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Optimization of Low-Temperature Torrefaction for Rice Straw Upgrading

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Abstract Rice straw is an agricultural waste most left in the field and is burned prior to the next crop. It is a biomass resource which has high potential to be used as an alternative fuel. However, it contains low fixed carbon and high volatile matters, giving low fuel characteristics. Hence, upgrading rice straw via low temperature torrefaction is of interest. Torrefaction is a thermal chemical process similar to drying, but it requires higher temperature with air absence environment. In this present work, central composite design is used for experimental plan. Two pertinent parameters, temperature and reaction time vary in ranges of 200-300 °C and 25.7-54.3 minutes, respectively. Optimization of the torrefaction is made by considering energy yield (%) and specific energy consumption (Wh/g) used during the process. The results show that at 200°C, 40 min, the test gives the best energy yields and specific energy consumption by 96.16% and 23.73 Wh/g and at 215°C, 30 min, the second best of 94.06% and 25.50 Wh/g are obtained. These two conditions are recommended for rice straw torrefaction.

INTRODUCTION

Increasing in population and technologies have resulted in high energy demand. Hence energy price has been risen(rising) as well as fossil energy resources have been in crisis in both quantity and environmental impacts. Renewable energy resources have, thus drawn much attention as alternative energy resources. Biomasses are agricultural wastes left in the fields and, sometimes, are burned before the next crops. These biomasses can be utilised as alternative fuels in "biomass power plants". However, they have shown low fuel characteristics such as high moisture content, low fixed carbon, and thus low heating values. Therefore, upgrading biomass properties is required for efficient utilisation.

Rice straw is one of promising biomass, particularly in Thailand. It is considered as waste left in the fields after harvesting period and mostly burned causing smoky and PM2.5 problems in the vicinities. Thus, rice straw utilisation is of interest. Collecting and compacting rice straw are the beginning steps for utilisation. Moreover, as it has low fuel characteristics, it is also required to improve its quality for the ease of storing and efficient combustion [1].

Upgrading rice straw by a thermal chemical process called "torrefaction" is a process using a temperature range of 200-300°C under air absence environment for removing moisture content and light volatile matters from the rice straw. The productions of torrefaction could be in solid, liquid and gaseous phases [2]. Nevertheless, as under low temperature, the main production is commonly in solid phase and called "torrefied biomass" [3]. Torrefied biomass has low moisture content and lower O/C and H/C ratios, resulting in higher heating value [4]. Moreover, torrefied biomass can improve grindability and resistance of biological degradation.

Lau et al. [5] studied effect of temperature on torrefaction of oil palm fronds in a horizontal tube furnace for 30 minutes. They found that when increasing temperatures from 200°C to 300°C (25°C interval), the energy yield

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diminished from 97.12% to 78.29%. They also noted that the temperature above 275°C, gave energy yields lower than 90%. In addition, they concluded that mass yield, volatile matters and energy densification ratio, were reduced as well as the fixed carbon and higher heating value were increased by higher temperature. Martin-Lara et al. [6] reported a torrefaction of olive tree pruning at 200-300°C (heating rate 15°C/min) and 10-60 minutes reaction time. They found that at 300°C and 60 min, O/C and H/C ratios were reduced, and fixed carbon to volatile matters ratio was increased from 0.23 to 0.39 compared to the raw biomass. This gave better fuel properties for torrefied olive tree pruning.

In 2018, Chen et al. [7] improved rice husk by torrefaction at 210-300°C for 30 min. They concluded that increasing temperature from 210°C to 300°C, could reduce volatile matters from 66.1%wt to 41.3%wt and solid yield from 95.3 to 64.4%wt. Later in 2019, Singh et al. [8] examined the torrefaction of *Acacia nilotica* at 220-280°C (heating rates of 5-15°C/min) and 20-60 min reaction time. They concluded that the temperature had a strong effect on torrefaction compared to reaction time and heating rate. The maximum value of higher heating value (HHV) and energy yield (EY) of 23.73 MJ/kg and 70.20, respectively, were obtained at 252°C, 60 min reaction time and 5°C /min heating rate. The moisture content, O/C and H/C decreased by 73.23%, 52.94% and 46.22%, while fixed carbon and heating value were increased by 75.54% and 18.62%, respectively, as compared to raw biomass.

Additionally, a study of pigeon pea stalk torrefaction was reported by [4]. The torrefaction was carried out at 225-275°C (15°C/min heating rate) and 15-45 min reaction time. They concluded that at 275°C and 45 min, the solid yield and energy yield was as low as 40.4% and 50% respectively. Moreover, the O/C and H/C ratios were reduced by temperature. This confirmed that the temperature had a strong influence on product characteristics.

From the brief literature review above, torrefaction can be used for biomass property improvement. None of rice straw torrefaction has been available. The aim of this study is to optimize the temperature and reaction time for rice straw torrefaction by using energy yield and specific energy consumption as the criteria. The temperatures were kept low in a range of 200-300°C and reaction times were set at 25.7-54.3 minutes. The process was also occurred under nitrogen rich environment and atmospheric pressure. Optimization of rice straw torrefaction giving best properties was carried out using by mass yield mass, energy density ratio, energy yield and specific energy consumption used during the process.

METHODOLOGY

Material Preparation

Rice straw was prepared by cutting into 2-5 cm pieces. Then HHV was examined as illustrated in Table 1. Proximate analysis and ultimate analysis of raw rice straw were also shown in Table 1.

TABLE 1. Raw rice straw characteristics

Proximate analysis (wt %, as-received basis) [9]				**Ultimate analysis (wt %, dry basis) [9]**					**HHV (J/g)**
Fixed carbon	**Moisture**	**Volatiles**	**Ash**	**C**	**H**	**N**	**S**	**O**	
11.56	4.35	74.86	9.23	42.57	5.84	2.13	0.13	49.33	14,743

Torrefaction Process

A fixed bed torrefaction reactor was made of stainless steel, having 50 mm outside diameter and 1000 mm length as seen in Fig 1. The temperatures were measured and controlled by K-type thermocouples and proportional integral derivative (PID) temperature controller. Air absence environment in the reaction was obtained by feeding nitrogen gas (99% purity) at 500 ml/min at the beginning until a set temperature was reached, then the flow rate was reduced to 200 ml/min during the reaction time. Then, 15 grams of rice straw were fed into the reactor. The heating rate was set at 5°C/min. Electrical energy consumption during the process was recorded by a power meter (HIOKI-CM3286-01).

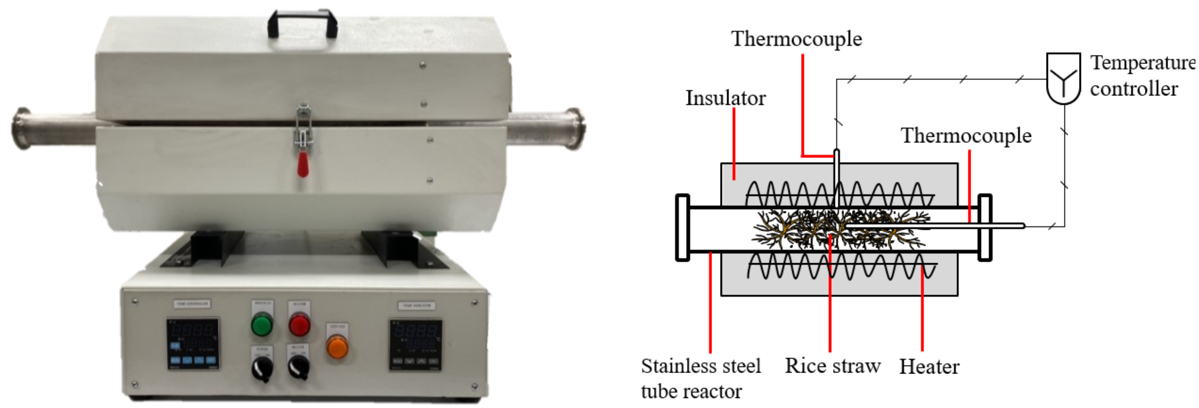

FIGURE 1. Torrefaction reactor

Experimental Design

Temperature and reaction time are two key factors and set at levels shown in Table 2. Experiments were planned by central composite design (CCD) giving 13 runs shown in Table 3. Each run was repeated 3 times and the results were averaged.

TABLE 2. Parameter levels (α = 1.4286).

Parameters	**Levels**				
	-α	**-1**	**0**	**1**	**+α**
Temperature (°C)	200	215	250	285	300
Time (min)	25.7	30	40	50	54.3

Torrefaction Performance and Optimization

Mass yield is a mass ratio of raw material and product, while the energy densification ratio is the ratio of HHV of raw and torrefied biomass as shown in Eq (1) and (2). The torrefaction was optimised by using energy yield and specific energy consumption during the process as determined by Eq (3) and (4).

$$\text{Mass yield } (\%) = \frac{\text{Mass}_{\text{torr}}}{\text{Mass}_{\text{raw}}} \times 100 \tag{1}$$

$$\text{Energy densification ratio, EDR } (\%) = \frac{\text{HHV}_{\text{torr}}}{\text{HHV}_{\text{raw}}} \times 100 \tag{2}$$

$$\text{Energy yield, EY } (\%) = \frac{\text{Mass}_{\text{torr}} \times \text{HHV}_{\text{torr}}}{\text{Mass}_{\text{raw}} \times \text{HHV}_{\text{raw}}} \times 100 \tag{3}$$

$$\text{Specific energy consumption, SEC (Wh/g)} = \frac{\text{Electrical energy}}{\text{Mass}_{\text{torr}}} \tag{4}$$

Where, Mass_{raw} is the mass of raw rice straw (g), $\text{Mass}_{\text{torr}}$ is the mass of torrefied rice straw (g), HHV_{raw} is the higher heating value of raw rice straw (J/g), HHV_{torr} is the higher heating value of torrefied rice straw (J/g) and Electrical energy is the energy used during torrefaction (Wh)

For optimization, EY and SEC are considered as the main factors to obtain an optimized temperature and time for the best rice straw torrefaction.

RESULTS AND DISCUSSIONS

Effect of Temperature and Time on Mass Yield, HHV and Energy Yield

As seen in Fig 2, the torrefied rice straw at some selected conditions were illustrated. It was obviously seen the differences of appearance. The colour of rice straw became darker when using higher temperature and longer time. The mass yield, HHV of product, EDR, EY, electrical energy consumption and SEC were determined for each condition and exhibited in Table 3.

FIGURE 2. (a) Raw rice straw, (b) Torrefied rice straw at 200°C and 40 min, (c) Torrefied rice straw at 215°C and 30 min, (d) Torrefied rice straw at 215°C and 50 min, (e) Torrefied rice straw at 250°C and 25.7 min and (f) Torrefied rice straw at 250°C and 40 min

It was found that mass yields were ranged from 35.98 ± 0.19 wt% to 86.24 ± 0.20 wt%. It was reported that torrefaction gave biomass valorisation because of moisture reduction and decomposition of hemicellulose [7, 9]. An increase in temperature resulted in lower mass yield and higher HHV. This agreed well with Ma et al. [10] which improved HHV of torrefied biomass, but less quantity was reported. For lower temperature, mass yield was higher, but HHV was slightly decreased compared with those of higher temperature. Moreover, the reaction time showed an effect on torrefied product. The mass loss increased with time, resulting in a lower mass yield. This was due to an increase in devolatilization.

As seen in Table 3, the EDR was risen from 111.5% to 147.1% when the temperature was increased from 200°C to 300°C for the 40 min reaction time. This indicated that the quality of rice straw was improved by 11.5%-47.1%. However, since a higher temperature decreased the mass yield, the energy yield, which is a combination of EDR and mass yield, would be diminished.

The energy yields of torrefied rice straw ranged from 52.91% to 96.16%. It was obvious that higher temperature would result in lower EY. The decrease can be explained by the thermal decomposition of rice straw. With increasing torrefied temperature and reaction time, the mass, in forms of moisture and volatile, was vanished resulting in a reduction of overall energy content of the torrefied rice straw.

TABLE 3. Mass yield, higher heating value (HHV), energy densification ratio (EDR), energy yield (EY), electrical energy and specific energy consumption (SEC) for every run order designed by CCD.

Run	Temperature (°C)	Time (min)	Mass Yield* (wt%)	HHV of product (J/g)	EDR (%)	Energy yield (%)	Electrical energy* (Wh)	Specific energy consumption* (Wh/g)
1	200	40	86.24 ± 0.20	16,438	111.5	96.16	306.9±7.21	23.73±0.59
2	250	54.3	69.60 ± 0.24	18,430	125.0	87.01	442.2±14.17	42.35±1.28
3	250	40	71.42 ± 0.34	17,703	120.1	85.76	400.9±0.38	37.42±0.19
4	215	50	81.53 ± 0.13	16,904	114.7	93.48	358.5±8.02	29.31±0.70
5	250	25.7	72.93 ± 0.18	17,522	118.8	86.68	378.0±8.60	34.55±0.84
6	215	30	83.80 ± 0.12	16,548	112.2	94.06	320.5±6.46	25.50±0.52
7	300	40	35.98 ± 0.19	21,681	147.1	52.91	522.8±3.63	96.88±1.09
8	250	40	71.40 ± 0.07	17,884	121.3	86.61	403.7±2.37	37.70±0.23
9	285	50	46.51 ± 0.10	20,481	138.9	64.61	520.3±12.48	74.58±1.95
10	250	40	71.44 ± 0.23	18,109	122.8	87.76	404.8±1.71	37.77±0.16
11	285	30	49.84 ± 1.24	20,407	138.4	68.99	452.3±2.65	60.52±1.18
12	250	40	71.13 ± 0.20	17,967	121.9	86.69	405.7±3.30	38.02±0.39
13	250	40	70.76 ± 0.20	18,161	123.2	87.16	402.2±2.42	37.90±0.20

Remark: Average±SD* and HHV of raw rice straw = 14,743 J/g

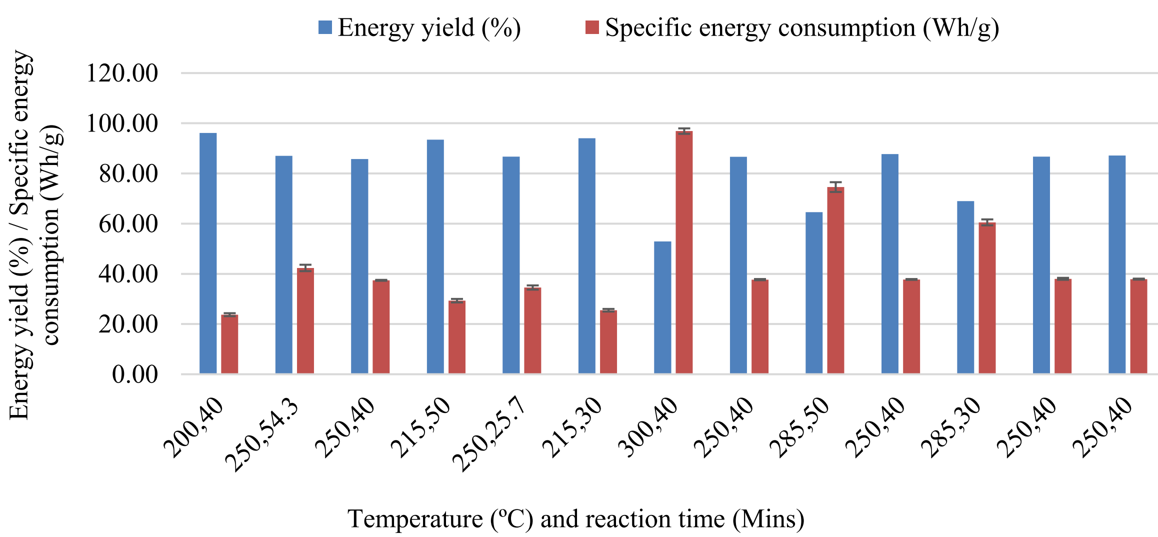

FIGURE 3. Effect of energy yield and specific energy consumption for every run

Specific Energy Consumption (Wh/g)

In optimization, not only energy yield, but also the specific energy consumption was considered. This was because the specific energy consumption indicated the energy used during the process per a unit of torrefied product which was practical for economic point of view. In this work, thus, the EY and specific energy consumption were determined and illustrated in Table 3. It can be said that optimised condition was obtained at high EY and low SEC. This led to the conclusion that there were two attractive optimised conditions which gave high EY and low SEC. Firstly, for

200°C, 40 min, SEC was 23.73 Wh/g were obtained. As shown in Fig. 3, it can be said that high temperature and long reaction time resulted in high energy consumption, but less mass yield. This gave high SEC, which is not suggested, though the HHV and EDR were high. It was noticed that not only high HHV but also mass yield must be considered for torrefaction optimization.

CONCLUSION

In this work rice straw was upgraded by torrefaction. Low temperature torrefaction was focused while reaction time was varied. The temperature and time were ranged as 200-300 °C and 25.7-54.3 min, respectively. The results showed that increasing in temperature and time caused a reduction in mass yield, but an increase in higher heating value and the energy densification ratio. This lowered the energy yield as a result. It was found that when energy yield was high, the specific energy consumption was low. Thus, the optimization of torrefaction was made by these two parameters. Based on the results, it was finally concluded that, the highest energy yield of 96.16% and lowest specific energy consumption of 23.73 Wh/g were achieved at 200 °C and 40 min while the second-best energy yield and specific energy consumption by 94.06% and 25.5 Wh/g respectively, were obtained at 215°C, 30 min. Thus, these two conditions were suggested for rice straw upgrading via torrefaction. In future work, investigation of pressure influence on torrefaction is being carried out to find the best torrefaction condition.

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