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Characterization of Biochar from Pyrolysis of Corn Residues in a Semi-continuous Carbonizer

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Thailand is a major agro-industrial country with many economic crops including corn. In northern part of the country, harvesting of corn grain generates massive amounts of agricultural waste, including corn cobs, peels, leaves and stalks. Open burning of biomass is a common practice as a low-cost, low-effort means in disposing of crop residues and controlling weeds in the field. It releases large quantities of particulate and gaseous pollutants to the atmosphere. The practice has significantly negative impact on the environment and human health. These corn residues can be utilized for renewable energy. A promising alternative to burning is carbonization. Carbonization or slow pyrolysis is a thermochemical conversion of solid organic materials at elevated temperature in the absence of air or oxygen. Through thermal decomposition processes, a solid product called biochar as well as gaseous and liquid byproducts are generated. The objectives of this work were to demonstrate a practical production of biochar from corn cobs in a modern semi-continuous carbonizer, and to evaluate its performance in terms of reaction temperatures attained, overall processing time, biochar yields and properties. Experiments were carried out in a retort typed, cylindrical drum mounted horizontally. Its dimension was 1.5 m long with inside diameter of 1.05 m. The carbonizer was externally heated by combustion of solid biomass and pyrolysis gas in a grated furnace. It was also equipped with slowly rotating paddle. For each test, about 90-120 kg of corn cobs was fed into the reactor. Temperatures at various locations inside the carbonization chamber were recorded and used as representative for pyrolysis temperature. The end of operation for a certain condition was determined by checking that combustible gas was no longer released and the pyrolysis flame was no longer sustained. The reactor was then unloaded and the resulting biochar was left to cool down to room temperature in a closed container. Subsequently, the solid char products were collected, weighed and sent for analysis. Large amount of corn cobs was successfully converted to good quality biochar in a semi-continuous carbonization reactor system. The system was shown to operate well. Biochar yields of 23 – 33 % were obtained, with the heating value as high as 24 MJ/kg. The process took around 2.5 h at maximum loading. The study showed that valuable solid products can be obtained from corn cobs via slow pyrolysis process.

1. Introduction

Biomass is an important source of renewable energy in Thailand, providing basic energy requirement for cooking and process heating in residential and industrial sectors. Major biomass resources are from different agro-residues from processing of major economic crops such as paddy rice, sugar cane, cassava and corn. According to the recent statistics, Thailand produced around five million tons of corn a year (Office of Agricultural Economics, 2018), generating around 10 million tons of corn residues. About 20 % of these residues are corn cobs and the rest are stalks, peels, and trash (Kerdsuwan and Laohalidanond, 2015), shown in Figure 1.

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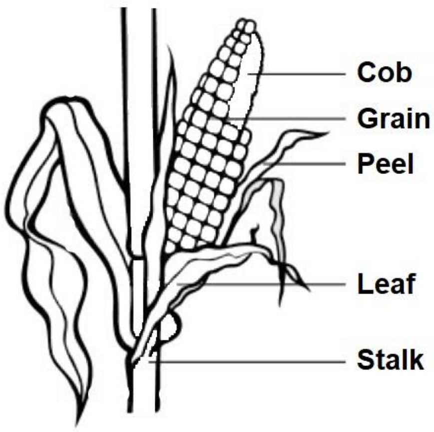

Figure 1: Grains and biomass residues from a corn plant

Corn plantation occupies a major portion of upland and highland farms of the northern part of the country. Harvesting is usually done in the fields where residues are left as wastes. Open burning is a common practice on Thai farms, thought to be essential to clear the lands, facilitate next planting, and control weeds and pests. This results in loss in organic matter, soil fertility, and soil ability to store nutrients. Furthermore, the practice has negative public health and climate impacts. It pollutes the air by releasing huge amounts of particulate matter as well as toxic gases locally and regionally (Kanabkaew and Oanh, 2011). During the dry season, all northern provinces of Thailand suffers from massive clouds of fine dusts and polluted air, resulting from open burning. Continual economic growth and industrialization are expected to generate stronger demand for corn production. Sustainable management in corn production and utilization of residues must be promoted.

Alternatives to open burning exist. One of the promising techniques is to utilize these agro-residues for energy. There are many routes to convert corn residues for energy, possibly via densification (Wongsiriamnuay and Tippayawong, 2015), densification with binder (Piboon et al., 2017), torrefaction (Kuzmina et al., 2016), gasification (Punnarapong et al., 2017), fast pyrolysis (Jaroenkhasemmeesuk and Tippayawong, 2015), combustion (Patronelli et al., 2017) and oxy-combustion (Sittisun et al., 2015). Production of solid fuel in form of biochar via slow pyrolysis or carbonization is simple, yet effective. Carbonization is among the most established method of material conversion. When biomass is heated, thermal decomposition occurs. Volatile matter is released and the solid biomass is transformed into biochar (Babu, 2008). These volatile organic gases can be burned to supply the process heat. Traditionally for local entrepreneurs, char is produced with earth pit, or simple earthen kilns. The current practice of charcoal production especially by small operators is simple but unpleasant. Major drawbacks are long process time, feeble process control, low yield and pollution from direct pyrolysis gas emission to the atmosphere (Tippayawong et al., 2010). Modern designs to improve existing charcoal kilns are available, but mostly for too small capacity in laboratory setup (Lin, 2006) or too big capacity in industrial setup (Adam, 2009). A carbonization system based on a semi-continuous operation with medium capacity suitable for local business operation has been developed by the Energy Research and Development Institute of Chiang Mai University (Tippayawong et al., 2017).

In this work, biochar production from corn cobs in a practical carbonizer was demonstrated. Performance of the carbonization system in terms of temperature evolution, overall process time, yield and properties of biochar was examined.

2. Materials and methods

2.1 Biomass sample

Corn cob samples were collected from an upland farm in Chiang Mai, Thailand. The corn residue samples were air dried naturally in a dry store room at ambient condition where impurities were removed. They were subsequently sorted in similar size range (20-25 mm in diameter, 65-75 mm in length) prior to pyrolysis runs. Some of the dried samples were milled, sieved and collected for property analyses. ASTM standard methods were adopted for proximate and ultimate analyses of the samples. The energetic content of the dried samples was evaluated using a bomb calorimeter. It was reported as a gross calorific value of combustion at constant volume.

2.2 Experimental setup and test procedure

A 150 kg capacity, horizontally mounted, retort typed, cylindrical reactor, shown in Figure 2, was employed in this study. The reactor system was developed by the Energy Research and Development Institute, Chiang Mai University. The design was based on a fixed bed pyrolyzer with external heating. An axial puddle typed agitator was installed inside the cylindrical drum to stir the raw feed. The reactor was heated from outer peripheral by hot flue gas from biomass combustion, since it was encircled by a secondary chamber directly above a grated furnace. They were all packed in a box configuration, occupying a 2.5 x 2.5 m^2 floor area. During operation, two separate gas streams existed. After transferring heat to the carbonizer, flue gas from combustion was directed out to stack, while pyrogas was piped to a tar condensing unit whose non-condensable component was input back to the furnace. A bypass piping was also available for the excess pyrogas to be delivered to a flare.

The carbonization system demonstrated in this work has several designs and differences, compared to traditional charcoal kilns and other modern carbonizers. These include (i) a semi-continuous operation with medium capacity of up to 150 kg loading per batch, (ii) management of pyrogas for possibility of generating wood vinegar, and for utilization of pyrogas as fuel, (iii) a horizontal installation with agitator used for stirring the feed during operation, as well as for fast unloading of biochar after operation, and (iv) external heating from combustion of biomass.

For each test, a known weight of corn residue was fed to the grated furnace to start and fuel a flame. Combustion of the residue was deployed as a simple means to provide heating to the pyrolysis reactor. As for carbonization, up to 120 kg of corn cobs was loaded into the reactor. Temperatures at various points were measured using thermocouples and automatically recorded by a data logger. Average temperature readings inside the carbonization reactor were used to indicate as reaction temperature. For each test condition, a stage when combustible gas was no longer released was used to signify the end of carbonization process. This was indicated by checking if a flame from burning the pyrogas was no longer endured. The reactor was then unloaded and the resulting biochar was allowed to cool down to room temperature. The solid biochar was collected and its remaining mass was determined and sent for analysis. In this demonstration experiment, several tests run for biomass loading of 90, 100 and 120 kg were undertaken, at fixed heat treatment temperatures, and agitation rate.

The International Biochar Initiative (IBI) made publicly available their standardized product definitions and product testing guidelines (Version 2.1) which set standards for physical and chemical characteristics for biochar (IBI, 2015). Analyses of biochar conducted in this work followed from the IBI guidelines, which includes the determination of moisture, total ash, carbon, hydrogen, nitrogen, sulfur content and volatile matter. Additional analyses were also carried out for fixed carbon, gross calorific value and bulk density.

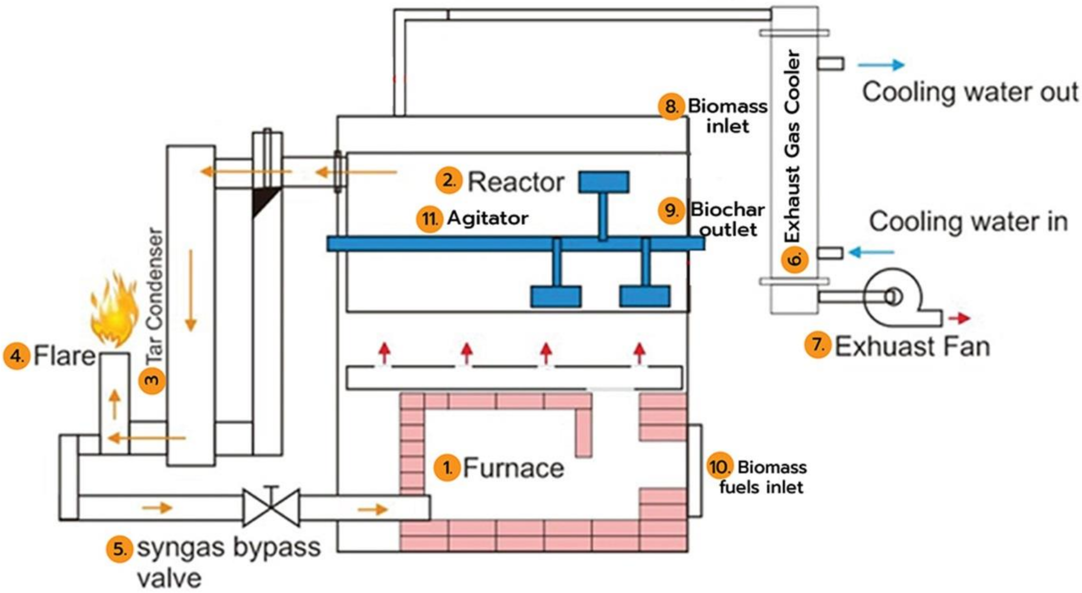

Figure 2: Experimental setup of the semi-continuous carbonization system

3. Results and discussion

Several test runs of the carbonizer with 90 to 120 kg loading of corn cobs were carried out. Temperature evolutions in various locations were monitored. Input corn cobs and biochar products were collected and analyzed. Figure 3 shows typical profiles of temperatures inside and around the carbonization chamber, for (a) 90 kg (b) 100 kg and (c) 120 kg loading, respectively, from the start of combustion in the biomass furnace. The internal temperature was used to indirectly represent pyrolysis temperature, while the external temperature was from flue gas temperature. Thermal energy from this flue gas was utilized to provide heating to the carbonization reactor. When the reactor was started cold, the internal temperature raised slowly from room temperature to about 200 °C in about 45 min. For subsequent test runs with hot start, the internal temperature reached 200 °C in shorter time. Once a stable flame from pyrogas was established, heat transfer from the surrounding flue gas greatly increased the internal temperature in the carbonizer to about 400 °C where majority of the biomass residues was thermally degraded. The end of carbonization process was determined at the point where no combustible pyrogas release was observed. This occurred within about 3 h at 120 kg loading. At lighter loading, the process time taken was generally less.

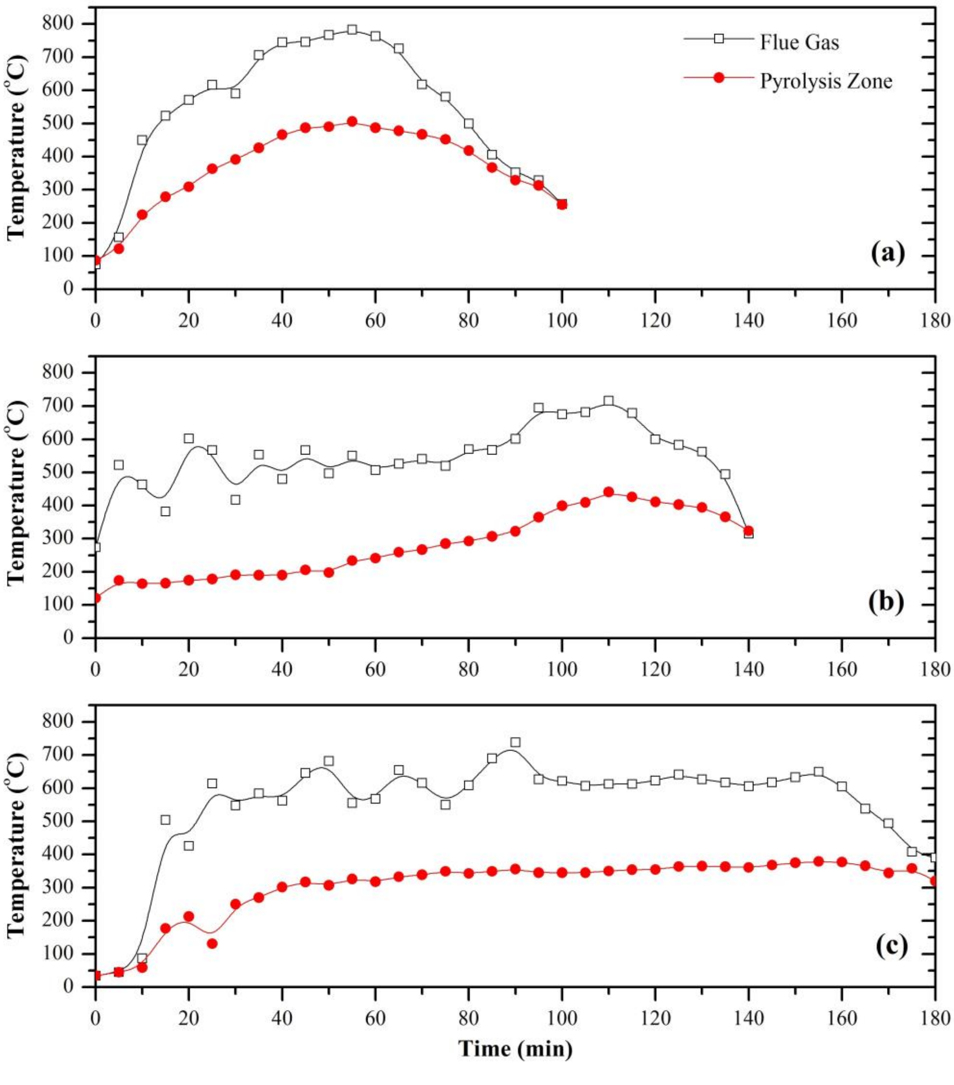

Figure 3: *Temperature evolution in and around the carbonization system during operation*

Yields of biochar product obtained were determined to be between 23 – 33 % w/w. Figure 4 shows pictures of typical biochar obtained from this work, against biomass feed or input. From visual observation, it can be seen that conversion of corn residues into biochar was realized. The biochar products were reduced in size, compared to raw biomass. For close inspection, it was revealed that no significant partially charred fraction was found.

Figure 4: Pictures of corn cobs and their typical biochar

Table 1 shows properties of the obtained biochar, against original corn residue used. Comparison was also made against typical Thai lignite and biochar reference properties as recommended by European Biochar Foundation (EBF). Since it is very difficult and costly to acquire a detailed physico-chemical characterization of biochar, in this work, only relevant properties (carbon content, C/H and O/H molar ratios) from the EBF recommendations were used. Improvement in carbon content and energetic value for the biochar was obvious, from the original corn cob. The biochar's carbon content was higher than 50 % w/w and the O/C molar ratio was less than 0.4, as recommended by the EBF. However, the H/C molar ratio was slightly higher than recommended value. The bulk density was decreased. Comparing against the Thai lignite, the biochar appeared to have higher carbon content, higher calorific value, lower moisture and ash content. The properties of the char product seemed to be slightly superior to the typical low rank coal found locally in Thailand.

Table 2 summarizes performance of the present carbonizer, and compares with the traditional system, and other modern reactors for different biomass materials. It can be seen that the present carbonization system produced similar biochar yield at a fast rate. It should also be noted that studies on corn cob derived biochar in medium to large capacity remain quite rare. Hence, comparison between corn cob biochar generated from different carbonizers of similar scale to this study was rather been difficult to make. Nonetheless, it was shown that the demonstrated system was able to offer improved environmental acceptability, relative to the traditional charcoal making system.

Table 1: Properties of corn cobs and their biochar

	Corn cobs	Corn biochar	Biochar ref.	Thai lignite
Proximate analysis (% w/w, as received basis)				
Moisture	9.6	4.1	-	10.1
Volatile matter	71.6	19.1	-	42.2
Fixed carbon	17.2	72.6	-	40.8
Ash	1.6	4.2	-	6.9
Ultimate analysis (% w/w, dry basis)				
Carbon	44.4	63.9	> 50	55.3
Hydrogen	6.5	4.0	-	5.9
Oxygen	48.8	30.6	-	36.6
Nitrogen	0.3	0.6	-	0.6
Sulphur	0.0	0.0	-	1.6
H/C molar ratio	1.76	0.75	< 0.7	1.28
O/C molar ratio	0.82	0.37	< 0.4	0.50
Gross calorific value (MJ/kg)	16.8	24.1	-	22.6
Bulk density (kg/m^3)	160	135	-	800

Table 2: Comparison against other slow pyrolysis systems

	Traditional kilns	Syred et al., 2006	Tippayawong et al., 2017	This work
Biomass type	logwood	logwood	cassava rhizome	corn cobs
Process time (h)	72-84	3-4	1.5-4	2-3
Char yield (%)	23-27	28-33	33-35	23-33
Partially charred fraction (%)	10-20	4-7	-	-
Pyrolysis gas utilization	Emitted directly to atmosphere	Burned internally to heat the system	Burned internally to heat the system	Burned internally to heat the system
Visible smoke during operation	high	low	low	Low

4. Conclusions

Corn cobs were successfully converted to biochar in an externally heated, retort typed, semi-continuous carbonizer. Biochar yields of 23 – 33 % were obtained. The biochar quality was similar to those produced from traditional charcoal kilns and other carbonizers. The conversion process took no more than 3 h at 120 kg loading, compared to 3 – 3.5 days for traditional charcoal kilns. The carbonization system was found to operate well. Further considerations with respect to technical and economic performance in field tests will be needed.

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