A feasibility study of hydrothermal treatment of rice straw for multi-production of solid fuel and liquid fertilizer

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Abstract. Energy use has increased steadily over the last century due to population and industry increase. With the growing of GHG, biomass becomes an essential contributor to the world energy need. Indonesia is the third rice producer in the world. Rice straw has been converted to solid fuel by Hydrothermal Treatment (HT) for electricity generation. HT is a boiling solid organic or inorganic substance in water at high pressure and temperature within a holding time. HT converts high moisture content biomass into dried, uniform, pulverized, and higher energy density solid fuels. HT can effectively transport nutrient components in biomass into a liquid product known as fertilizer. This paper deals with an evaluation of hydrothermal treatment of rice straw for solid fuel and liquid fertilizer. An investigation of rice straw characteristics were completed for Bandung rice straw with various condition of temperature, biomass-water ratio, and holding time in the purpose to find the changes of calorific value for solid product and (N, P, K, and pH) for liquid product. The results showed that solid product at 225 °C and 90 min consists in a heating value 13.8 MJ/kg equal to lignite B. Liquid product at 225°C and 90 min had the NPK content similar to that of micronutrients compound liquid fertilizer. The dried solid product should be useful for Coal Fire Power Plant, and the liquid product is suitable for plants. This research proves that hydrothermal process can be applied to rice straw to produce solid fuel and liquid fertilizer with adequate quality.

1. Introduction

Energy consumption has augmented gradually over the last century as world population has grown and more countries have become industrialized since 1900. Fossil fuel, especially crude oil, is currently the more noticeable energy source around the world. However, the reserves of fossil fuel are limited and will be reduced in the near future at its recent use rate.

Moreover, burning fossil fuels causes environmental issues including GHG emission, the main cause of climate change[1]. Because of the insufficient oil availability in the future, there is a good interest in discovery alternative energy sources. Due to the bad environmental impact of burning fossil fuels, the
alternative energy source should be sustainable and environmental-friendly. Utilization biomass for energy production can have a balanced CO$_2$ production and consumption compared to CO$_2$ from burning fossil fuels. Nowadays, energy production from biomass is only a small production of the total energy production. The resources of biomass materials such as crops, grasses, wood, agricultural residues, and organic wastes are abundant, so there is a great potential to augment energy production from biomass materials.

Renewable energy plays a crucial role in Indonesia’s national energy policies, especially as maximizing renewable resources helps strengthen the security of energy supply. On the other hand, Indonesia is recently exploiting only around 5% of its renewable energy capacity. The government intends to speed up the exploitation of renewable energy and to increase its share of primary energy to 23% by 2025. Renewable energy accounted for 33.4% of total primary energy supply (TPES) in Indonesia in 2012[2]. This amounts to 71.4 million tons of oil-equivalent (Mtoe) (282.3 million barrels of oil-equivalent), made up primarily of biofuels and waste biomass (25.3% of TPES). The remainder is from geothermal (7.6%), hydro (0.5%) and negligible levels of wind and solar power. Current capacity of on-grid biomass power plants in 2013 was 90.5 MW, mainly located in Sumatra Island (Northern Sumatra and Riau), Bali, West Java and Kalimantan. Biomass power plant feedstock in Indonesia is usually comprised of palm oil residues, municipal solid waste, sugar residues and other solid biomass, including rice residues, rubber wood and wood chip. Smaller quantities are available from other agricultural waste, such as logging residues, sawn-timber residues and coconut residues.

The rice production in Indonesia were increasing from years to years[3]. Indonesia is the world’s third-largest rice producer and also one of the world’s biggest rice consumers[4]. The country’s rice area expanded from 11.4 million ha in 1995 to 13.2 million ha in 2010, which represented 24% of the total agricultural area. Rice yield increased slightly from 4.3 t/ha in 1995 to 5 t/ha in 2010. Rice production is heavily concentrated on the islands of Java and Sumatra; nearly 60% of total production emanates from Java alone. Data from the International Fertilizer Industry Association (IFA) reveal that the country’s fertilizer consumption increased enormously from 0.14 million t in 1961 to 4.47 million t in 2009. FAO recorded that about 52% of all fertilizer use in Indonesia is for rice.

In 2008, about 620 million tons of rice straw were produced in Asia, and this quantity is increasing every year[5]. Burning of rice straw causes the effects on soil and atmosphere[6]. In Cambodia, sustainable rice straw management technologies are becoming more important as rice farming produces million tons of material every year. Mechanization for rice production has increased resulting more rice straw being left in the field[7].

According to the above description, one of the appropriate solution is to invent rice straw to become a useful solid fuel which can be mixed with coal for Coal Fire Power Plant by hydrothermal process. It will benefit not only in solving GHGs emission problem but also decreasing the coal consumption in power plant.

The liquid organic fertilizer potentially holding solubilized nutrient is being rarely used. Now, the liquid residue of hydrothermal treatment is considered as wastewater, and there is a limited study on this liquid product. During HT, some inorganic and organic contents in rice straw may dissolve into the liquid phase. Thus HT can effectively transport nutrient components in biomass into a liquid product. This nutrient source might be used for organic fertilizer [8].

The objective of the study is to investigate the possibilities of using HT in producing solid fuel and bio-organic fertilizer. In this study, the influences of some operating parameters such as temperature and holding time to the product will be also investigated.
The hydrothermal process involves the application of heat and pressure in aqueous medium, similar to the natural processing of organic remains from plants or animals to become coal or crude oil we consume today. Hydrothermal treatment breaks the physical and chemical structure in the materials such as cellulose, hemicellulose, and lignin, and these biomasses are broken down into smaller and simpler molecules, see Figure 1 and Figure 2.

![Figure 1. Visualization of particle breakage due to HT][9]

![Figure 2. Physical structure change of biomass by HT][9]

2. **Experimental Procedure**
The rice straw samples used were obtained from the rice field around Bandung. The experimental apparatus setup consists of a 2-liter-capacity autoclave in Thermodynamic Laboratory, see Figure 3. In this experiment, 150 g of chopped rice straw and distilled water in 1:5 biomass-water ratio was put into the reactor. The reactor temperature was varied at 150, 175, 200 and 225 °C with the varied holding time of 30 min and 90 min. After having finished, the product was sent out from the reactor. The solid part was separated from the liquid by using a filtration.
Hydrothermal process produces two kinds of product, see Figure 4 and Figure 5. Solid product and raw rice straw characteristics were analyzed in term of calorific value. The tests were done at chemical department. The total nitrogen in the liquid residue and the concentrations of P and K in the liquid residue are analyzed[10]. The micronutrient (N, P, K and pH) was defined for liquid products. The tests were done in Thermodynamic Laboratory. Two replications of N, P and K test were carried out.

![Figure 3. Autoclave in Thermodynamic Laboratory](image)

![Figure 4. Hydrothermal treatment experimental flow chart](image)
Solid product and raw rice straw were dried in the oven at 40 °C. The sample has been pulverized to pass 250-μm (No.60) sieve as prepared in accordance with Method D 346 or Method D 2013. Moisture was determined by establishing the loss in weight of the sample when heated under rigidly controlled conditions of temperature, time and atmosphere, sample weight, and equipment specifications. Samples were dried in the oven at 40 °C for surface moisture and temperature regulation between limits of 104 and 110 °C for inherent moisture[11].

3. Result and Discussion

3.1. Fuel properties of solid product

Higher heating value (HHV) is defined as the amount of heat released by the unit mass or volume of fuel (initially at 25 °C) once it is combusted and the products have returned to a temperature of 25 °C. It includes the latent heat of vaporization of water. HHV can be measured in a bomb calorimeter [12]. The calorific values of rice straw after hydrothermal treatment are presented in Table 1 based on ASTM D5865 standard in Chemical Department.
Table 1. Calorific value of rice straw after HT

| Holding Temperature | Holding Time | Calorific Value (MJ/kg) (adb) |
|---------------------|--------------|------------------------------|
| 150 °C              | 30 min       | 10.55                        |
|                     | 90 min       | 11.28                        |
| 175 °C              | 30 min       | 10.96                        |
|                     | 90 min       | 11.67                        |
| 200 °C              | 30 min       | 12.92                        |
|                     | 90 min       | 12.95                        |
| 225 °C              | 30 min       | 11.88                        |
|                     | 90 min       | 13.80                        |
| Raw rice straw      |              | 10.44                        |

At 225 °C and 90 min, solid product contains a heating value 13.8 MJ/kg equal to lignite B which is less than 14.65 MJ/kg [13]. It reveals the possibility of using the product of HT as co-firing fuel with coal. According to Figure 6, the calorific value of solid products have increased in function of temperature and holding time after HT. If the holding time is increased from 30 min to 90 min, the average increment of the calorific value is about 0.84 MJ/kg. So, the holding time has a little effects on the caloric value. Moreover, if the temperature is increased from 150 °C to 225 °C, the calorific value increases from 10.55 to 13.8 MJ/kg. Thus, the effect of temperature on the calorific value is higher than that of holding time.

Figure 6. Variation of calorific value after hydrothermal treatment

3.2. Main nutrient elements in the liquid residue

The primary macronutrients utilized by plants in large amounts for crops growth are nitrogen, phosphorous and potassium. Table 2 reveals the main nutrient elements of liquid fertilizer after hydrothermal treatment.
Table 2. Main nutrient elements of liquid fertilizer after HT

| Holding Temperature | Holding Time | Main nutrient elements |  |  |  |
|---------------------|--------------|------------------------|---|---|---|
|                     |              | N(%) | P(%) | K(%) | pH  |
| 150 °C              | 30 min       | 0.02±0.00 | 0.09±0.02 | 1.35±0.31 | 5.6 |
|                     | 90 min       | 0.20±0.16 | 0.16±0.02 | 1.28±0.24 | 5.2 |
| 175 °C              | 30 min       | 0.29±0.20 | 0.14±0.06 | 1.45±0.31 | 5.5 |
|                     | 90 min       | 0.22±0.17 | 0.14±0.07 | 4.66±0.07 | 4.8 |
| 200 °C              | 30 min       | 0.30±0.26 | 0.12±0.03 | 5.28±0.82 | 4.4 |
|                     | 90 min       | 0.44±0.08 | 0.12±0.06 | 5.03±0.63 | 4.9 |
| 225 °C              | 30 min       | 0.28±0.24 | 0.12±0.04 | 6.87±0.03 | 4.8 |
|                     | 90 min       | 0.35±0.21 | 0.15±0.06 | 9.48±1.28 | 4.6 |

Data show mean±standard error

The percentage of N fluctuates when the holding temperature and holding time increase, see Figure 7. The percentage of P has increased when the reaction temperature and holding time have increased, see Figure 8. The percentage of K increases when the treatment temperature and holding time increase, see Figure 9.

Figure 7. Variation of nitrogen percentage in liquid product after hydrothermal treatment

Figure 8. Variation of phosphoric percentage in liquid product after hydrothermal treatment
Figure 9. Variation of potassium percentage in liquid product after hydrothermal treatment

As shown in Figure 7, Figure 8 and Figure 9, the holding time had little effects on the percentage of N, P and K. However, variation of reaction temperatures provides the significant differences of the percentage of N, P and K.

Table 3. Representative commercial liquid fertilizer [10]

| Types                                | N(%) | P(%) | K(%) |
|--------------------------------------|------|------|------|
| Urea compound liquid fertilizer      | 2-16 | 1-14 | 1-10 |
| Organic liquid fertilizer            | 1.5-12 | 1-12 | 2-11.5 |
| Micronutrients compound liquid fertilizer | 1.5-12 | 0.8-4 | 2-12 |

Percentage of N, P and K in Table 2 are considerably low compared with that of commercial liquid fertilizer in Table 3. However, this liquid product can be used as the liquid fertilizer because the value of N, P and K are almost equal to the micronutrients compound liquid fertilizer in the condition of 225 °C temperature and 90 min holding time.

The optimum value of pH at which plants can take up nutrients to the root zone and the foliage best is ranging from 5.5 to 8.5 [8]. The pH of sewage sludge after HT is equal 5.17 so it can applied directly to plants and soil because pH is not much low [10]. At (150 °C and 30 min), (150 °C and 90 min), and (200 °C and 90 min), pH of liquid products are good for crops, see Table 2.

4. Conclusion

From the carried out experiment in this study, it was found that hydrothermal treatment can produce solid fuel and liquid fertilizer from rice straw at the same time. The best operating parameter is at 225 °C temperature and 90 minutes holding time, producing solid fuel with calorific value 13.8 MJ/kg and liquid fertilizer containing the compositions of N, P and K with value 0.57%, 0.22% and 8.2%, respectively. The temperature has significant effect while the holding time has the lower effect for the calorific value, N, P, and K. Calorific value and soluble nutrients are linearly increased as the reaction temperature and holding time are increased.

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References
[1] Cheng J 2010 *Biomass to Renewable Energy Processes* (Boca Raton: CRC Press)
[2] Anonim 2015 *Indonesia 2015* (Paris: International Energy Agency)
[3] Anonim 2012 *Ricepedia* (http://ricepedia.org/indonesia)
[4] Idrees K 2015 *World Knowing* (http://worldknowing.com/top-10-largest-rice-producing-country-in-the-world/)
[5] Anonim 2008 *IRRI* (http://irri.org/our-work/research/value-added-rice/rice-straw-and-husks)
[6] Anonim 2009 *Recycling of Rice Straw*
[7] Anonim 2016 *IRRI* (http://news.irri.org/2016/05/cambodia-assesses-new-technologies-for.html)
[8] Nurdiawati A et al. 2015 Evaluation of hydrothermal treatment of empty fruit bunch for solid fuel and liquid organic co-production. *Energy Procedia* **79** 226-232.
[9] Yoshikawa K and Prawisudha P 2014. Hydrothermal treatment of municipal solid waste for producing solid fuel *Application of Hydrothermal Reactions to Biomass Conversion, Green Chemistry and Sustainable Technology* pp. 355-383.
[10] Jambaldorj G, Takahashi M, and Yoshikawa K 2007 Liquid fertilizer production from sludge by hydrothermal treatment *Proceedings of International Symposium on EcoTopia Science* **07** 605-608
[11] ASTM International. 1981 *Annual Book of ASTM Standards Gaseous Fuels, Coal and Coke; Atmospheric A.* (USA: ASTM International)
[12] Basu P 2010 *Biomass Gasification and Pyrolysis, Practical Design and Theory* (USA: Elsevier Inc.)
[13] Matuszewski M 2012 *Quality Guidelines for Energy System Studies, Detailed Coal Specifications* (USA: National Energy Technology Laboratory)