Biochar production investigation from pyrolysis of lamtoro wood as a coal blend for fuel substitution in steam power plants

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Abstract. The biochar utilization reduces CO₂ emissions. This study aims to investigate the optimum pyrolysis temperature of lamtoro wood (Leucaena leucocephala) to produce suitable biochar for coal blends as fuel in the steam power plant. The experiment was carried out in a batch process, applied to a fixed bed reactor, 10 °C/minute heating rate, three different variables temperature (300, 450, 600 °C), and 60 minutes residence time. The biochar yield for each pyrolysis temperature is 61.77%, 26.45%, and 24.89%. This shows that the pyrolysis is carried out at a temperature of 300 to 450 °C, then ramps up to 600 °C. The volatile matter was released during the pyrolysis and raise the fixed carbon content. The fixed carbon content for each pyrolysis temperature is 26.35%, 61.82%, and 65.66%. Fixed carbon content at 450 and 600 °C identical to bituminous coal. The increase in fixed carbon content in biochar leads the heating value to increase. The heating value of lamtoro wood was 19.15 MJ/kg (db), increasing to 22.92, 28.01, and 29.73 MJ/kg (db) for each pyrolysis temperature. The biochar heating value is close to bituminous coal. The biochar energy content of original lamtoro wood for each pyrolysis temperature is 81.72%, 42.77%, and 42.71%. Biochar reaches its optimal point at pyrolysis temperature 450 °C, which has a yield and heating value almost the same at pyrolysis temperature of 600 °C. The biochar characterization results indicate that it can be used as a coal blend for steam power plants.

Keywords: lamtoro wood (Leucaena leucocephala), pyrolysis, biochar, coal blends, steam power plant, carbon neutral.

1. Introduction
CO₂ emissions have become a global issue related to environmental problems. The coal power plant is one of the big emitters of CO₂. The utilization of coal in power generation to produce electricity is cheaper than other fuels, but CO₂ emissions generated are higher than those of other fuels [1]. CO₂ emissions from coal combustion take up over 40% of global CO₂ emissions [2]. In 2012, Indonesia was included in the top 5 emitter countries in the world [3]. Alternative fuels are needed to replace coal for steam power plants. Biomass is one of the promising choices, which can be used as the raw material to generate electricity [4].

There are limitations on biomass utilization, such as the problems of availability, collection, and transportation. Therefore, fast-growing tree plantation for biomass production is one solution and the most sustainable fuel supply mechanism for biomass utilization as a power plant feedstock. Lamtoro wood has the potential as a steam power plant feedstock with a fast growth rate and can be produced on a large scale [5] [6].
One of the big problems in biomass utilization as power generation feedstock is the low calorific value of biomass. It will reduce power plant performance. Pyrolysis is a process of thermal decomposition under conditions of limited oxygen content. Biomass begins to decompose around 350-550 °C to 700-800 °C into char, tar, and gas [7].

Biochar is a solid residue obtained from pyrolysis. It has high fixed carbon, low oxygen content, and almost similar characteristics as coal in calorific value and fixed carbon content. The biochar could be utilized as coal blending for power plant feedstock. It can also be used 100% as feedstock for small capacity power plants. Biochar can be blended up to 5% for large capacity power plants. This research goal is looking for the optimum pyrolysis temperature to produce biochar and suitable coal blending for steam power plant fuel.

2. Experimental details
2.1. Equipment and materials
The equipment used in this study is a fixed bed reactor, manometer, and heat exchanger (HE)/condenser. Fixed bed reactor made of quartz glass and equipped with electric heaters. A manometer is used to measure reactor pressure and check for equipment leaks. The condenser cools and condenses liquid products (water and tar) carried in the NCG products. The test equipment can be seen in Figure 1 [8].

![Figure 1. Process scheme of pyrolysis](image)

The materials used in the study consisted of lamtoro wood from Gorontalo province, nitrogen gas (N2), and anisol (benzene methoxy) as a solvent to absorb tar in gas products. The first process is the lamtoro sample dried in an electric oven at 110 °C for 24 hours.

2.2. Experiment procedure
There are two variables in this study. The first is a fixed condition: 10 °C/minute of heating rate and -32+42 mesh of sample size. The second is variable: 300, 450, and 600 °C. In this study, experimental procedures are preparation and testing, measuring the yield of pyrolysis products, determining the quality of biochar, and calculating heat and material balance. In the preparation and
testing stage, pyrolysis was carried out in the batch scheme. 20 grams of +32 mesh lamtoro wood were put into the reactor and tested according to parameter variation (300, 450, and 600 °C) in a batch scheme.

The experiment was started by flowing nitrogen gas into the pyrolysis equipment. Nitrogen gas (N\textsubscript{2}) was streamed to the reactor and gas cooling equipment to remove trapped air. The nitrogen gas flow rate was regulated at 24 mL/minute. Gas products flowed through the top of the reactor and then cooled through a condenser. Nitrogen gas was also used as a carrier gas during the experiment and tracer for mass balance calculations. When the experiment occurred, the nitrogen flow rate used was 0.05 mL/min. The gas out of the condenser was analyzed with a gas analyzer.

The pyrolysis reactor was heated at 10 °C/minute with 60 minutes of residence time. The gas product would flow out from the top of the reactor and then streamed into a condenser equipped with cooling water circulation (5-10 °C). The components of pyrolysis gas would be condensed and separated from non-condensable gas (NCG). These will be collected in a condensing bottle (tar container). NCG was collected in a sampling bag. The NCG in the sampling bag was routed to 4 pieces of impinger. The first three impinger units contained 60 mL anisols, and the last one was filled with filters to ensure all tar is removed from NCG. The clean NCG is connected to a coal gas analyzer, and gas composition analysis can be performed. The composition of the NCG measured is CO, CO\textsubscript{2}, H\textsubscript{2}, CH\textsubscript{4}, O\textsubscript{2}, C\textsubscript{6}H\textsubscript{n}, and N\textsubscript{2}.

After the experiment, the yield measurement of pyrolysis products was carried out to obtain the values of biochar, NCG, and tar. Biochar was measured by analytical balance. NCG was measured by material balance calculation with N\textsubscript{2} as a gas carrier. The stages are, record the N\textsubscript{2} flow rate (F\textsubscript{N2}) and then record N\textsubscript{2} composition in NCG (X\textsubscript{N2}). The final stage is to calculate the NCG flow rate (F\textsubscript{gas} = F\textsubscript{N2}/X\textsubscript{N2}). Tar value was obtained by calculating the difference (F\textsubscript{tar} = Flamtoro + F\textsubscript{N2} – F\textsubscript{gas}).

The quality of biochar yield was conducted by ultimate and proximate value. 100 kg of lamtoro wood was made as a basis of calculation. The assumption is the lamtoro was dried, TM = 0, and fixed carbon and ash are in biochar. Mass of ash = %ash * mass of lamtoro, %ash = mass of ash/mass of biochar, the mass of fixed carbon = %fixed carbon * mass of lamtoro, %fixed carbon = mass of fixed carbon/mass of ash, the mass of volatile matter = mass of ash difference – (ash + fixed carbon), and % volatile matter = mass of volatile matter/mass of biochar.

The final step was the calculation of heat and material balance. First, 100 kg of lamtoro is used as the basis for the calculation. The energy content of lamtoro = 100 kg * calorific value of lamtoro wood (ar basis), the mass of biochar = %biochar * 100 kg, energy content of biochar = mass of biochar * calorific value of biochar (ar basis), and energy in biochar = energy content of biochar/energy content of lamtoro.

3. Results and discussion

3.1. Pyrolysis products

Figure 2 shows the mass balance of feed and pyrolysis products at each temperature. The results showed that the yield of biochar decreased with increasing pyrolysis temperature, while on the other hand, tar and NCG increased. [9]. This occurs due to the loss of moisture content and volatility of organic compounds in biochar and an increase in the decomposition process of organic compounds such as hemicellulose, cellulose, and lignin when the pyrolysis temperature increases.
A significant decrease in biochar yield occurred from 300 °C to 450 °C and tended to flat from 450 °C to 600 °C. This shows that the optimal temperature of lamtaro wood pyrolysis is 450 °C. Increasing the temperature above 450 °C will require more energy while the resulting biochar yield is not too different. The yield of biochar produced at 300 °C was higher than the yield of biochar at 450 °C and 600 °C.

3.2. Biochar quality

Pyrolysis is a decomposition process that occurs when volatiles is driven out from hydrocarbon material under heating conditions. The higher the pyrolysis temperature, the biochar produced will have lower volatile matter (Table 1). The ratio of a sharp decrease in volatile matter occurred at temperatures of 300 - 450 °C, then sloping towards 600 °C. This will lead to increased carbon and fixed ash. This shows that the pyrolysis peak occurs at a temperature of 450 °C.

The carbon content in lamtaro wood char has increased after the pyrolysis process. Before the pyrolysis process, carbon content was 49.03%, increased to 57.56% at 300 °C, 76.08% at 450 °C, and 81.80% at 600 °C. The carbon content in biochar increases with increasing pyrolysis temperature. This is because the biochar produced at high pyrolysis temperature contains low volatile matter and more carbonized carbon. Therefore, high carbon products can be obtained by increasing the pyrolysis temperature. The results showed that the biochar content of H, O, N, and S decreased with increasing temperature (Table 1). This decrease can be caused by pyrolytic processes, which result in the loss of surface functional groups containing O and H by dehydration of organic biomass compounds (such as hemicellulose, cellulose, and lignin) [10][11].

Biochar characterization shows similarities with bituminous coal from East Kalimantan, including fixed carbon content and heating value. The fixed carbon content at 450 °C pyrolysis temperature was 61.82% and increased from the initial lamtaro feed, which was 16.35%, while the fixed carbon content in bituminous coal was 52.67%. Fixed carbon will produce heat in the process of fuel combustion that occurs in a fluidized bed reactor. The combustion energy will be absorbed by the water wall in the furnace wall. The same fixed carbon content will produce the same combustion energy. This will result in the same heat transfer to the water wall so that the plant performance will not be disturbed by biochar utilization.
An increase in pyrolysis temperature between 300-450 °C will increase the calorific value of biochar sharply and then sloping towards 600 °C (Table 1). The increasing of fixed carbon causes this at 300-450 °C of pyrolysis temperature then sloping at 600 °C. Fixed carbon contains a large energy density. The higher the fixed carbon, the higher the calorific value of biochar [12].

3.3. The energy content of biochar
The energy content of biochar to the lamtoro feed resulted from the calculation of mass and energy balance (Table 2). Biochar energy content in pyrolysis temperatures of 300 °C, 450 °C, and 600 °C was 81.72%, 42.77%, and 42.71%. From that result, the recommended pyrolysis temperature is 450 °C.

The remaining biomass energy was found in other pyrolysis products (tar and NCG). Pyrolysis products that increase with the increase of pyrolysis temperature were tar and NCG, as shown in Figure 2. The mixture of tar and NCG was known as a volatile matter (VM). VM has high energy content and must be utilized. At the low rank-coal fired power plant, VM will be used as fuel in the coal dryer unit, so no additional equipment was needed. Meanwhile, tar and NCG can be further processed into liquid fuels or chemical products if a power plant uses high-rank coal.

### Table 1. Lamtoro properties

| Parameter       | Unit | Lamtoro | Biochar | East Kalimantan Coal |
|-----------------|------|---------|---------|----------------------|
| Proximate       |      |         |         |                      |
| Fixed carbon    | %db  | 16.35   | 26.35   | 61.82                | 65.66                | 52.67                |
| Volatile matter | %db  | 83.16   | 72.86   | 36.33                | 32.37                | 39.14                |
| Ash             | %db  | 0.49    | 0.79    | 1.85                 | 1.97                 | 8.20                 |
| Ultimate        |      |         |         |                      |
| Ash             | %db  | 0.49    | 0.79    | 1.85                 | 1.97                 |                      |
| Carbon          | %db  | 49.03   | 57.56   | 76.08                | 81.80                |                      |
| Hydrogen        | %db  | 6.03    | 5.69    | 3.15                 | 2.92                 |                      |
| Nitrogen        | %db  | 0.22    | 0.34    | 0.83                 | 0.83                 |                      |
| Sulphur         | %db  | 0.11    | 0.05    | 0.37                 | 0.07                 |                      |
| Oxygen          | %db  | 44.12   | 35.57   | 17.72                | 12.41                |                      |
| Calorific value | MJ/kg| 19.15   | 22.92   | 28.01                | 29.73                | 30.58                |

### Table 2. Lamtoro biochar analysis

| Parameter       | Unit | Lamtoro | Biochar |
|-----------------|------|---------|---------|
| Weight          | %    | 100.00  | 61.77   | 26.45   | 24.89   |
| Calorific value | MJ/kg| 19.146  | 22.916  | 28.008  | 29.727  |
| Energy balance  | MJ   | 1,732   | 1,415   | 740     | 739     |
| Biochar energy content to lamtoro wood | %    | 100     | 81.72   | 42.77   | 42.71   |
4. Conclusions
Pyrolysis temperature greatly affected lamtoro wood biochar characteristics. Biochar produced at 450 °C possessing a 36% volatile matter. Our results suggest that the biochar from lamtoro may represent potential alternative fuels as coal blends for steam power plants. The utilization of volatile from the pyrolysis process needs to be further investigated so the pyrolysis technology can be applied in an integrated manner at the power plant.

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