, thermal, microwave, or enzymatic hydrolysis, can induce the formation of fermentable sugars in biomass. It was reported that an increase for both glucose and xylose yields were derived from different bamboo species pre-treated with hydrogen peroxide–acetic acid (HPAC) and enzymatic hydrolysis procedure (Song *et al*. 2022). The bamboo species, *Phyllostachys pubescens*, *Sasa coreana* Nakai, and *Sasa borealis*, were subjected to HPAC and enzymatic hydrolysis before undergoing separate hydrolysis and fermentation (SHF) processes. Approximately 90.1% of cellulose and 80.7% of xylan were converted into 311 and 103 g of glucose and xylose, respectively, through the SHF procedure. The final fermentation process produces 134 g of ethanol.

Livelihood Improvements, Climate Action, and Land Restoration

The production from the agriculture industry rises as the global population continues to grow (Verma 2018). Efficiency of the agriculture industry is commonly related to the improvement of livelihood for the rural population (Joshi and Narayan 2019). The agricultural activities include farming and livestock production and have a vital role in improving the nation's economy (Praburaj 2018). The bamboo plantation is also a part of agricultural activity that can benefit the environment and society.

The processes related to culm cuttings and managing bamboo crops are part of the agriculture activities that require labor-intensive measures to sustain the agriculture productivity, thus providing the opportunity for the community to generate income as well as improving agricultural skills (Kapur 2019). This initiative can eventually reduce the unemployment rate and increase the quality of life for the community. Moreover, farmers can improve existing incomes by selling bamboo culms and edible shoots from the plantation. It was reported that the global bamboo market is expected to increase from USD 1.82 billion in 2020 to USD 2.4 billion by the end of 2027. Thus, utilizing bamboo as part of the agriculture industry is a lucrative business that can increase the farmers' income.

However, improper management of agriculture activity can induce harmful impacts on the environment. Excessive agriculture activity can emit high amounts of greenhouse gases that can lead to climate change (Baccour *et al*. 2021). The agriculture industry was reported to contribute about 13.5% of greenhouse gas emissions globally (Mohammed *et al*. 2020). Carbon dioxide, methane, and nitrous oxide are the three major greenhouse gases that are currently drawing significant global concern. Based on their global warming potentials, these gases were estimated to contribute 72%, 19% and 6%, respectively (Olivier and Peters 2020). In the lower part of the atmosphere, these gases trap heat and allow less heat to escape back into space, thus potentiating a rise in global temperature with the increasing amount of these gases (Klugmann-Radziemska 2020; Yoro and Daramola 2020). As a consequence, there is a concern on the rise in global mean surface temperature (GSMT) and global sea level (GSL) at 29% to 35% and 11% to 14%, respectively (Ekwurzel *et al*. 2017).

Planting crops that can sequester as much carbon as possible can regain balance in the carbon cycle and help reduce the climate crisis. Bamboo has the ability to improve climate change issues by fixing carbon dioxide from the atmosphere (Thokchom and Yadava 2017). This evergreen plant acts as a carbon sink, whereby its durable products can store carbon for the entire lifespan of the product. Moso bamboo is one of the species that has a high capacity to sequester carbon and plays a crucial part in overcoming climate issues (Xu *et al*. 2020a). It was reported that moso bamboo sequestered between 6.0 and 7.6 million tonnes of carbon per hectare every year (Xu *et al*. 2018). Hence, this indicates that the approach is applicable in utilizing bamboo until further information is obtained to suggest otherwise.

Land degradation can occur due to the improper management of the agricultural area (Ahmad *et al*. 2018). Abadega and Abawaji (2021) reported that approximately 25% of the land has been degraded throughout the Earth. This issue has become more severe over the years as a consequence of human activities and climactic factors (Narayanasamy *et al*. 2020). Land degradation can lead to desertification, which can reduce the productivity of the land. Desertification is estimated to cause the loss of 20,000 km^2 of fertile land per year (Nunes *et al*. 2020). Yet the bamboo plant is still capable of surviving on degraded land aided by a small volume of fertilizers (Sharma *et al*. 2018). This is because bamboo possesses a unique root system that can withstand arid conditions. The restoration of land can also be developed with the cultivation of the bamboo plant, as it can recover fertility by supplying nutrients and decreasing the acidity of the soil (Abadega and Abawaji 2021). It was reported that *Bambusa vulgaris* biochar with a concentration of 20 tonne/ha was able to increase the fertility of the soil and nutrient cycling due to its carbon, phosphorus, and organic matter contents (Gutiérrez *et al*. 2021). Therefore, utilizing bamboo as biochar can improve the properties of the soil.

Environmental, Ecological, and Economic Risks and Challenges to Bamboo Cultivation

Although bamboo has beneficial properties, cultivating this plant on a large scale can also cause negative impacts on society. The production of bamboo biomass can give rise to environmental and ecological issues. Energy plays a significant role in the development of the economy and ecosystem (Del Real *et al*. 2020). As this situation occurs, the demand for biomass production to be utilized as a source of renewable energy increases. Unfortunately, this will eventually give rise to competition for the use of agricultural areas for food and fiber production (Searchinger and Heimlich 2015).

Considering the beneficial properties the bamboo plant offers for the economy and society, agricultural lands have been filled with bamboo plantations for the last two decades (Xu *et al*. 2020b). It was reported that bamboo forests cover 6.01 million hectares, with moso bamboo covering approximately 4.43 million hectares and a total of 1.58 million hectares for other bamboo species (Liu *et al*. 2018b). Nevertheless, people tend to practice monoculture to intensify the production of bamboo. Such practice can lead to the disruption of the ecosystem as well as decreasing the biodiversity throughout the forest and taxa (Ganeshamurthy *et al*. 2017; Wang *et al*. 2019). The deterioration of biodiversity can interfere with the overall productivity of the ecosystem.

Bamboo plantations can also give rise to economical risks for forest investment and management. Uncertainties of the natural growth processes for the bamboo plant could also be an issue for the production system. The bamboo plant itself could be a threat to other crops by invading other areas. This is mainly due to its vigorous rhizome root system. Bamboo is classified according to the growth patterns of its rhizomes, which can either be running or clumping bamboo. However, running bamboo is the main species that can possess the invasion mechanism (Xu *et al*. 2020b). In a single growth cycle, rhizomes of the running bamboo can extend horizontally over wide areas and are able to create new culms at the nodes (Lieurance *et al*. 2018). Bamboo can grow at a rate of 2 inches per hour and is able to reach a height of 60 feet in 3 months (Emamverdian *et al*. 2020). Hence, the bamboo plant could be a threat to other crops by invading other areas. Nevertheless, this situation occurs if the crops are not properly managed and eventually affect the well-being of the bamboo.

The Supply Chain and Challenges in Commercially Producing Biofuels

Sustainable supply chain strategies

Sustainable supply chain is the fundamental integration for business operations that allows corporations and their supply network to achieve economic, environmental, and social objectives (Florescu *et al*. 2019). In the context for the biofuel industry, the supply chain strategy is crucial for applying green fuel on a larger scale for the replacement of conventional fuels with economical cost and energy-efficiency. The supply chain of biofuel is comprised of biomass production, pre-treatment activity, storage, and the conversion of biomass into biofuel. Thus, it is important to prepare strategies for these activities, as they can affect the supply chain in the biofuel industry.

Economics is one of the major aspects that can impact the growth of the supply chain in the biofuel industry. The development and utilization of biofuels could be highly influenced by formal bodies and government intervention (Moncada *et al*. 2017). This situation occurs as the authority can act upon the distribution of income in many ways apart from taxes, transfers, and spending in various sectors such as agriculture, health, and education. Hence, this institution has the capabilities to stimulate production and increase the application of biofuels throughout the nation.

Therefore, planning and managing the bamboo-based biofuel industry must be done carefully, as future production depends on the sustainable supply chain. Figure 1 shows the two segments of the bamboo-based biofuel supply chain, where the upstream segment refers to the element input required for production, while the downstream segment involves the conversion of bamboo-based biomass into biofuel and its applications. Various factors can affect the preparation and administration of the bamboo-based biofuel supply chain. This includes ensuring that bamboo is accessible as a biomass feedstock all year round (Wahono *et al*. 2018). Implementing a harvest rotation cycle can secure the availability of bamboo, as this initiative will prevent the scarcity of raw materials from occurring. A mature crop that is well-managed is able to produce up to 25 tonne/ha/year (Van Dam *et al*. 2018). In addition, applying the tissue culture technique can aid in the production of bamboo plantlets for planting irrespective of seasonal variations. Each of these factors must undergo crucial decision making, starting from project planning to the final product (Atashbar *et al*. 2018).

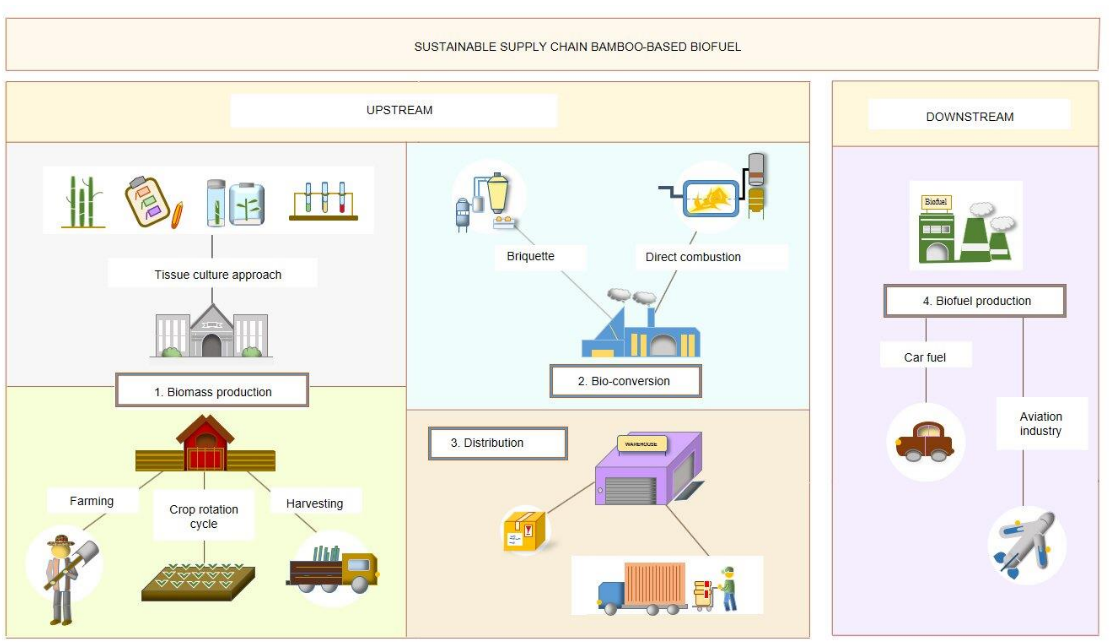

Fig. 1. Sustainable supply chain for bamboo-based biofuel

Current Challenges in Commercially Producing Biofuels

Despite the advantageous attributes of biofuels that can benefit the environment and society, there are a few challenges in biofuel production that need to be addressed. The crop feedstock is the main element of biofuels, whereby it is mainly from an agricultural industry. Hence, if the demand for biofuel production increases, then the use of land to cultivate only feedstock crops will also increase. This may cause a loss of biodiversity as farmers will implement monoculture activity to increase their targeted yield (Liu *et al*. 2018a). Biodiversity plays a significant role in making sure that the ecosystem is functioning and balanced (Mamabolo *et al*. 2020). However, the acceleration of agricultural activity will eventually disrupt the biodiversity of crop plants (Brown and Williams 2016).

The sources for renewable feedstock can be obtained using biotechnology approaches (Yi 2021). Nevertheless, the expenses involved in capital and developing bioethanol production are still high (Raud *et al*. 2019). The capital cost for ethanol production ranges from USD 3051 /kW to USD 4334 /kW (Brown *et al*. 2020). This is mainly due to the use of high-tech equipment in converting lignocellulosic biomass. In the long run, this situation can lead to technology and financial constraints for generating biofuels (Alam and Tanveer 2020). For Asian countries, the production of biofuels is attainable though most likely to be challenging for large-scale production (Elder and Hayashi 2018). This is because most Asian countries would not be able to afford to utilize bioenergy due to financial barriers (Pittard 2018).

Moreover, the global COVID-19 pandemic situation caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a current imminent challenge for the biofuel industry (Shereen *et al*. 2020). Society is facing a great challenge not only with health but with the instability of the economy as well. Social isolation restrictions such as 'lockdown' have been imposed to avoid the COVID-19 outbreak (Atalan 2020). During the lockdown, both the price and the demand for fuel dropped. Fuel prices declined 50% to 85% in 2020, based on the oil price of USD 30 per barrel (Anderson and Engebretsen 2020). This situation has caused biofuels to be less cost-competitive with the fossil fuel industry (Elleby *et al*. 2020). Harvesters were also unable to obtain the expected feedstock yield (Lim and Nimellnair 2021). It will eventually cause the demand for biofuels production to decrease because the request for feedstock yield could not be fulfilled.

MALAYSIA'S PERSPECTIVE

Energy has a significant role in providing support and stimulation for the socio-economic growth of a country. Nevertheless, the energy demand of a country varies based on several socioeconomic aspects (Kiliç and Özdemir 2018). These include population size, the development of technology, as well as the industrialization activity involved in the country. Malaysia is a newly industrialized country that aims to achieve high-income status with a population of 32.7 million. Over the last few decades, the economy in Malaysia has increased with substantial development of the gross domestic product (GDP) annually (Seng and Fauzi 2019). This situation has led to an increase in energy demand to spur the economy and accommodate population growth (Zakaria *et al*. 2021).

Malaysia relies heavily on fossil fuel as the power generation system. In 2016, Malaysia produced 156,665 gigawatt-hours (GWh) of electricity, wherein coal contributed to 48.4% (17,101 ktoe) of the resources (Hamzah *et al*. 2019). However, the resource for fossil fuels might deplete in 40 years to support the population growth and industrialization activity (Rezania *et al*. 2020). Thus, the utilization of renewable energy is necessary to replace the conventional power generating system.

Malaysia is one of the countries in Asia that is endowed with the most biologically diverse tropical rainforests. The forest areas comprise 63.2% of the land, which is about 20,456,000 hectares. Because of this, Malaysia is rich in renewable resources like biomass due to its geographical properties (Bujang *et al*. 2016). There are about 168 million tons of biomass being produced annually (Rezania *et al*. 2020).

Bamboo is one of the renewable lignocellulosic biomasses that is capable of producing bioenergy. This evergreen plant can grow fast and is able to produce a high amount of biomass yield annually (Azeez and Orege 2018). There are certain bamboo species that are recognized as the fastest-growing plants, because the rate of growth is up to 3 cm/h (Chin *et al*. 2017). As for Peninsular Malaysia, about 50 species of bamboo have been discovered in this region. It was estimated that the monopodial and sympodial bamboo can generate about 9 to 30 tonne/ha and 10 to 37 tonne/ha of their total biomass, respectively. Hence, due to the high availability of this monocotyledon plant, bamboo can be a good source for bioenergy production in Malaysia.

Malaysia has already made efforts to improve its bamboo plantations. Three national policies have highlighted the need in developing the bamboo industry as a source of non-timber forest products. As for the National Timber Industry Policy (2006 to 2020), this policy emphasizes bamboo to be utilized as raw material for the development of the downstream timber sector (Maguigad 2020). This policy also suggested surveying the accessibility of bamboo resources for crafting purposes in cottage industries. In contrast, the National Agriculture Policy (1998 to 2010) highlights the participation of the private sector to maximize the use of undeveloped land by cultivating bamboo under agroforestry activity. It is estimated that there are 30,000 hectares of undeveloped lands in Malaysia (Azizan *et al*. 2020). Thus, utilizing the lands for agricultural activity can benefit the local communities and the environment. The National Forest Policy, 1987 (revised in 1992) underlines the need to increase the non-timber forest resources using scientific and sustainable approaches (Moktshim 2020). This policy also emphasizes the involvement of local citizens participating in forestry programs. All of the policies involved provide strategic suggestions and policy direction for the bamboo industry. This is to ensure that the bamboo industry in Malaysia remains competitive and sustainable.

CONCLUSIONS

1. This paper reviewed the use of bamboo as a potential feedstock for bioenergy production. Bamboo consists of high lignocellulose content with a fast growth rate and possesses excellent fuel qualities.
2. The micropropagation technique can increase bamboo production, which is crucial to fulfilling the availability of biomass.
3. The two biological methods (thermochemical and biochemical conversions) might be promising and practicable to convert bamboo biomass for power production.
4. Further research regarding sustainable ways to utilize bamboo-based biomass may help in the future power production of the bioenergy industry.
5. The development of biofuels and the bamboo industry could be highly influenced by formal bodies and government interventions.

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