STUDY ON THE VALORIZATION OF RICE WASTE BY USING TORREFACTION METHOD

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ABSTRACT

Biomass plays a crucial role as the source of renewable carbon which can be utilised in the production of biofuels to bring about the desired fossil energy independence in the future. However, the raw biomass itself has some undesirable properties such as high moisture content, low energy density and deterioration after a short duration of storing period. Hence, a thermochemical process, commonly known as the torrefaction technology or mild pyrolysis is normally used to preliminary treat the biomass to enhance its physical properties. Torrefaction process is also acknowledged as a valorisation process of biomass. By means of this technology, it not only helps to increase the calorific value of the biomass but also eases the process of storage, transportation, and usage of biomass. In terms of abundance, rice waste is one of the vital biomass contributors in Asia. Rice is the primary calorific source for mankind and its significance is comparable to maize, sorghum, wheat, barley and the other major crop grasses from the family *Poaceae (Gramineae)*. In Malaysia, an enormous amount of biomass is generated annually after the harvesting of rice. As for this study, the objective is to investigate the effect of torrefaction on the physical characteristics of the rice waste at different temperature. The torrefaction is carried out at 220 ℃, 250 ℃ and 280 ℃ with the heating rate of 15 ℃/min and residence time of 30min. Generally, moisture content, calorific value characterization as well as constituents' degradation under different temperatures will be inspected on both the raw and torrefied biomass to reveal the effect of torrefaction on the biomass. The preliminary results show that the moisture content of rice husk is 6.53wt% while rice straw is 8.31wt%. The slight deviation from the literature source is deemed to be reasonable due to different pre-drying period. Next, from the experimental results, it is noticeable that torrefaction increases the calorific value of the biomass by 3-17% for rice husk and 4-20% for rice straw. At the same time, it also removed all the moisture content in the rice biomass. The mass yield of the torrefied rice-based biomass is between 78.98-91.20% for rice husk and 82.28-89.85% for rice straw. Meanwhile, the energy yield for rice husk is in the range of 92.51-95.41% and 93.77-98.83% for rice straw after torrefaction. Diagnosis on the physical characteristics of the torrefied biomass is accomplished through Thermogravimetric (TGA) analysis and Fourier Transform Infrared (FTIR) Spectroscopy. In conclusion, the aim of this study is achieved by proving that 250 ℃ is the optimum torrefaction temperature for the conversion of rice waste into valuable biofuels.

ABSTRAK

Biomas memainkan peranan penting sebagai sumber karbon yang boleh diperbaharui serta boleh digunakan dalam pengeluaran biofuel untuk membawa kemerdekaan tenaga yang diingini pada masa akan datang . Walau bagaimanapun , bahan mentah itu sendiri mempunyai beberapa ciri-ciri yang tidak diingini seperti kandungan air yang tinggi , ketumpatan tenaga yang rendah dan mengurai selepas tempoh penyimpanan yang singkat. Oleh itu, satu proses termokimia , biasanya dikenali sebagai teknologi torrefasi atau pirolisis ringan yang digunakan untuk merawat biomas demi meningkatkan sifat-sifat fizikalnya. Proses torrefasi juga diakui sebagai satu proses peningkatan nilai biomass. Teknologi ini bukan sahaja dapat membantu untuk meningkatkan nilai kalori biojisim tetapi juga memudahkan proses penyimpanan, pengangkutan, dan penggunaan biomass. Dari segi quantitinya, sisa beras adalah salah satu penyumbang biomass paling penting di Asia. Beras merupakan sumber kalori utama bagi manusia dan kepentingannya adalah setanding dengan jagung, sekoi, gandum, barli dan tanaman lain-lain dari keluarga *Poaceae (Gramineae*). Di Malaysia, jumlah biomass yang sangat besar dihasilkan setiap tahun selepas penuaian padi. Bagi kajian ini, tumpuan akan diberikan kepada pencirian sifat-sifat fizikal biomass beras torrefied bawah berbeza suhu 220 °C, 250 °C dan 280 °C dengan kadar pemanasan 15 ℃/min dan masa operasi 30min. Secara amnya, kandungan kelembapan, nilai kalori pencirian serta degradasi juzuk 'di bawah suhu yang berbeza akan dianalisasikan terhadap kedua-dua biomas mentah dan torrefied untuk memberitahu kesan torrefaction arah biojisim. Keputusan awal menunjukkan bahawa kandungan lembapan sekam padi adalah 6.53 wt% manakala jerami padi adalah 8.31wt %. Sisihan sedikit dari sumber sastera itu dianggap sebagai munasabah kerana tempoh pra-pengeringan yang berbeza. Seterusnya, keputusan uji kaji adalah ketara kerana nilai kalori biojisim berjaya ditingkatkan sebanyak 3-17 % untuk sekam padi dan 4-20% untuk jerami padi. Selain itu, torrefasi juga membantu untuk membuangkan semua kandungan lembapan dalam biomas padi. Jisim biomas selepas torrefasi adalah dalam lingkungan 78.98-91.20% untuk sekam padi dan 82.28-89.85% untuk jerami padi. Kelebihan proses torrefasi ialah dapat memudahkan proses penyimpanan, pengangkutan, dan penggunaan biomas. Sementara itu, hasil tenaga untuk sekam padi adalah dalam lingkungan 92.51-95.41% dan 93.77-98.83% untuk jerami padi selepas torrefasi. Diagnosis ke atas ciri-ciri fizikal biojisim dicapai dengan analisis Termogravimetri (TGA) dan Fourier Transform Infrared (FTIR) Spektroskopi. Kesimpulannya, tujuan kajian ini berjaya dicapai dengan membuktikan bahawa 250 ℃ adalah suhu torrefasi optimum bagi penukaran biomas padi kepada biofuel yang berharga.

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dt	change in temperature
e_1	correction in calories for heat of formation of nitric acid (HNO_3)
e_2	correction in calories for heat of formation of sulphuric acid
e_3	correction in calories for heat of combustion of fuse wire
m	mass of sample
W	initial weight of raw material
W_s	weight of dry solid
X_t	moisture content
H_g	heat of combustion in Parr Bomb Calorimeter in cal/g

LIST OF ABBREVIATIONS

CV	Calorific value
DTG	Derivative Thermogravimetric
EY	Energy yield
FTIR	Fourier Transform Infrared Spectroscopy
GHG	Greenhouse gases
MAP	Microwave-assisted pyrolysis
MY	MassYield
TGA	Thermogravimetric Analysis
VOC	Volatile organic compound

1 INTRODUCTION

1.1 Motivation and Statement of Problem

In the recent years, our world has experienced the mitigation of climate change together with the energy crisis due to the depletion of non-renewable resources of energy such as petroleum oil, natural gas and coal. This phenomenon has promoted the considerable attention towards the energy utilization from the sustainable biomass resources (Mckay, 2006). Like forestry biomass, the great amount of organic constituents, mainly cellulose, hemicellulose and lignin, and high energy content are found in the agricultural waste, securing its place as one of the favourable biomass for energy production. However, the drawbacks of raw agricultural biomass are the heterogenous nature of the biomass and degradation with time. Furthermore, biomass has relatively low energy density and high moisture content in the untreated form compared to fossil fuel. Thermochemical conversions for example pyrolysis, gasification, and combustion are presently the most prominent pretreatment methods for energy intensification of biomass. In this study, the aim is to perform the mild pyrolysis on rice waste by manipulating the temperature parameter. Mild pyrolysis is a promising route in transforming the biomass waste into the stable, torrefied form at a lower temperature range of 200-300 ℃ in the absence of oxygen (Medic *et al*., 2012).

Generally, there are two approaches for the conversion: conventional torrefaction and microwave-induced torrefaction. Despite many researchers such as Goyal *et al*. (2008) Kirkels & Verbongm (2011) and Svanberg *et al*. (2013) have performed study on the application of torrefaction, but most of them emphasized on the microwave-induced method, there is very limited study accomplished using the conventional torrefaction method. Microwave pyrolysis is the latest technology invented after rectifying the defects of the conventional pyrolysis. The most successful feature of it is that its operation temperature is lower than the conventional pyrolysis (Shuttleworth *et al*., 2012). Nonetheless, microwave heating with the conversion of energy from the electrical energy to electromagnetic energy and lastly to heat, some energy will be lost and its efficiency will be reduced (Osepchuk & Fellow, 2002.). Complexity of the apparatus for the microwave heating is also a fact that we could not evade. In addition, cost of a microwave pyrolysis is also disproportional with its size (Russell & College, 2012). Although the advantages shown by the microwave pyrolysis, many characterizations of microwave pyrolysis process has yet to be discovered such as the side toxic products that might be produced due to the microwave radiation. Hence, in this study, conventional pyrolysis will be selected to carry out the torrefaction of rice waste as it is a cheaper and safer in terms of installation and handling.

Whilst in the selection of biomass, rice waste, the end product attained after the harvesting season which has low commercial value was being chosen. For convenient purpose, open burning is usually carried out to effortlessly settle the rice biomass disposal issue. The impact of this traditional handling of rice biomass is the released of greenhouse gases which contributes to global warming. When the raw biomass stalk undergoes torrefaction, the discharge of carbon dioxide, can be reduced by 1.49-1.01mmol/g, about 69-79% as compared to the raw biomass (Chen et al., 2013). The theory lies behind this is that the release of CO_2 is greatly due to the decomposition of hemicellulose and cellulose during pyrolysis (Chen & Kuo, 2011). Hence, this study is not only going to provide a fundamental support in commercializing and turning rice waste into wealth by investigating the physical properties enhancement during torrefaction process which favors the rice waste to serve as an energy generation feedstock but also to alleviate the elevating environmental issue.

1.2 Objectives

The following are the objectives of this research:

- o To investigate effect of torrefaction on the physical characteristics of the rice waste at different temperature.

1.3 Scope of This Research

The following are the scope of this research:

i) Perform an experimental study on the pyrolysis process at the temperature of 220 ℃, 250 ℃ and 280 ℃ with the customized Grade 304 stainless steel tubular reactor at constant residence time of 30minutes.

ii) Characterization analysis on the enhancement of physical properties of torrefied rice waste in terms of calorific value (CV), percentage of mass yield as well as energy yield, FTIR and TGA

iii) Inspection on the heating rate in the customized Grade 304 stainless steel tubular reactor during the pyrolysis process by the utilization of a thermocouple.

1.4 Organisation of This Thesis

The structure of the reminder of the thesis is outlined as follow:

Chapter 2 provides a description of the applications and general design features of biomass pretreatment technologies. A general description on the scale up feasibility and current status of the torrefaction is elaborated. Lastly, a summary on the previous parameter practice is being identified to give an overview on the variation by manipulating each parameter.

Chapter 3 gives a review on the characterization efforts in the process of investigating the effect of torrefaction on the physical properties of biomass. This chapter also provides a discussion on the modification made in the torrefaction process.

Chapter 4 is devoted to a comparative study on the experimental results with the literature value. Further discussion and justification regarding the deviation of data are provided. Overall, a detailed delivery of preliminary results and final results such as the moisture content, calorific value, mass yield and energy yield is presented with proper clarification in this chapter.

Chapter 5 concludes the optimum torrefaction temperature for both rice husk and rice straw. The decision making is justified according to the physical properties analysis in Chapter 4.

2 LITERATURE REVIEW

2.1 Overview

This chapter presents the previous studies of torrefaction, pretreatment technology that has been invented to elevate the status of biomass as an alternative fuels. The chapter starts with the classification of the types of biomass and the method to obtain it until the real life application of the advanced technique in the scale up plant, precise and details explanation are stated. From the minor to the major reasons given, factors that influence the selection of rice waste as a study material are further elaborated. In addition, extensive reviews and critically argues on the energy conversion routes and previous research parameters also led to the objective temperature studies formulated for the torrefaction process. Lastly, the properties study in this research will be reviewed and discussed with proper justification.

2.2 Biomass Sources

The word biomass formally is just a scientific term being used in the field of ecology to refer to animal and plant. After the crisis of fossil fuels arises, the interpretation of this word has gone beyond the ecological field and came to incorporate the term "biological resources as energy sources" (Ministry of Agriculture, Forestry, and Fisheries, Japan, 2008). This concept has been instilled in the mindset of many people since many researches vigorously proposed that alternative path of energy sources should be uphold for energy security in the future based on the Ministry of Agriculture, Forestry, and Fisheries, Japan (2008). Typically, the biomass sources include the forestry and agricultural crops' residues, industrial wastes, animal residues, sewage and municipal solid waste. Among all these, the main concern was driven towards the sources of biomass derived from the agricultural and forestry due to the potential for energy conversion. According to United Nations Environmental Programme, UNEP (2009), 140 billion metric tons of agricultural biomass is produced globally. This vast volume of biomass can be transformed into a tremendous amount of renewable energy proportionate to the energy generated by 50 billion tons of oil. Thus, the biomass wastes have a bright potential to be commercialized and suitable for large-scale industries. Generally, biomass can be categorized into various types either in the form of shells, fronds, stovers, straw, stalks, seed, husk or trunk.

2.2.1 *Agricultural Biomass*

Green biomass is a scientific term often used to describe the agricultural wastes. Basically, biomass is derived from the building blocks of plants, carbohydrates which are constructed in a process called photosynthesis. During photosynthesis, the cellulose in the plants will capture the solar energy from the sunlight, carbon dioxide (CO_2) from the atmosphere and further oxidised the CO_2 into chemical energy. This cyclic consumption of CO_2 produced from industrial activities, vehicles and respiration of organic matters is therefore important in maintaining the concentration of CO_2 of the atmosphere. Uncontrolled burning of fossil fuels will only discharge excessive amount of CO_2, however if biomass is being used as a fuel, the carbon dioxide released to the atmosphere is merely seems as a growth cycle for new biomass as it can be encountered by replanting the harvested crops (McKendry, 2002).

Recently, community is dedicating a growing effort towards the development of renewable energy. The awareness is always inclined to the green biomass due to environmentally sustainable criteria for long term exploitation. This promotes extra emphasize on the valorization of local resources mainly the agricultural biomass (McKendry, 2002). The familiar biomass feedstock for power generation encompasses sugarcane bagasse, rice husk and straw, saw dust, corn stover and palm oil based wastes. Although in many developing countries like India, Indonesia and Malaysia, the technology and infrastructure for biomass energy recovering has yet to be fully developed but one thing that can be confirmed are the sizeable biomass resources furnishing assurance (UNEP, 2009; Singh *et al.*, 2008).

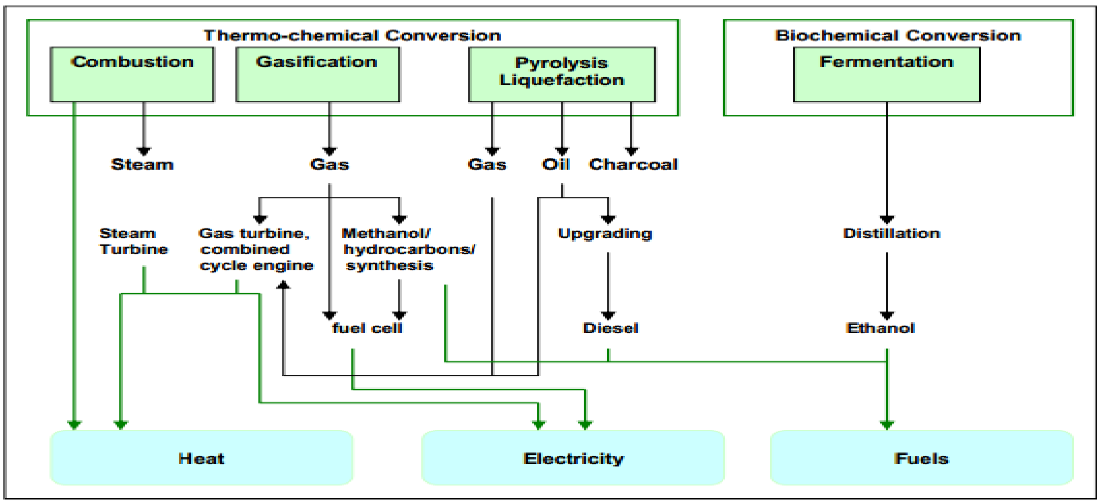

Figure 2-1: Illustration of the conversion routes for cellulosic agricultural biomass waste by UNEP, (2009)

2.2.2 *Forestry Biomass*

Biomass obtained from the forestry sector is normally due to pruning or logging. Many types of woods are suited for energy extraction purposes in lignocellulosic biofuel production. For an instance, out of 22 bioenergy feedstocks listed in Table 2-1, 3 of them are forestry-related material. Although only 1% of the woody biomass from the volume of 775 million m^3 in forest-based industries is available for wood fuel processing purpose as stated in Mantau et al., (2007), but due to the export oriented mind set, the interest towards the processed wood fuel from forestry biomass has not faded as no special care is needed for storing the torrefied biomass. In European market, the wood-pellet business is expanding rapidly. However, one of the disadvantages of forestry biomass is that the productivity highly depends of the minerals availability and soil condition (Kirschbaum, 2000). A simply lack of any favoured condition will lead to a problem in the supply chain. Next, implication of policy engagement in different countries is also another inhibiting issue of exploiting this type of biomass. However, the interest towards the forestry biomass can be strengthened with the support of governments, institution and local authorities.

Table 2-1: List of feedstocks used for bioenergy development in UK (Thornley *et al.*, 2009)

	Feedstock
Indigenous waste materials and by-products	1. Mechanically and biologically treated municipal waste 2. Used cooking oil 3. Waste wood 4. Poultry litter 5. Straw
Forestry-related material	6. Forestry residues 7. Arboricultural arisings and sawmill co-product 8. Wood pellets (indigenous and imported)
Indigenous energy crops	9. Short rotation coppice 10. Short rotation forestry 11. Miscanthus 12. Switchgrass 13. Reed canary grass 14. Oil seed rape 15. Wheat
Imported feedstocks	16. Jatropha 17. Corn/maize 18. Palm oil 19. Palm kernel expeller 20. Soya 21. Sugar cane 22. Olive cake

2.3 Rice Waste

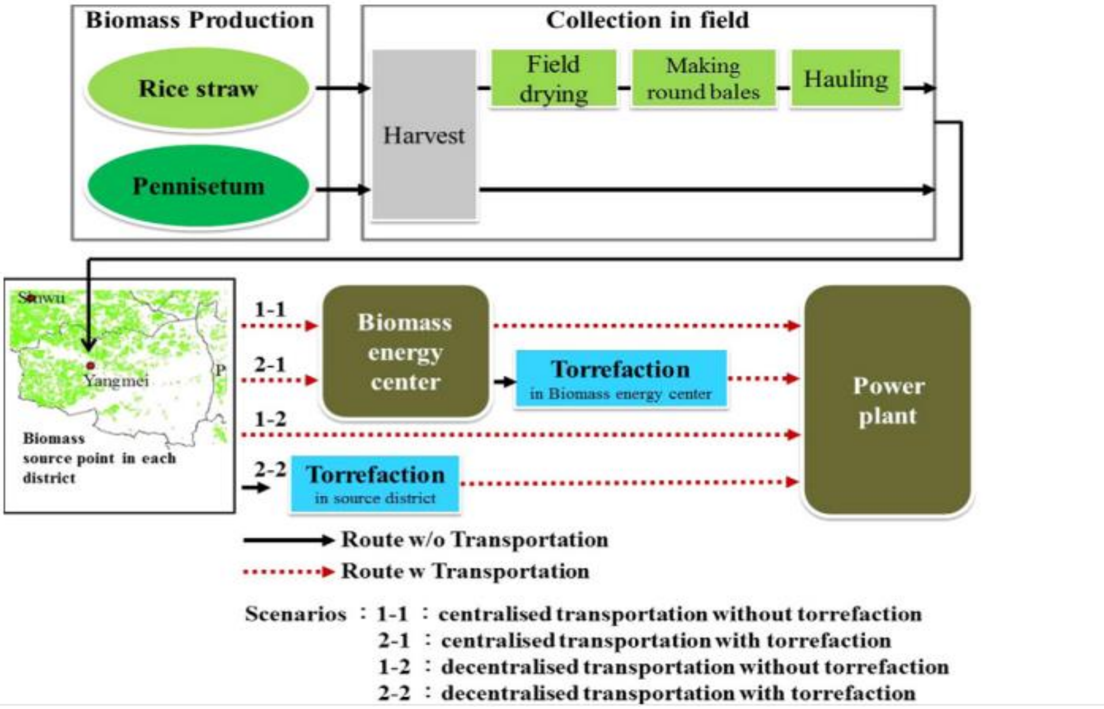

Figure 2-2: Scenarios in biomass supply chain by Chiueh *et al.*, (2012)

Rice is customarily grown under continuously flooded conditions. Thus, the three-quarters of the global rice production occur in irrigated low-lands Asian countries (Maclean *et al*., 2002). Figure 2-2 clearly illustrates the rice biomass supply chain in Taiwan. After harvesting, the rice waste will be collected for field drying before turning it to round bales for hauling purpose. In Taiwan, the management of biomass is regard as a crucial stage. In the transportation means, four systematic routes are drafted to efficiently deliver the waste or biomass to the nearest power plant for power generation. This includes the centralised transportation without torrefaction, centralised transportation with torrefaction, decentralised transportation without torrefaction and also decentralised transportation with torreafaction (Chiueh *et al.*, 2012). Growing attention towards the torrefaction of rice biomass is undeniable as many Asian countries that rely mainly on agricultural sector are in search of a method to solve the burdening storage, handling and upgrading of the fuel properties of rice biomass.

2.3.1 Rice Straw

Rice is a staple food grain for two thirds of the world's population. The demand towards the rice will grow as the population grows. Rice straw, a major agricultural residue from the rice crop accounting for 731Tg/yr since the year of 1997 (Kim & Dale, 2004) and this statistical value is expected to grow further as the world's population has drastically grew for the past few decades. Malaysia as one of the top 25 rice producing countries in the world solely has an annual production of 2.75million metric tons (Faostat, 2014). According to Kadam *et al.* (2000), 1.35 tons of rice straw is produced in order to obtain one ton of rice. The advantages of using rice waste as a study material is due to its availability from agricultural sector in Malaysia. The conversion of rice straw waste into value-added torrefieds may improve crop productivity, reduces environmental pollution and local pollution caused by open burning (Roca- P'erez *et al*., 2009).

2.3.2 Rice Husk

Rice husk is a type of waste obtained after harvesting the rice crop. The fact that rice husk has a cellulose-hemicellulose-lignin ratio of about 2:1:1 as mentioned in Chen *et al*. (2012) makes it an ideal target for mild pyrolysis. Normally, rice husk has very low commercial value, hence instead of recycling rice husk to other useful products, many farmer prefer to burn it when the harvesting season is over. The smoke produced from the direct open burning of rice husk can cause severe air pollution as the ash content in rice husk is as high as 11wt% (Chen *et al*., 2012; Wang *et al*., 2012). Its further properties will be listed in Table 2-2.

Table 2-2: Type of rice biomass and its physical properties (Chen *et al*., 2012; Huang *et al*., 2012; Wang *et al*., 2012)

Analysis (wt%)	Rice straw	Rice husk
Hemicellulose	19.50	21.34
Cellusose	42.32	36.06
Lignin	25.79	21.16
Moisture	5.46	11.51
Ash	9.82	10.99
Higher Heating Value (MJ/kg)	16.16	17.4

2.4 Conversion of Biomass into Energy

In large population countries, such as China and India, reliance on the biomass as a traditional fuel has been in a ramp patent and it has been reported that 80% use of residential energy in both countries is harvested from the biomass (Pachauri & Jiang, 2008). Biomass substitution can actually affect energy and carbon balances through several mechanisms (Sathre & O'Connor, 2010). In this modern century, a variety of technologies are being embraced for the energy conversion. This includes biodiesel production, direct combustion, pyrolysis, gasification and fermentation. The conversion process can be classified into several types: thermochemical, biochemical and chemical process. Direct combustion is among the most prevalent thermochemical technique in converting biomass into energy in the form of heat or steam to rotate turbines for electricity generation. However, there are some arguments regarding this method as it produces pollutions to the environment and has low heating efficiency. The advanced version of thermochemical process, gasification and pyrolysis technologies are discussed in the pretreatment chapter. Apart from that, the ethanol manufactured from the fermentation is a unique process as it requires the aid of biological catalyst such as yeast in the production mechanism. Depending on the catalytic feasibility of the yeast species, the yield of the liquid fuel, ethanol may differ in purity. Lastly, in terms of chemical means, waste vegetable oil and soy beans can also be processed into biodiesel oil via chemical reaction (UNEP, 2009)

2.5 Pretreatment of Biomass

In order to scale down the oil dependency of energy sector, the transformation of fossil fuel to renewable energy is currently on its evolution path. However, the analysis of the biomass supply chain costs always encounters a massive problem in the biomass transportation handling due to high bulk-volume and a large bulk of moisture content. Apart from this, the procurement of agricultural biomass would also be costly as the source of biomass is located at the rural area (Moller & Nielsen, 2007) and is scattered in small quantities over a broad field (Gronalt & Rauch, 2007). Hence, to increase the hauling efficiency, consolidating the pre-processing of biomass in the supply chain to improve the product properties is often utilized to bridge the gap of fluctuation in profits and transportation prices.

2.5.1 Pyrolysis

Pyrolysis is a process of turning waste into wealth. This technology is also known as thermochemical process by which is used for the pretreatment of biomass. Generally, the operating temperature is between 200-300 ℃ with a heating rate less than 50 ℃/min. The main objective of torrefaction is depolymerized the complex polysaccharide chains and to remove the moisture and volatiles compounds contained within the biomass (Wang *et al*., 2012).

Typically, pyrolysis process can be divided into four types including the mild pyrolysis, fast pyrolysis, flash pyrolysis, and catalytic biomass pyrolysis. In general, the difference between mild, fast and flash pyrolysis method are merely in terms of heating rate whereby the catalytic biomass pyrolysis is to further improve on the quality of the pyrolysed product (Goyal *et al*., 2008). Since the materials under studied in this research are the rice husk and rice straw, mild pyrolysis is used to prevent the ruining of the sample under extreme high heating rate. The optimum heating rate is studied while the residence time is fixed at 30 min. According to Deng *et al*. (2009), hemicellulose as the first component that decompose, it will break down at temperature of 200-250 ℃, then followed by cellulose at temperature of 240-350 ℃. Lignin is the last component that decomposed at 280-350 ℃. Thus, a range of temperature from 220- 280 ℃ is satisfactory in providing a comprehensive study on the breaks down of the hemicellulose, cellulose and lignin constituents in the biomass samples.

2.5.2 Microwave and Conventional Pyrolysis

Microwave-assisted pyrolysis (MAP) is an evolution from the conventional pyrolysis technique. Ever since this new technology has been publicized, many researchers have diverted into the study of pyrolysis with microwave-induced heating method. Despite the fact that with the aid of microwave, the gas devolatilisation can be achieved with the lower temperature (Shuttleworth *et al.*, 2012), but many researchers are just focused on the path where they can maximize the quality of the fuels with synchronization of technology without considering the application feasibility. This is one of the main reasons that pyrolysis technology still locate in the pilot demonstration stage after many years of groundwork (UNEP, 2009).

The shifting of conventional to microwave protocol has indirectly induces the abandon of conventional pyrolysis investigation although the fundamental knowledge towards the conventional mean is not yet matured. In the investors’ prospective, the economical aspect such as cost of installation is the predominant concern (Jaap *et al.*, 2012). In addition, to reveal the pyrolysis technology to the market, the affordability of the power generation operators and suitability of location have to be taken into account as normally these plants are built at a location neighbouring to the source of biomass where plantation of agricultural crops wastes can be easily collected. Considering the current status of many developing countries, a high installation cost will only reduce the plant establishment chance. So, in the comparison case, a lower cost conventional pyrolysis is more fitted to play the role in energy security advancement course. Thus, in my study, pyrolysis on rice biomass is going to provide an insight on the physical properties changes of the torrefied materials by conventional route.

2.5.3 Gasification

Gasification is a competent thermochemical conversion technology in turning carbonaceous materials into syngas but with significant amounts of carbon monoxide (CO) and hydrogen (H) as a by-product. Previously, gasification technology is purely developed and commercialized by using fossil fuels as the feedstock but this process produces an enormous amount of greenhouse gases. To curb this problem, biomass gasification approach has been studied. Other than able to reduce environmental pollution, biomass has an extra recognizable superiority as compared to other renewables such as solar energy, geo-power, wind power which have intermittent energy generation (Faaij, 2007). Nonetheless, currently this method is still in research or pilot demonstration state and yet to be matured to be launch in the market (UNEP, 2009). According to Ahrenfeldt & Knoef (2005), by 2005, in spite of the significance interest but the progressiveness of the upscaling plan was always hindered. A gasifier plant does not only consist of a gasifier but also include the pretreatment and feeding, gas cleaning and application of end products. Hence, besides the challenge of scaling up, this presents key issues is dealing with a mismatch with the dispersed availability of biomass of low energy density and transportation cost. With the practice of local pyrolysis plant, these disadvantages can eventually be changed into advantages by transforming the biomass into rich energy carrier by enhancing energy density (Kirkels & Verbongm, 2011). Overview on this method is that continuous research and development need to be done in order to bring up this technique to a commercialization stage.

2.6 Torrefaction

The concept of using biomass as an energy carrier has been proposed since past few decades. However, the implementation foresees a defect in the supply chain and commercializing purpose. The expensive logistics cost is always a weakness in the competition with the high value commodities such as paper and fibreboard (Jaap *et al.*, 2012). Therefore, after further research and development, a technology known as torrefaction (currently still in pilot demonstration stage), predicted as a crucial leap stone in pushing the biomass energy sector to the peak has been introduced (Svanberg *et al.*, 2013).

Lignocellulosic biomass sources are obtained from disposed segments of plants from the agricultural or forestry fields. Having a clean, dry criteria and ample fractions of cellulose, hemicellulose and lignin are among the essential reasons lignocellulosic biomass became the selected biomass for torrefaction market besides the easily accessible sources. In general, the current interest towards torrefied fuels is due to two circumstances; to conjugate the aspiration of closing old power stations which have reached their regulated lifespan limit and the potential of torrefaction to enhance the fuel quality of biomass. Whilst in the investors' views, the assessment of the economical aspect for the torrefied pellets and conventional wood pellet (biopellets) production chain are the main concern (Jaap *et al.,* 2012).

The most influential industrial challenges in advancing the torrefaction technologies are the volatile organic compounds (VOC) handling, upscaling practice, homogenous quality of the torrefied product, controlling the thermal efficiency and densification process (Jaap *et al.,* 2012). The goal of torrefaction is to upgrade the fuel properties of by thermal conversion. Practically, for real life application, in a scale up plant, all the products derived from the torrefaction process can be turned into good use. The volatile organic compounds (VOC) which are regularly being pointed out as the by-products of the torrefaction can be channelled into a burning chamber to be combusted together with the powder from milling as start-up and auxiliary fuel as shown in the Figure 2-3 (Svanberg *et al.*, 2013). The appropriate practice of this design and operation ensures that the content of energy within the torrefaction gases is adequate in sustaining both the drying and torrefaction processes (Jaap *et al.,* 2012).

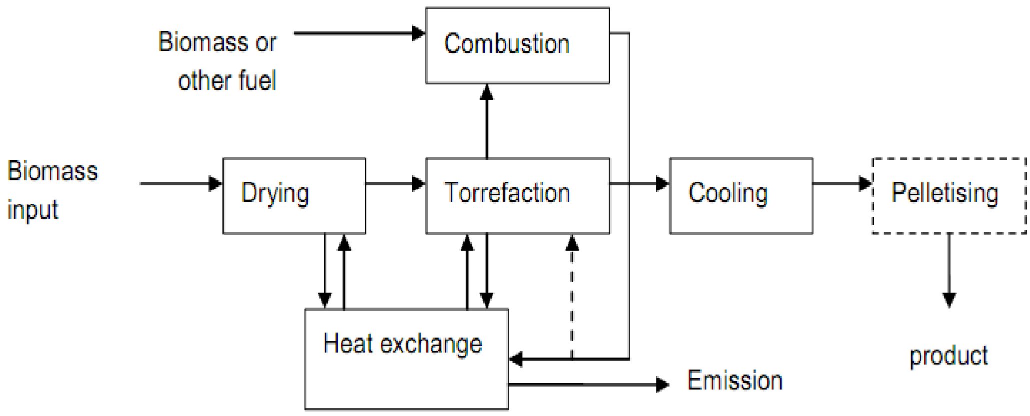

Figure 2-3: Plant layouts process diagram incorporating both torrefaction and densification process by Jaap *et al*., (2009)

During the process of pyrolysis, the thermal efficiency is highly affected with the disappearance of the volatiles and moisture content of the raw biomass (Jaap *et al*., 2012). From Figure 2-4, the thermal efficiency of the torrefied materials has soared up to a value exceeding 90% energy efficiencies when 20% of dry mass is being vaporized as volatiles organic compound or torgas. This phenomenon is commonly seen in a torrefaction process. Since an optimum devolatilisation rates is proportional to the heating temperature and the heating temperature is directly proportional to the percentage of mass loss, a temperature of 200-300 ℃ has always been suggested for torrefaction of agricultural biomass (Eseltine *et al*., 2013; Medic *et al*., 2012).

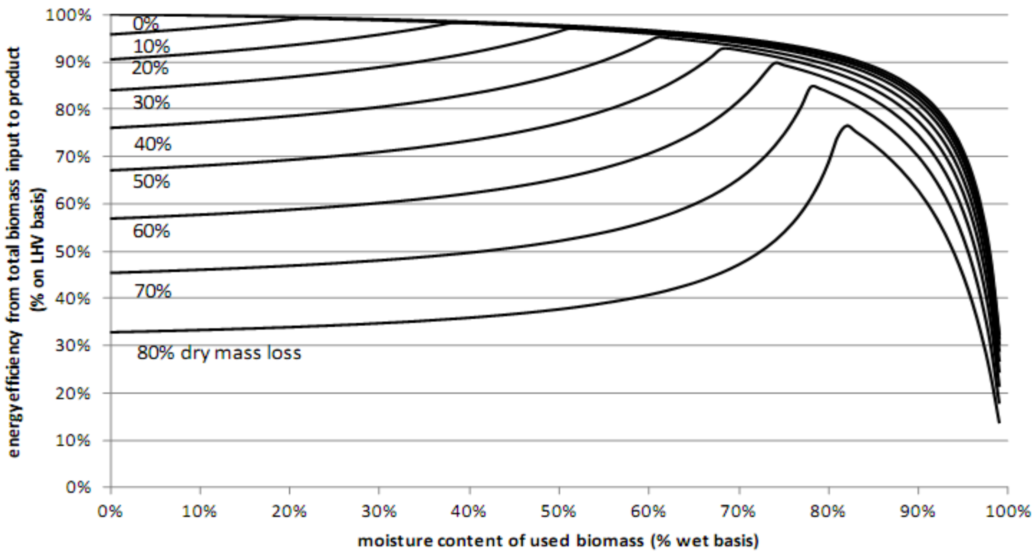

Figure 2-4: Theoretical thermal efficiency of an intergrated torrefaction process by taking clean wood (0.5 ash %) as raw material by Jaap *et al*., (2009)

Next, although homogenous quality is also one of the main involvements in promoting the product however, investors are more worried and concerned about the prices. Many power plant owners preferred to evade from the costly handling expenses. Hence, torrefaction technology with various advantages is suggested to solve all these foreseeable issues. Comparisons between the characteristics of raw and torrefied biomass are shown in Table 2-3.

Table 2-3: Comparisons of characteristics between raw and torrefied biomass.

Raw biomass characteristics	Enhancements via torrefaction
Low energy density and high moisture content. The energy density of woods chips is only about 2-4GJ/m^3, compared to 25-40GJ/ m^3 of coal (Crocker & Andrews, 2010).	Increases weight percentage of fixed carbon content and thus able to burn longer than raw biomass (Bridgeman *et al*., 2008). Torrefied biomass also experienced a 3-45% decrease in mass density and 1-35% decrease in energy yield but 2-19% increase in energy density (Wang *et al*., 2012).
Hydrophilic property that tends to attract and absorb moisture from the air. This property burdens the storage and transportation process (Crocker & Andrews, 2010).	Enhances the hydrophobicity. The equilibrium moisture content is as low as 1-3wt% relies upon the torrefcation condition (Lipinsky *et al.*, 2002).
Tough, fibrous and hard to fragmentized (Van der Stelt *et al*., 2011).	Depolymerisation of the tenacious fibre structure via the breakdown of hemicellulose and cellulose molecules. The material tends to become brittle and easy to grind (Ciolkosz & Wallace, 2011).
Heterogenous characteristics. Presence in different shape, size and types which induces deviation in calorific value and combustion properties (Tumuluru *et al*., 2012).	Improves the solid uniformity and eliminate the volatiles and moisture. Particle surface areas resemblance can be further improved by grinding (Phanphanich & Mani, 2011).
Biodegradable. Degradation over time if not well preserved.	Eradication of the hydroxyl group provides resistant towards biological degradation

	and therefore, can be stored for a longer time (Bergman, 2005).

2.7 TOP (Torrefaction and Pelletisation)

Biopellet offers many conveniences as a domestic fuel compared to unprocessed biomass. The growing demand towards biopellets is clearly seen in the world market. To be regard as a high quality fuel, there are still some controversies concerning the biopellets durability. Upon contacting with the water or snow, the biopellets will immediately swell and disintegrate. Thus, it has to be sheltered and protected from any possibility of contact with water. Specific care and handling need to be performed from time to time (Alakangas & Paju, 2002). Hence, TOP technology has been invented to deal with the deficiency of biopellets.

TOP stands for torrefaction and palletisation. From the research conducted by Bergman *et al*. (2005), the density of the torrefied biomass is between the range of 180-300kg/m^3, proven that it is 10-20% reduced as compared to raw biomass feedstock. Considering the status of the current investment and operation technology, TOP uses the similar operational equipment and technique as applied on the conventional biopellets but at the same time, it could save up to 30% of the operational cost due to its lower volume but with higher thermal efficiency. In addition, losses on the stocked up pellets can therefore be minimised as the hydrophobic property is established during the torrefaction stage (Bergman *et al*., 2005). The comparison of auxiliary properties possessed by the pellets from TOP as compared to other fuels can be seen in Table 2-4.

Table 2-4: Characteristics of various fuels by KEMA, (2010)

	Wood	Wood pellets	Torrefaction pellets	Charcoal	Coal
Moisture content (% wt)	30 – 45	7 – 10	1 – 5	1 – 5	10 – 15
Lower heating value (MJ/kg)	9 – 12	15 - 18	20 – 24	30 – 32	23 – 28
Volatile matter (% db)	70 – 75	70 – 75	55 – 65	10 – 12	15 – 30
Fixed carbon (% db)	20 – 25	20 – 25	28 – 35	85 – 87	50 – 55
Density (kg/l) Bulk	0.2 – 0.25	0.55 – 0.75	0.75 – 0.85	~ 0.20	0.8 – 0.85
Energy density (GJ/m^3) (bulk)	2.0 – 3.0	7.5 – 10.4	15.0 – 18.7	6 – 6.4	18.4 – 23.8
Dust	Average	Limited	Limited	High	Limited
Hydroscopic properties	hydrophyllic	hydrophilic	hydrophobic	hydrophobic	hydrophobic
Biological degradation	Yes	Yes	No	No	No
Grindability	Poor	Poor	Good	Good	Good
Handling	Special	Special	Good	Good	Good
Quality variability	High	Limited	Limited	Limited	Limited