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Bio-oil Production from Napier Grass Using a Pyrolysis Process: Comparison of Energy Conversion and Production Cost between Bio-oil and Other Biofuels

Wasakorn Treedet*, Ratchaphon Suntivarakorn*,[1], Ilham Mufandi* and Piyapong Singbua*

Abstract – *This article presents bio-oil production from Napier grass by using a pyrolysis process. The comparative potential of energy conversion and the cost of production among bio-oil, bio-ethanol, biogas and syngas from gasification by using Napier grass as raw material were also analyzed. The pyrolysis in this study was developed from previous work in order to improve the yield of bio-oils. The circulating fluidized bed reactor (CFBr) was used as the reactor, and a new scrub condenser was applied in order to increase the performance of condensing vapor into bio-oil. This system had the ability to feed Napier grass between 45-75 kg/hr, and it could create a solid-recirculating rate of about 52.36 kg/m*^{2}*s at 7 m/s of maximum superficial velocity. From the results of the bio-oil production, it has been concluded that the maximum yield of bio-oil production is 44.60 wt% at a feed rate of 60 kg/hr and bed temperature of 480°C. The properties and chemical components of bio-oil were also determined. A comparison of energy conversion from Napier grass to products such as bio-oil, ethanol, biogas and syngas through the gasification process as well as an analysis of cost of production revealed that syngas production through gasification has a greater potential energy conversion and cost of production than other technology, which had an energy conversion efficiency and cost of production of about 72.65% and 0.26 USD/GJ, respectively. However, as compared to liquid fuel, the gas fuel has greater limitations in terms of utilization and transportation. The bio-oil production from pyrolysis in this study had a cold efficiency and cost of production of about 28.24% and 17.98 USD/GJ, which proved a more advantageous trend of cold efficiency and production cost than bio-ethanol production, thus it can support a large energy project to create more energy security.*

Keywords – *bio-oil, CFBr, energy conversion, Napier grass, production cost.*

1. INTRODUCTION

Energy crises are a present-day problem for nearly every country in the world. Thailand is reputed to be a developing country in the agro processing industry, and it has recently seen a substantial increase in investors, technology and labor in businesses each year. For this reason, Thailand has increased its energy consumption by approximately 1% every year; in contrast, the energy source for energy production in Thailand was imported from a neighboring or producing country [1]. In 2017, the percentage of energy imported per total energy usage in Thailand was 57.77%, which shows the instability of energy consumption in this country [1]-[2]. The energy policy and planning office of Thailand predicted that Thailand will increases its energy consumption by 87.14% by 2036; thus, many policies have been introduced to support sustainable energy in the future. Alternative Energy Development Plan 2015 (AEDP) is one such policy that aims to find a way of integrating energy plans with alternative forms of energy. In the AEDP 2015 plan, the utilization of heating energy and electricity production from biomass must be increased from 2,451 MW to 6,250 MW in the next 20 years [3].

Napier grass (Pennisetum purpureum Schumach) has one of the highest potentials amongst other forms of biomass because it is fast growing in each harvest season (around 60 days), and it has high productivity growth (an average of 90-120 tons per hector), weather endurance, low producing cost and high protein content [4]-[5]. Due to the fact that Napier grass is an energy source of high heating value (average of 16 MJ/kg), it is widely used as a solid fuel source for industries. Moreover, in the AEDP 2013 plan, Thailand intended to use Napier grass to produce biogas as fuel for the production of electricity, of which it expects to produce about 3,000 MW in the next 20 years [6]. However, there is no the data in Thailand to support the method or the value of investment of the Napier grass conversion to energy.

The method to convert Napier grass to biofuel has been studied and explored by many researchers. The results have concluded that the energy source from Napier grass can be divided in 3 categories: solid phase, liquid phase and gas phase. In order to utilize solid fuel from Napier grass, moisture content must be reduced and converted to bulk solid before use because a lower value of moisture content and higher bulk density directly affects the heating value of solid fuel. The ideal value of moisture content and bulk density of Napier grass is 10-15 % wt and 1-1.28 kg/cm3, which shows the need for a power consumption in order to convert to solid fuel of about 50 kWh/Ton [7]. However, the study result of Rocha *et al.* [8] indicated that the thermal combustion of other biomass, such as Pinus or Eucalyptus, must be superior to Napier because Napier has a high content of ash. The study results found that the conversion of Napier grass to solid fuel had a high efficiency of energy conversion and a low production

* Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, P.O. Box 123, Mitrapap Road, Nai Muang Sub-district, Muang District, Khon Kaen, 40002, Thailand.

[1]Corresponding author:
Tel: + 66 043 009 700, Fax: +66 043 362 142.
Email: ratchaphon@kku.ac.th.

cost, which suggests that solid fuel from Napier grass could be used instead of fossil fuels. However, the limitations in the utilization and the environment have led to the present-day use of solid fuel; the combustion of solid fuel creates more greenhouse gases than liquid fuel or gas fuel. For this reason, many countries such as the USA [9], the EU [10], Thailand [11] and G20 countries [12] have created a number of policies to encourage the production and utilization of liquid fuel or gas fuel to support sustainable energy and to solve global warming in their countries. Thus, the conversion of Napier grass to liquid fuel or gas fuel is more interesting than solid fuel.

In the present day, bio-ethanol, bio-diesel and bio-oil are popular energy sources in the conversion to liquid fuel. Lignocellulosic is used as the major material to produce bio-ethanol, which involves about 3 processes to produce: pretreatment, hydrolysis and fermentation [13]. Meanwhile, bio-diesel is made through a transesterification process. Napier grass cannot be made into Bio-diesel because it does not have a composite of oil or fat, but Napier is a popular source for conversion to ethanol. Many researchers have reported on the method to convert Napier grass to bio-ethanol [14]-[20], and their reports indicated that all components of Napier grass, such as leaves, stalk and trunk, can produce bio-ethanol [18]. After a process which takes around 94 hours, Napier grass can be converted to bio-ethanol at a rate of more than 18.97 wt% [15]. Moreover, Napier grass can be converted to another liquid fuel, called bio-oil, using a pyrolysis process. The pyrolysis process is a molecular thermal decomposition process that occurs in the absence of oxygen or when there is very little oxygen content at atmospheric pressure [21]. Furthermore, the pyrolysis process quickly produces bio-oil from biomass (around 0.5-2 seconds), and it can produce a high yield of product (around 50.57 wt% of bio-oil yield [22]). The ability to produce the highest yield of bio-oil from biomass depends on many factors: reaction temperature, size of particle, feed rate of biomass into reactor, moisture content of raw material, etc. However, the most important factor that affects the yield of bio-oil is the heat transfer behavior in the reactor of the production process [23]-[24]. Several reactors were applied to produce bio-oil through the pyrolysis process: fixed bed reactor [25]-[27], rotary kiln reactor [28]-[29], screw reactor [30] and circulating fluidized bed reactor [31]. The results of Suntivarakorn, *et al.* [31] indicated that the bio-oil production from Napier grass had yield production 2-3 times higher than bio-ethanol. Even though the bio-oil had a heating value of less than half of bio-ethanol, the shorter production time of the bio-oil production process as compared to the bio-ethanol production process makes it more suitable as an alternative energy.

The method used to convert Napier grass to gas fuel can be divided into 2 methods: syngas from a gasification process and biogas from an anaerobic digester. Khezri *et al.* [32] has studied the syngas production from a gasification process by using Napier grass as a raw material. A fluidized bed reactor was employed in this work, which can generate an electric power of about 1-5 kW. The maximum composition of syngas, such as H2, CO and CH4, was produced at an equivalence ratio, and reaction temperatures were 0.2 and 750-800°C, respectively. Many researchers have explained that the method to convert Napier grass to biogas uses decomposition process of anaerobic organic substances, and they mixed inoculum, such as chicken manure [33], slaughterhouse wastewater [34], cow dung [35] and sewage sludge [36], in order to control the organic loading of bacteria.

From the information mentioned above, it can be concluded that Napier grass has suitable properties in order to be converted into solid fuel, liquid fuel and gas fuel. In regard to the utilization and environmental emissions, it has been found that liquid fuel and gas fuel from Napier grass had better performance than solid fuel. Moreover, the results from Suntivarakorn *et al.* [31] and Treedet and Suntivarakorn [37] indicated that the bio-oil had a greater ability to expand at a commercial scale and to be more competitive than other alternative fuels because of its unique processing time, the yield of product, energy storage and transportation. However, there are no studies following the potential of energy processing and the cost of production of Napier grass conversion to alternative energy, which would be necessary in order to make a decision for investment. Thus, this study aims to compare the potential of energy conversion and the production cost of using Napier grass as a raw material, as well as to compare Napier grass used to produce bio-oil from pyrolysis process, a bioethanol, a biogas and a syngas from gasification. The bio-oil production from this work was developed from previous studies in order to increase production efficiency and decrease the production cost [31], [37]. The results from this work expect to show that Napier grass is helpful in regard to energy conversion technology, and this data can help to encourage alternative energy policies in future research studies as well.

2. EXPERIMENTAL MATERIALS, DEVICES, METHODS AND YIELD ANALYSIS

2.1 Experimental Materials of Bio-oil Production

Napier grass, Pakchong 1 species, was used as raw material in this experiment. Table 1 shows the physical properties, such as density, mean diameters, and heating values of the Napier grass, and the proximate analysis and ultimate analysis were investigated. This raw material was the same sample as the sample used in the previous work.

2.2 Experimental Devices and Method of Bio-oil Production

2.2.1 Experimental devices

The bio-oil production system in this study was performed at Khon Kaen University in 2019, and over the course of a year, it was scaled up to maximum Napier grass feeding rates of 75 kg/hr. As shown in Figure 1, the experimental devices consisted mainly of a circulating fluidized bed reactor (CFBr) which had a diameter of 0.1 meters and a height of 4.5 meters. The gas combustor was employed to generate the heat of the process. A feeder system with pneumatic conveying was selected in this work in order to prevent the bed material from flowing out of the reactor. A hopper and a blow-through rotary valve were used to control a feed rate. Two cyclones, one of general propose and one of high-efficiency, were employed. A gas pre-heater, a condenser, a scrub condenser and a filter-packing column were selected for the quenching unit. A scrub condenser and filter-packings were developed from previous work [30] in order to increase an ability to trap bio-oil before entering the recirculating blower in order to increase the yield of bio-oil in the collector as well.

Table 1. The physical properties of the experimental materials.

Properties	Napier	Units
Mean diameter (the Sauter's mean diameter)	1-3	mm
Bulk density	138	kg/m^3
Heating value (ASTM D240)	15.23	MJ/kg
Proximate analysis (Shimadzu TGA 50)		
- Moisture	12.14	wt%
- Volatile matter	75.37	wt%
- Fixed Carbon*	7.33	wt%
- Ash	5.15	wt%
Elemental analysis (Perkin Elmer PE2400 Series II)		
- C	40.03	%
- H	6.02	%
- N	1.69	%
- S	1.08	%
- O*	51.18	%

*Fixed carbon and oxygen were calculated by difference.

Labview software was used to control and collect the data. The instruments, used in this system, consisted of 29 pressure sensors, 25 thermo-couples, 2 sets of strain gauges, 1 power analyzer, 1 gas component analyzer, and 1 liquid flow ultra-sonic. The 25 sets of pressure sensors, which ranged between 0 – 50 kPa, were installed at the riser, the down-comer, and the blower to measure the hydrodynamics, while the remaining high accuracy pressure sensors with a range from 0-2 kPa were used to measure the pressure differences of the pitot tube. All of the pressure sensors were calibrated and amplified along a linear scale from 0 to 5 VDC using the IC code INA122. 24 sets of thermo-couples (type K) with a ranging from 0 to 1,000°C were used to measure the temperature around the plant, and one ceramic thermo-couple (type B) probe with a range from 0 to 1,700°C was installed on the gas combustor to measure the exhaust gas temperatures before entering the CFBr. The two sets of strain gauges were installed at the down-comer and the LPG tank to measure the bed inventory and the fuel consumption, respectively. A Micronics PF330 ultrasonic flow meter was used to measure the volumetric flow rate of the cooling water. Finally, a Chauvin Arnoux model (C.A.8332B) was installed to measure the electricity consumption of this plant.

2.2.2 Experimental methods

The Napier grass, a raw material in this work, was fed continuously into the reactor at a rate of between 45-75 kg/hr. The superficial velocity of CFBr in this experiment was constantly set at 7 m/s because this velocity can make the high solid-recirculating rate of bed material, which was induced to produce the maximum yield of bio-oil [37]. The bed temperature of the reactor was set at a range of 440ºC - 520ºC while the bed inventory of CFBr was set at 4.5 kg under atmospheric pressure. In the quenching unit, the temperature of cooling water at the condenser and scrub condenser was 25ºC. The volumetric flow rate of the condenser and scrub condenser were 100 and 60 lite per minute, respectively.

In addition to the bio-oil, two by-products, namely charcoal and NCG, were also obtained when Napier grass was pyrolyzed. The yield of the bio-oil was determined by the total weight of condensed liquid in the bio-oil collector per total weight of feedstock, and the yield of the charcoal was determined by the total weight of char in the char collector per total weight of feedstock. The yield of the NCG was determined by the fact that the sum of the three product yields should be equal to 100%.

2.3 Yield Analysis of Bioethanol Production

Bioethanol production from Napier grass can be collected in two ways: calculation and using actual data from literature. The calculation method to predict yield of bioethanol was surmised by using the quantity of cellulose and hemi-cellulose. The study results of the ethanol yield calculation were cited from Wongwatanapaiboon *et al.* [38], while the real data from the experiment were cited from literature [15], [39], [65]-[66].

2.4 Yield Analysis of Biogas Production

As stated above, the biogas production from Napier grass can be collected in two ways: calculation and using actual data from literature. The equation to predict the yield of biogas can be shown in Equation 1 [40].

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 \quad (1)$$

The study of Somsiri and Vivanpatarakij [41] showed a method to predict the yield of biogas production, and the result concluded that 1 hector of Napier grass can produce around 17,903.75 kg/year of Methane gas. Moreover, the report from the Energy Research and Development Institute-Nakornping illuminated the suitable conditions in which to produce biogas from grasses in Thailand [42]. This report predicted biogas production from Napier grass in Thailand, stating that it could produce around 10,001.75 kg/year of Methane gas, and the real data from experiments were cited from the literature [67]-[69], [72].

2.5 *Yield Analysis of Syngas from the Gasification Process*

As stated above, the yield of syngas production from the gasification process of Napier grass can be collected in two methods: calculation and using actual data from literature. The equation to predict the yield of syngas can be shown in Equation 2 [43].

$$C_uH_vO_w + u.CO_2 \rightarrow 2u.CO + \left(\frac{v}{2} - w\right)H_2 + w.H_2O \quad (2)$$

The study of Somsiri and Vivanpatarakij [41] also explained the method to predict the yield of syngas production from the gasification process. The constant value of u, v and w was calculated from an elemental analysis of Napier grass. The study result of Somsiri and Vivanpatarakij [41] indicated that flammable gases such as carbon monoxide and hydrogen can be generated using a gasification process, which produces energy at a rate of around 1,905.75 GJ/ha/year. Moreover, much literature [44], [71]-[72] has studied Napier gasification to produce syngas for its utilization as a fuel source for power generation, which this study has cited in order to compare energy conversion and production cost from Napier grass to alternative fuel.

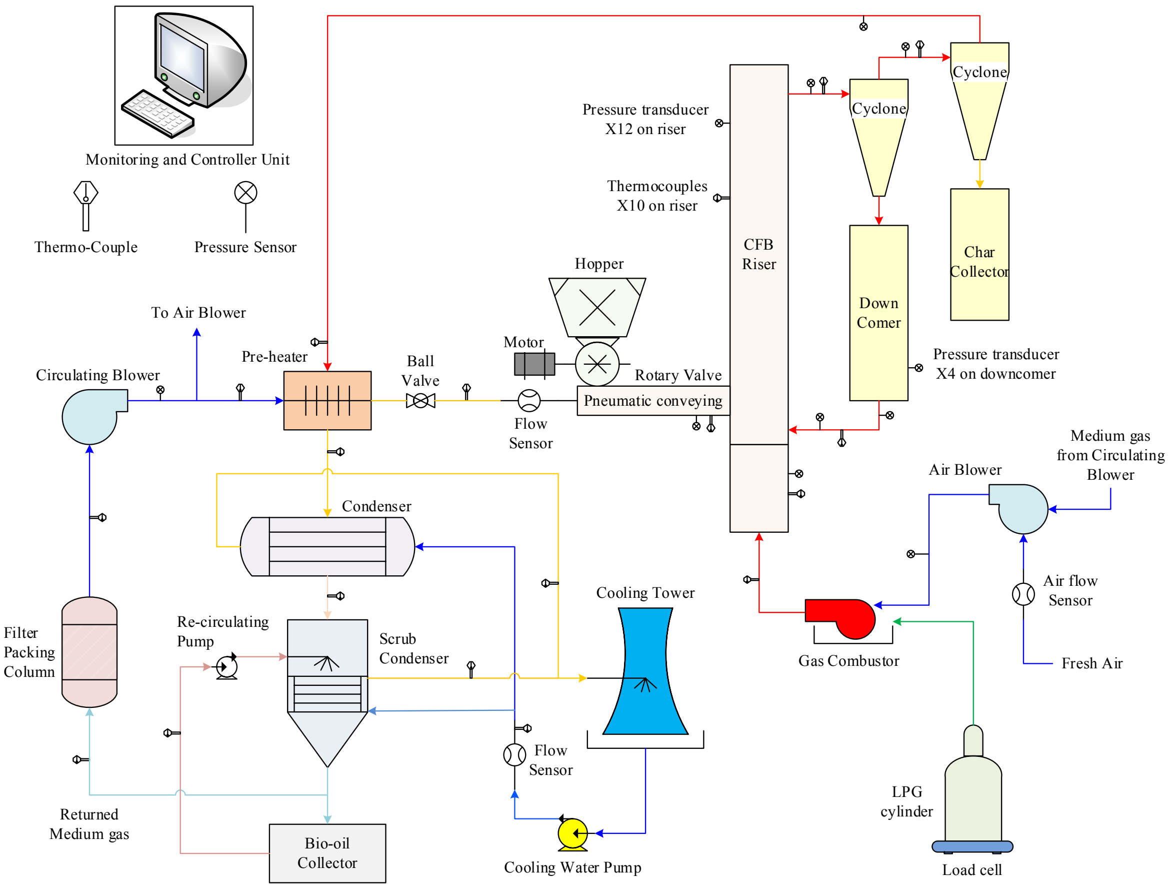
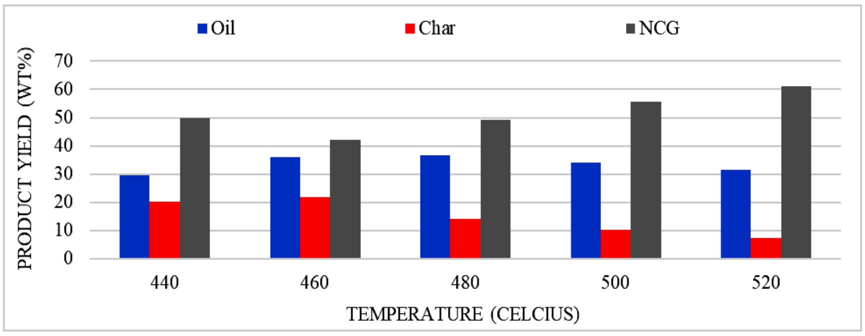


Fig. 1. A schematic diagram of the bio-oil production system.

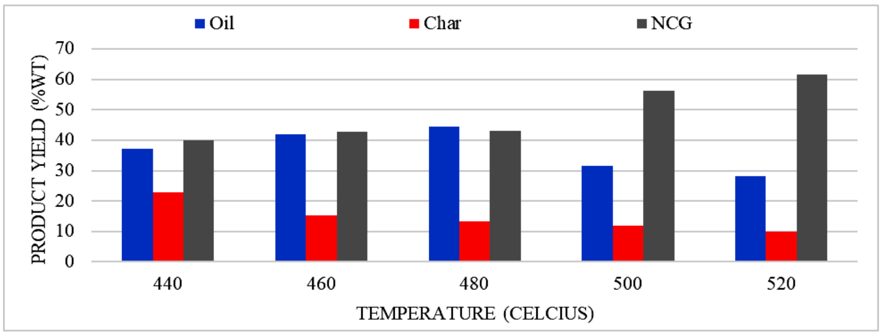
3. RESULTS AND DISCUSSION

3.1 *Results of Bio-oil Production*

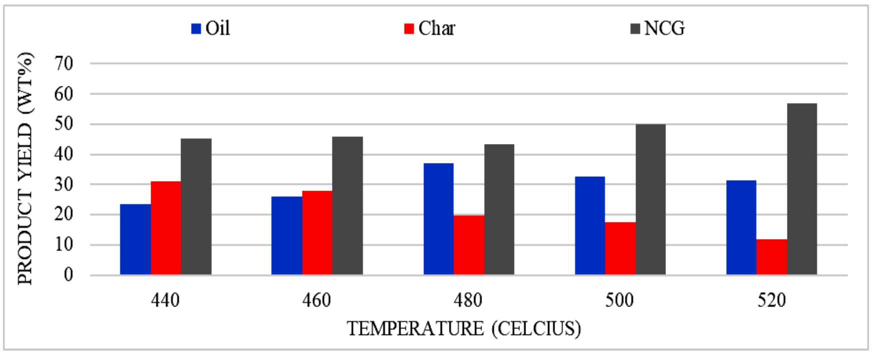
Figure 2 shows the actual production of bio-oil from Napier grass at a feed rate between 45 - 75 kg/hr, respectively. From these results, it is clear that this system has the ability to produce a maximum yield of bio-oil at 44.60 wt% at 480°C of bed temperature and 60 kg/hr of feed rate, a higher yield of bio-oil than previous work in all test results [31]. All of the test results regarding the bed temperatures revealed that the maximum pyrolysis oil production was generated at a bed temperature of 480°C. Furthermore, it found that: (1) the pyrolysis oil yields first increased and then decreased with the increases in reactor temperatures; (2) the Non Condensable Gas (NCG) yields first decreased and then increased with the increased reactor temperatures; and (3) the charcoal yields steadily decreased with increases in the reactor temperatures. In regard to the influence of the pyrolysis temperatures, these findings were consistent with results from studies by Suntivarakorn *et al.* [31] and Treedet and Suntivarakorn [37].



a) Bio-oil production at a feed rate of 45 kg/hr.



b) Bio-oil production at a feed rate of 60 kg/hr



c) Bio-oil production at a feed rate of 75 kg/hr

Fig. 2. Bio-oil production at a feed rate between 45 – 75 kg/hr.

3.2 *Product Properties*

Table 2 shows properties of bio-oil and char at a bed temperature of 480°C and at a feed rate of 60 kg/hr. The property indicated that bio-oil had a low viscosity, with a value of about 2.32 cSt. The low viscosity of the aqueous fraction makes it suitable for combustion in different types of equipment, such as boilers, turbines, and engines [45].

Moreover, the quality of feedstock affected the quality of bio-oil. The high value of moisture content in feedstock increased the oxygen in the bio-oil directly, which created significant amounts of acid compound and water content in the bio-oil. The pH value and the water content from the bio-oil were 2.8 and 30.28 wt%, respectively. However, the heating value of bio-oil used in the engine was low when compared to the heating value of conventional fuel. The bio-oil production from this work had a heating value of about 13.83 MJ/kg. This makes it difficult to directly use in engines. For this reason, crude bio-oil should be upgraded before it can be used in engines.

The bio-oil was tested by GC-MS. The gas chromatography/mass spectrometry analysis of pyrolysis oil was conducted by using Agilent 7890A for gas chromatography and Agilent 7000A for mass spectrometry with a DB-wax capillary column, 60 m ×

0.25 mm, with a film thickness 0.25 µm. The 200 µl of bio-oil was diluted in 1 ml of Methyl Alcohol, and the samples were filtered through a membrane with a pore size of 0.45 µm.

Testing conditions were as follows: an injection volume of 1 µl, a temperature of 250°C, a Helium carrier gas, a gas flow rate of 1.0 ml/min, and a 2008 identification NIST mass spectral library. The testing found that the compositions of bio-oil are organic compounds and hydrocarbon compounds. Hydrocarbon compounds make the bio-oil combustible. Most hydrocarbons are used as engine and industrial fuels. Moreover, an organic compound consists of acids and heterocyclic substances that can make the bio-oil viscous and easily polymerized. The chemical components of bio-oil at a bed temperature of 480°C and a feed rate of 60 kg/hr are reported in Table 3, while Figure 3 also shows chromatograms of bio-oil at a feed rate of 60 kg/hr and bed temperature of 480°C.

Table 2. The properties of bio-oil and char.

Properties	Bio-oil	Char	Units
Heating value (ASTM D240)	13.83	9.81	MJ/kg
Density (Density bottle)	1,145	141	kg/m^3
Viscosity (ASTM D445)	2.32	-	cSt
Acidity (pH meter)	2.8	-	-
Water content (ASTM E203)	30.28	-	wt%
Proximate analysis (Shimadzu TGA50)			
- Moisture	-	6.25	wt%
- Volatile matter	-	28.49	wt%
- Fixed carbon*	-	58.88	wt%
- Ash content (700°C)	-	6.36	wt%
Ultimate analysis (Perkin Elmer PE2400 Series II)			
- C	37.89	25.23	%
- H	9.26	2.04	%
- N	0.53	0.93	%
- O*	52.32	65.70	%
- S	N.D.	0.52	%

*Fixed carbon and oxygen were calculated by difference, and N.D. was not detected.

Table 3. Chemical components of bio-oil at 480°C of bed temperature, and 60 kg/hr of feed rate.

Compound name	%
Methylamine, N,N-dimethyl-	0.51
Methyl formate	0.18
Acetic acid, methyl ester	0.05
Ethanol	0.10
Acetic acid ethenyl ester	0.28
Undecane	0.05
Pyridine	0.51
Pyridine, 2-methyl-	0.07
Furan, tetrahydro-2,5-dimethoxy-	0.08
Acetoin	0.10
Tridecane	0.18
2-Propanone, 1-hydroxy-	3.10
Pyridine, 3-methyl-	0.11
Pyridine, 4-methyl-	0.10
2-Cyclopenten-1-one	0.45
1-Hydroxy-2-butanone	0.64
2-Cyclopenten-1-one, 2-methyl-	0.19
Tetradecane	0.26
Butanoic acid, hexyl ester	0.41
2(5H)-Furanone, 5-methyl-	1.11
Acetic acid	13.51

…cont'd

2-Propanone, 1-(acetyloxy)-	0.57
Furfural	1.14
Formic acid	3.21
Ethanone, 1-(2-furanyl)-	0.26
2,5-Hexanedione	0.13
Propanoic acid	1.29
2-Cyclopenten-1-one, 3-methyl-	0.52
2-Cyclopenten-1-one, 2,3-dimethyl-	0.23
2-Furancarboxaldehyde, 5-methyl-	0.23
Propylene Glycol	0.17
Hexadecane	0.34
Octanoic acid	0.45
1,2-Ethanediol	0.50
1,2-Ethanediol, monoacetate	1.16
Butanoic acid, 4-hydroxy-	0.47
3-Furanmethanol	0.34
Pentadecane, 2,6,10,14-tetramethyl-	0.48
2(5H)-Furanone, 5-methyl-	0.26
Heptadecane	0.30
4-Hexen-3-one	0.47
2(5H)-Furanone	1.95
Acetamide	0.19
Octadecane	0.27
1,3-Cyclopentanedione, 2,4-dimethyl-	0.23
2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.92
Phenol, 2-methoxy-	3.15
Nonadecane	0.31
2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	0.61
4-Methyl-5H-furan-2-one	0.34
Glycerin	0.31
Creosol	0.96
Maltol	0.46
Phenol, 2-methyl-	1.09
Phenol	3.46
Phenol, 4-ethyl-2-methoxy-	0.58
1H-Inden-1-one, 2,3-dihydro-	0.34
2-Vinyl-9-[3-deoxy-β-d-ribofuranosyl]hypoxanthine	0.96
2(3H)-Furanone, 5-acetyldihydro-	0.26
p-Cresol	1.00
Phenol, 3-methyl-	0.27
Heneicosane	0.19
Cyclopentanol	2.88
Phenol, 2-ethyl-	1.44
2-Hydroxy-gamma-butyrolactone	1.25
2-Methoxy-4-vinylphenol	1.09
Hexadecanoic acid, methyl ester	0.86
1H-Imidazole, 4-methyl-	0.29
Phenol, 2,6-dimethoxy-	3.89
3,4-Anhydro-d-galactosan	0.78
2,3-Anhydro-d-mannosan	0.82
Glycerin	0.87
1,2,4-Trimethoxybenzene	0.50

…. *cont'd*

Benzofuran, 2,3-dihydro-	2.51
1,4:3,6-Dianhydro-α-d-glucopyranose	2.01
3-Pyridinol	0.97
11-Octadecenoic acid, methyl ester	0.43
5-Hydroxymethyldihydrofuran-2-one	2.51
5-Hydroxymethylfurfural	0.88
Phenol, 2,6-dimethoxy-4-(2-propenyl)-	0.19
Vanillin	3.51
Sucrose	0.41
Apocynin	0.75
2-Propanone,1-(4-hydroxy-3-methoxyphenyl)-	0.56
Catechol	5.02
1,2-Benzenediol, 4-methyl-	0.36
n-Hexadecanoic acid	1.81
Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	0.64
Benzaldehyde, 4-hydroxy-	1.64
Orcinol	0.62
Ethanone,1-(4-hydroxy-3,5dimethoxyphenyl)-	0.53
Hydroquinone	3.20
Octadecanoic acid	0.72
Oleic Acid	1.71
Total	100.00

3.3 *Energy Consumption, Efficiency of Energy Conversion and Production Cost of Bio-oil Production*

The energy source in this plant used LPG to generate heat and electricity in many machines, such as the blower, feed motor, cooling tower, cooling pump, and the spark ignition. The energy consumed in the process at a bed temperature of 480°C was selected to calculate energy consumption and production cost because these conditions created the maximum yield for bio-oil production. Furthermore, this section showed an ability of cold efficiency and total energy conversion of bio-oil, and both relations can be expressed in Equations 3 and 4, respectively.

$$Cold\ efficiency = \frac{Energy\ of\ bio-oil}{Energy\ of\ feedstock} \times 100\% \quad (3)$$

$$Total\ energy\ conversion = \frac{Energy\ of\ bio-oil}{Total\ energy\ input} \times 100\% \quad (4)$$

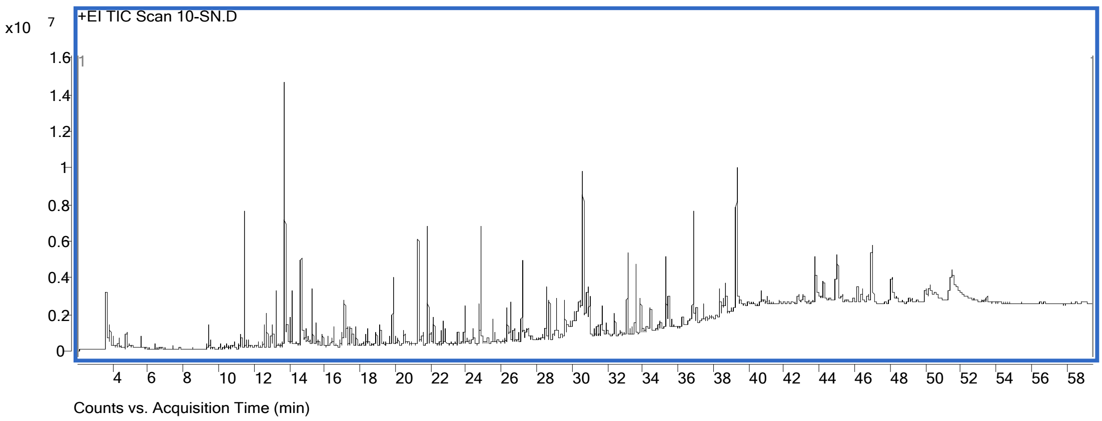


Fig. 3. Chromatograms of bio-oil at a feed rate of 60 kg/hr and a bed temperature of 480°C.

Table 4. The energy consumption and production cost of bio-oil production system.

No.	Description	Feed rates)kg/hr(		
		45	60	75
-Energy input to system (MJ)				
1	Feedstock	685.3	913.8	1142.2
2	Air blower 1	7.02	7.02	7.02
3	Air blower 2	6.30	6.30	6.30
4	Re-circulating blower	4.32	4.32	4.32
5	Feed motor	0.72	0.79	1.19
6	Water pump	5.22	5.22	5.22
7	Cooling tower motor	1.26	1.26	1.26
8	Spark ignition	0.05	0.05	0.05
9	LPG	198.9	211.3	222.3
-Energy from Bio-oil (MJ)				
10	Bio-oil	159.3	258.0	268.5
Cold efficiency (%)		23.25	28.24	23.51
Total energy conversion (%)		17.53	22.44	19.32
Yield of bio-oil (wt%)		36.73	44.60	37.13
Actual production of bio-oil(kg/hr)		11.52	18.66	19.42
Operating cost ($/hr)		4.32	4.53	4.74
Cost of bio-oil production ($/liter)		0.429	0.278	0.279
Cost of energy ($/GJ)		27.75	17.98	18.05

Table 4 shows the cold efficiency and the total energy conversion of bio-oil, where cold efficiency represents the ratio of energy from the bio-oil to the energy of feedstock. It was found that a feed rate of 60 kg/hr shows the value of cold energy, and total energy conversion was greater than other feed rates because the maximum yield of bio-oil can be produced under this condition. The bio-oil production from Napier grass in this study had a maximum cold efficiency and maximum total energy conversion of 28.24% and 22.44%, respectively.

Moreover, the data concerning the other production costs, such as labor, raw material preparation, and transportation is also shown in this table, and it can be calculated that the bio-oil with the lowest production cost in this system was 0.278 $/liter or 17.98 $/GJ at the 60 kg/hr feed rate. Although the operating cost was variable according to the feed rate in terms of the LPG increasing with the feed rate, the 60 kg/hr feed rate had the lowest production cost, more so than other conditions due to the highest actual bio-oil production.

Table 5 shows a comparison of the costs of pyrolysis oil production in the present study and in related literature. The data from the literature relates to pyrolysis oil production on a commercial scale, which has a feed capacity ranging from 2.4 to 2,000 tons per day. The data on pyrolysis oil production from many research studies is different due to the following factors: the efficiency of the processes used, the quality of the pyrolysis oil produced, and the global economic factors of the time period. However, the production cost in this study was compared to other studies in which the production costs were considered to be “moderate”, and this cost will be compared to bioethanol, biogas and gas from gasification.

3.4 Comparison of Energy Conversion and Production Cost between Bio-oil, Bioethanol, Biogas and Syngas from Gasification Process

Cold efficiency was considered in order to indicate the performance of the energy conversion factor. The production cost of each fuel was expressed in the format of USD/GJ. Table 6 shows a comparison of cold efficiency and production cost in each technology using Napier grass as fuel.

From a comparison of cold efficiency and production cost in Table 6, it was observed that syngas derived from a gasification process performs better than biogas, bio-oil and bio-ethanol, respectively, in converting Napier grass to alternative energy. The syngas produced from a gasification process has a high value trend of cold efficiency, and it also has low production cost when compared to other technology. Even through syngas from a gasification process proved to have the best performance producing alternative energy, it is not popularly used as compared to biogas produced from a fermentation process. The gasification process is a complicated procedure, and it requires knowledgeable personnel in order to control the production process; thus, biogas production is a suitable application of alternative energy and is of significant interest in Thailand. However, syngas derived from a gasification process and biogas have limitations in terms of utilization in regard to transportation as compared to liquid fuels [24]. With regard to bio-oil and bio-ethanol, it was concluded that bio-oil has an advantageous trend of cold efficiency and production cost when compared with bio-ethanol, and it can support mega-projects to develop more production factories than bio-ethanol because of the diversity of raw materials, the time to produce, the complication of the process, *etc*.

Table 5. A comparison of costs for bio-oil production as compared to the literature.

Study results	Bio-oil cost $/liter	Bio-oil cost $/GJ	Tons per day	Year
Solantausta, *et al.* [46]	0.156	7.30	1000	1992
Cottam and Bridgwater [47]	0.108	5.00	1000	1994
Gregoire and Bain [48]	0.132	6.10	1000	1994
Islam and Ani [49]	0.458	21.20	2.4	2000
Islam and Ani [49]	0.217	10.10	2.4	2000
Mullaney, *et al.* [50]	0.320	14.50	100	2002
Mullaney, *et al.* [50]	0.235	10.60	400	2002
Peacocke, *et al.* (Wellman plant) [51]	0.204	9.50	48	2004
Peacocke, *et al.* (BTG plant) [51]	0.172	8.00	48	2004
Marker, *et al.* [52]	0.114	5.10	2000	2005
Marker, *et al.* [52]	0.146	6.77	500	2005
Ringer, *et al.* [53]	0.164	7.62	550	2006
Uslu, *et al.* [54]	0.177	6.00	132	2008
Velden, *et al.* [55]	0.241	11.63	-	2008
Dynamotive [56]	0.196	4.04	200	2009
Badger, *et al.* [57]	0.249	11.54	100	2010
Czernik, *et al.* [58]	0.127	6.00	-	2010
Wright, *et al.* [59]	0.220	10.19	2000	2010
Rogers and Brammer [60]	0.242	11.25	400	2012
Jones and Male [61]	0.156	7.24	2000	2012
Brown, *et al.* [62]	0.466	21.73	15	2013
Czernik and French [63]	0.206	9.57	-	2014
Mirkouei, *et al.* [64]	0.304	14.11	13.6	2016
Treedet and Suntivarakorn [37]	0.353	9.56	1.08	2017
Suntivarakorn, *et al.* [31]	0.481	19.06	1.8	2018
The Present Study	0.278	17.98	1.8	2019

Table 6. A comparison of cold efficiency and production cost in each technology by using Napier grass as fuel.

Type of fuel technology	Cold efficiency (%)	Production cost (USD/GJ)
Bio-oil		
-The present study	28.24	17.98
-Badger, *et al.* [57]	53.33	11.54
-Suntivarakorn, *et al.* [31]	24.88	19.06
-Treedet and Suntivarakorn [37]	46.06	9.56
Bio-ethanol		
-Yasuda *et al.* [15]	33.58	-
-Wongwatanapaiboon, *et al.* [38]	48.37	-
-Yasuda *et al.* [39]	39.77	-
-Zhao *et al.* [65]	-	36.25
-Humbird, *et al.* [66]	-	16.65
Biogas		
-Somsiri and Vivanpatarakij [41]	50.14	-
-Udomsin and Rean-aree [67]	10.87	1.17
-Noikaw [68]	12.41	0.48
-Ministry of Energy, Thailand [69]	15.60	4.49
-Kamutavanich [72]	7.83	2.18
Syngas from gasification		
-Somsiri and Vivanpatarakij [41]	95.21	-
-Zhezri, *et al.* [44]	85.40	-
-Jeenanurugk [71]	72.65	0.26
-Kamutavanich [72]	72.70	0.70

4. CONCLUSION

This work focused on studying improvements of bio-oil production systems by adding the installation of a new scrubbing condenser in order to improve yield of bio-oil as compared to previous work [31]. Napier grass was used as raw material because this material has the potential to be used as an alternative energy source. Moreover, the comparison of energy conversion efficiency and production cost were also shown in order that these results can help to assist Thailand's policies on alternative energy.

The results of bio-oil production showed that the improvement of the bio-oil production system can produce a maximum yield of bio-oil at about 44.60 wt% at 480°C bed temperature, 7 m/s superficial velocity and 60 kg/hr feed rate. The yield of bio-oil in this work had a higher quantity of yield than previous work, but the properties of bio-oil were similar to previous work. Moreover, the bio-oil production from Napier grass in this study had the maximum cold efficiency and the maximum total energy conversion and cost of production of 28.24%, 22.44% and 0.278 $/liter, respectively. However, when the cost of production was compared with other studies researching bio-oil production from biomass, the production costs were considered to be "moderate".

When comparing cold efficiency and the cost of the production of bio-oil as alternative energy from Napier grass, such as bio-ethanol, biogas and syngas created from a gasification process, it can be concluded that the syngas from gasification process provides the best alternative energy and has an advantageous trend of cold efficiency and cost of production. The minor trend is biogas, bio-oil and bio-ethanol, respectively. However, the decision to encourage investment or policy creation should consider many factors, such as: utilization, environment pollution, transportation, knowledge of personnel to control production process and possibility to develop production technology in the country, *etc*.

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