Technical Paper

Development of a Thermochemical Conversion Unit for Corn Residues

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(Received March 24, 2020)

The utilization of corn residues as a potential biomass for thermochemical conversion was investigated. The general objective of the study was to design and develop a thermochemical conversion unit and evaluate its performance in terms of the production of bio-oil, bio-char and syngas. The developed thermochemical conversion unit comprises a hopper, modified worm drive, reactor, cyclones separator, and syngas condenser. Three kilograms of size-reduced corn cobs were loaded to the reactor, then subjected to thermochemical conversion varying the operating temperature (with and without heater) and three airflow rates. Results showed that the highest percentages of biochar, bio-oil and syngas collected using the developed machine were 24%, 37% and 59%. Bio-char contained 34% of volatile combustible matter, 60% of fixed carbon and a heating value of 26.3 MJ/kg. The thermochemical conversion unit has a waste to energy conversion efficiency that could reach as high as 91%. To achieve the highest percent recoveries of bio-oil and syngas, the machine should be operated at an airflow of 84 L/s. On the other hand, to obtain the highest recovery of bio-char, the unit should be operated at lower airflow. The conduct of up-scaling of the developed thermochemical conversion unit, testing and evaluation under field condition, and perform financial analysis are recommended.

Key Words

Agricultural wastes, Thermochemical, Gasification, Corn cob, Corn by-products

1. Introduction

Crop residues are a valuable resource both in the field and as a potential biofuel. Crop residues are critical in protecting and maintaining our nation's valuable natural resource (soil and clean water). A wide range of agricultural residues (e.g., corn stover, straw, etc.) can produce second-generation biofuels. Such biofuels are generally considered sustainable as they use waste materials from food crop production and do not compete with food crops for land. Among the renewable energy sources, only biomass offers the possibility to produce liquid, carbon-neutral fuels¹⁾. Some advantages of the biomass are a low-cost by-product in agriculture and forestry, low ash and sulfur contents, and no CO₂ level increase in the atmosphere, since the biomass

consumed does not exceed the forest production²⁾.

During the torrefaction process, solid biomass is heated in the absence of or drastically reduced oxygen to a temperature of approx. 250-350 °C, leading to a loss of moisture and partial loss of the biomass's volatile matter³⁾. Pyrolysis and gasification are typically multi-step processes with many similar steps, including (1) feedstock preparation, (2) introduction of the feedstock into the reactor, (3) the pyrolytic decomposition or gasification reaction, and (4) separation and post-processing of the gases, oils (in the case of pyrolysis), solid char, and ash⁴⁾.

Many studies^{5) ~ 10)} have examined the economics of corn stover supply for biofuel production. While these studies have focused on estimating the costs of harvesting corn stover as a whole, only a few studies have particularly emphasized examining the costs of supplying corn cobs as a potential feedstock using up-to-date harvesting technologies. Corn stover was identified by Environmental Protection Agency and United States Department of Agriculture as the third feedstock in importance to meet the annual mandate. Corn stover is expected to provide about 25% of

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the total advanced biofuels supply. Due to high density and yields, the bulk of corn residue is expected to come from the Corn Belt ¹¹⁾.

As a result of considerable research, development, and pilot-scale demonstration work done during the past 25 years ¹²⁾, large-scale biomass gasifier technologies could be commercially ready within two or three years with concerted development efforts, but commercial-scale projects are needed to demonstrate viability. There is already the extensive worldwide commercial application of gasification of fossil fuels such as coal ¹³⁾. The experience being accumulated from these activities is relevant to the gasification-based conversion of biomass. Biomass can be co-gasified with coal, which may offer some valuable synergies ¹⁴⁾. Biomass is already being commercially co-gasified with coal today at one electricity-generating facility in the Netherlands, the 250 MWe Buggenum facilities ¹⁵⁾.

Torrefaction, gasification and pyrolysis have become the emerging technologies for converting biomass into energy from a different form of biofuels. Biofuels from these processes include combustible gases, bio-oil and bio-char. Bio-oil can be processed further into different hydrocarbon fuel by fractional distillation while bio-char is used for soil amendments and activated carbons. Bio-oil contains several functional groups including alcohols, aldehydes, carboxylic acids, esters, ethers, furans, ketones, phenols and sugars ¹⁶⁾. Combustible gases, commonly called syngas, can be used directly for engine fuels to produce electricity or be now utilized for the cookstove.

This study envisioned to develop these three thermochemical processes using corn residues and vary the operating conditions to allow the production of any desired primary output (i.e., syngas, bio-oil, or bio-char). It would be beneficial to develop a versatile system that can operate on pyrolysis mode, gasification or torrefaction. This is because farm operations throughout the year are variable. The need to produce carbon from biochar may be a priority for soil conditioning purposes while utilizing bio-oil and syngas for energy while, at some point, the farmer may need to produce bio-oil more than biochar and syngas. Since the three energy conversion products are dependent on operating conditions, one thermochemical conversion system that could accommodate such variations is economically significant.

This study focuses on corn residues since corn is the primary agricultural crop in the Northern Mindanao region with more than 50,000 ha of the plantation. Corn residues that include corn cobs and corn stalk constitute 50% (by weight) of the total agricultural wastes collectibles in Region 10 ¹⁷⁾. With this study, it is expected that energy

generation will be augmented using biomass-based power. Small to medium-scale farmers could utilize such technology to mechanize farming activities while producing soil conditioner from bio-char. The mechanization level could be increased due to the additional energy from corn residue. Once implemented, the conversion system could be retrofitted to accommodate any agricultural waste. The general objective of the study was to design, fabricate and evaluate the performance of a thermochemical energy conversion system for corn residues.

2. Materials and Methods

2.1 Design consideration and preparation

The thermochemical conversion unit design was based on the existing gasifier owned by the Department of Energy in the Philippines and the bench-scale fluidized pyrolyzer developed within the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA). AutoCAD software was used to prepare the design, measurement of dimensions that served as a guide in the fabrication of the thermochemical conversion unit.

2.2 Fabrication of thermochemical conversion unit

The thermochemical conversion unit comprises the following components: motor, gearbox, hopper, conveyor, reactor, two cyclone separators and the syngas condenser (with four condenser canisters in series). The system components were fabricated using locally available materials in Cagayan De Oro City. It comprises the reactor vessel system and associated supplementary systems for air distribution, biomass feeding and entry, and vapor condensation for bio-oil recovery. Such design features are described in Table 1.

2.3 Collection and preparation of samples

Corn cobs (CC) samples used in the study were collected from Baungon, Bukidnon. Corn cobs were immediately placed in sacks after the shelling process, tied and stored inside the building while waiting for the succeeding processing operation. Since the corncobs were already air-dried in the field at a moisture content of 15%, it was placed in a container for weighing prior to loading into the hopper.

2.4 Description of thermochemical conversion unit

The fabricated thermochemical conversion unit is consisted of the reactor vessel system and associated supplementary systems for air distribution, biomass feeding and injection, and vapor condensation for bio-oil recovery

Table 1 Design features of the thermochemical conversion system

Major part	Description
Electric motor	The electric motor served as the driver/prime mover of the thermochemical conversion unit's hopper-conveyor system.
Gearbox	The gearbox facilitated the reduction of the prime mover's speed and, at the same time, increases the torque.
Biomass feeding and entry system	The hopper served as the container of the feedstock to be used during the thermochemical conversion. The conveyor fed the feedstock to the reactor. The conveyor also facilitated the reduction of the size of the feedstock.
Reactor vessel system	The reactor served as the house the feedstock and facilitated the process of thermochemical conversion. Along with an air distribution system when needed, the feedstock was ignited in the reactor using a nichrome heater, deprived with oxygen and undergo gasification or pyrolysis, depending on the heat source.
Cyclone separator	The cyclone separators removed the particulates produced during the gasification or pyrolysis through vortex separation. There are two cyclone separators: the 1D-2D cyclone or low-efficiency cyclone separator (LECS) and the 1D-3D cyclone or high-efficiency cyclone separator (HECS) adopted from Parnel (1996) ¹⁸⁾ .
Syngas condenser	The syngas condenser is comprised of a water tank and four condenser canisters. The water tank contained water or ice to provide the temperature gradient for bio-oil recovery through better condensation. The four condenser canisters are cylindrical on the upper part and conical at the bottom to induce the flow of bio-oil down to its catchment by gravity.

as shown in Fig. 1. The unit included the following major components: electric motor, gearbox, hopper and conveyor, reactor, cyclone separator and syngas condenser.

This newly developed energy conversion system could operate continuously with an initial 8 kg of full-size corncobs and a reactor capacity of 3 kg corncob particles with an average size range of 14 mm to 30 mm. The uniqueness of having a higher capacity conversion system is tantamount to a pilot-scale set up ready for field operation in most farm settings. This development of having such a thermochemical conversion unit makes it more attractive for the farm-level operation to utilize bio-oil, biochar and syngas

for fuel. Other uses of bio-oil and biochar are common in farming communities such as bio-oil for flavoring of smoked fish and meat, bio-char for soil conditioner, water filter, and fuel briquettes.

2.5 Testing and evaluation

Prior to laboratory testing and evaluation, the preliminary test run was conducted to determine each component's functionality. The machine's hopper was filled with 8 kg of CC to help maintain pressure in the reactor, while the reactor was filled with 3 kg of size reduced CC. The experiment utilized three airflow rates and two heating temperatures, as shown in Table 2.

During laboratory testing, the reactor was covered, locked and sealed properly. Ignition of the biomass feedstock was done by turning on the 1 kW nichrome coil heater for 5 min and setting the airflow rate of the variable speed drive blower at 10 Hz for 30 min. Each experimental run requires 90 min to complete. Once the reactor cooled down, the yields of unburnt cobs, bio-char and bio-oil were then obtained (Fig. 1). Unburnt cobs and bio-char were manually separated carefully, weighed and photographed. The bio-oil yield was obtained by getting the differential of the known weight of the bio-oil catchments to the weight of the bio-oil catchments after each run. The syngas yield was obtained by getting the difference of the starting biomass feedstock (3 kg) and the sum of the obtained unburnt corn cobs, bio-char and bio-oil yields.

Fig. 1 Schematic diagram for the newly developed thermochemical conversion unit

Table 2 Operating conditions in the conducted testing and evaluation

Variables	Corresponding Code		
Heating device usage	H _w	H _o	
Equivalent	(with heating device)	(without heating device)	
Airflow rate	A ₁	A ₂	A ₃
Equivalent	38.8 L/s	61.3 L/s	83.8 L/s

2.6 Chemical composition and physicochemical properties

Representative samples were collected for proximate chemical analysis. These sample's proximate chemical analysis was analyzed at STEAG, Inc. (PHIVIDEC Industrial Estate, Villanueva, Misamis Oriental) and Department of Science and Technology – Industrial Technology Development Institute – Standards and Testing Division (DOST-ITDI-STD), DOST Compound, Gen. Santos Ave., Bicutan, Taguig City, Philippines.

2.7 Calorific value

The analyses for the heating value of bio-char were carried out following ASTM D-3286. The calorific value of the bio-char was determined using a LECO AC-350 bomb calorimeter. The test was done at the Forest Products Research and Development Institute (FPRDI) of the Department of Science and Technology.

2.8 Experimental design

The data gathered was analyzed using two factorial in a complete randomized design. Analysis of Variance (ANOVA) table and the Duncan Multiple Range Test (DMRT) were used to determine the level of significance and comparison among means. Three trials were conducted in each test run.

3. Results and Discussion

3.1 Comminution and feeding rate

The size reduction of the corn cobs sample was made to make it suitable for thermochemical conversion as it will improve the reaction and increase heat transfer. Table 3 affirms the installed worm gear screw conveyor's capability to reduce raw corn cobs' size, especially its length and thickness. The worm drive screw conveyor reduced the corn cobs' length and thickness by 75.54% and 51.03%, respectively. The size reduction was brought about by the blades' shearing ability and the small clearance in the pipe between the hopper and the reactor (approx. 1.40 cm). The installed worm gear screw conveyor worked like a multiple-fracturing size-reduction implement with the small clearance in the pipe between the hopper and the reactor serving as a screen or diaphragm (Fig. 2). The corn cob feeding rate is approximately 11 kg/h.

Table 3 Average dimensions of corn cobs using modified worm gear screw conveyor

Corn Cobs	Length (mm)	Thickness (mm)
Raw Dimension (inside the Hopper)	129	27
Final Dimension (inside the Reactor)	30	14
Size Reduction Difference (%)	75	51

Fig. 2 Size reduction auger

3.1.1 Unburnt corn cobs

Table 4 shows the percent recovery of unburnt corn cob from the thermochemical conversion unit. The average percent recovery of unburnt corn cobs at 38 L/s, 61 L/s and 84 L/s was 12.50%, 7.67% and 4.50%, respectively. However, the average recovery of both with and without a heater was 8.22%. This can be associated with an increase in oxygen content. Consequently, this increases the temperature due to increased activity in the oxidation zone¹⁹.

3.1.2 Bio-oil collected from syngas condenser canisters

Bio-oil is usually dark brown and free-flowing liquids having a distinctively smoky odor. It is composed of very complex mixtures of oxygenated hydrocarbons with a substantial amount of water from both the original moisture and reaction²⁰. Table 5 shows the percent bio-oil yield obtained from the syngas condenser canisters after the thermochemical conversion process. The highest obtained bio-oil was 18% at 84 L/s airflow and without heater settings. As the airflow increased, the bio-oil recovery from the syngas condenser canisters also increased. The increase in airflow promotes shorter residence time of the hot vapor, which leads to high liquid production²¹. Moreover, the gradual increase of the bio-oil yield can be associated with

Table 4 Recovery of unburnt CC from thermochemical conversion unit, %

Heating Element	Airflow			Average
	38 L/s	61 L/s	84 L/s	
With Heater	12.00±0.30	7.33±0.02	5.33±0.33	8.22
Without Heater	13.00±1.42	8.00±0.12	3.67±1.07	8.22
Average	12.50 ^a	7.67 ^b	4.50 ^c	

Average or means with the same superscript letters within a column indicate no significant difference ($p < 0.05$)

Table 5 Bio-oil collected from syngas condenser canister using thermochemical conversion unit, %

Heating Element	Airflow			Average
	38 L/s	61 L/s	84 L/s	
With Heater	11.67±2.92	15.00±0.18	16.33±0.52	14.33
Without Heater	13.00±0.58	15.33±1.82	18.00±0.48	15.44
Average	12.33 ^a	15.17 ^{ab}	17.17 ^b	

Average or means with the same superscript letters within a column indicate no significant difference ($p < 0.05$)

increased reactions during the thermochemical conversion due to the increase in temperature that is more volatiles are produced²²⁾.

3.1.3 Bio-oil collected from cyclone separator

Table 6 shows the average bio-oil yield obtained from the cyclone separator canisters. The highest obtained bio-oil was 18.67% at 38 L/s airflow and with heater settings. The airflow increases as the amount of bio-oil recovered from the cyclone separators decreases. In the cyclone separator, more bio-oil was produced when using a heater.

3.1.4 Bio-char

Bio-char is the solid material obtained from the thermochemical conversion of biomass. It is a fine-grained, highly porous charcoal substance that has been produced by heating organic material under minimal to no oxygen to achieve high surface area per unit volume, thus increasing porosity, high adsorption and minimal residual resin²³⁾. Table 7 shows the inverse relationship between the airflow and the amount of bio-char recovery. The highest obtained bio-

char was 24% at 38 L/s airflow and without heater settings. The average percent of bio-char recovery of airflows 38 L/s, 61 L/s and 84 L/s across the heating element are 19%, 12% and 6%, respectively. Thus, increasing the airflow decreases bio-char recovery. On the other hand, the percent recoveries across different airflows are 9% and 16% with heater and without the heater. The increase in airflow rate brought about a decrease in bio-char recovery by increase in the system's oxygen content. The increased reaction occurs which consequently, increases the yield of volatiles and decrease in bio-char^{24)~26)}. Operating without a heater therefore produces higher bio-char than using it.

3.2 Syngas

The gaseous fraction among the products of thermochemical conversion is, in general, referred to as synthesis gas (abbreviated as syngas). It is composed of various gases such as CO₂, CO, NO_x, SO_x, H₂S, H₂, aldehydes, ketones, volatile carboxylic acids, and gaseous

Table 6 Bio-oil collected from cyclone separator using thermochemical conversion unit, %

Heating Element	Airflow			Average
	38 L/s	61 L/s	84 L/s	
With Heater	18.67±1.73	18.00±1.27	15.33±0.77	17.33 ^a
Without Heater	16.33±2.17	12.33±0.08	12.00±0.82	13.56 ^b
Average	17.50	10.17	13.67	

Average or means with the same superscript letters within a column indicate no significant difference ($p < 0.05$)

Table 7 Bio-char produced of thermochemical conversion unit, %

Heating Element	Airflow			Average
	38 L/s	61 L/s	84 L/s	
With Heater	14.33±2.87	6.33±0.15	5.33±1.38	8.67 ^a
Without Heater	23.67±2.77	17.67±0.22	6.33±1.88	15.80 ^b
Average	19.00 ^a	12.00 ^b	5.83 ^c	

Average or means with the same superscript letters within a column indicate no significant difference ($p < 0.05$)

hydrocarbons²⁷⁾. Table 8 shows that the highest obtained syngas was 59% at 84 L/s airflow and without heater settings. As the airflow increased, the syngas yield increased. The syngas yield values were computed to be the difference of the biomass feedstock fed to the system and the sum of the obtained bio-oil, unburnt cobs, and bio-char.

3.3 Characteristics of bio-char

Tables 9 and 10 show the proximate and ultimate analysis of bio-char yields from thermochemical conversion runs under different operating parameters. The proximate and ultimate analysis was undertaken to assess the bio-char's suitable application as a potential fuel source. In terms of fixed carbon, operating with a heater produces a slightly higher composition than without a heater. Ash percentage also increased when the heater was used in operation hence promoting possible combustion inside the reactor.

Bio-char samples subjected to proximate analysis were mixtures of the bio-char produced from each replicate for each treatment. The sample was approximately bone-dry due to the temperature inside the reactor reaching 500 °C. On the other hand, the ultimate analysis shown in Table 10 portrays the increase in bio-char's carbon element compared to the raw corn cobs. Such an increase in carbon

leads to an increase in heating value which is a very important fuel consideration.

3.4 Mass and energy balance

The energy generated by corn cob wastes was characterized in different phases such as bio-char, bio-oil and syngas. Syngas energy in most biomass materials is primarily a combination of combustible gasses like methane, carbon monoxide and hydrogen gas. In the study of Capareda *et al.*²⁸⁾, average syngas produced has 20% H₂, 10% CH₄ and 15% CO by volume at Standard Temperature and Pressure (STP). Such gasses H₂, CH₄ and CO have heating values of 142 MJ/kg, 55.5 MJ/kg and 10.1 MJ/kg, respectively. However, Zainal *et al.*²⁹⁾ found a heating value of 4-6 MJ/Nm³. Using the heating values of corn cob by-products in Table 11, the mass and energy balance can be depicted below in Fig. 3. Losses from unburned corncobs and ashes could be avoided if the system is fully insulated to maintain a uniform temperature inside the reactor.

With the newly developed energy conversion system, the energy stored in the corn cob could not balance the energy output. However, ashes and unburned corncobs could be utilized in different beneficial ways. Thus, the system's efficiency is computed below, which shows a 91% waste to energy conversion.

Table 8 Syngas produced of thermochemical conversion 5unit, %

Heating Element	Airflow			Average
	38 L/s	61 L/s	84 L/s	
With Heater	43.30±7.67	52.50±0.80	56.80±0.80	50.87a
Without Heater	34.00±1.43	45.50±1.63	59.00±0.48	46.16b
Average	38.65 ^a	49.00 ^b	57.90 ^c	

Average or means with the same superscript letters within a column indicate no significant difference ($p < 0.05$)

Table 9 Proximate analysis of bio-char from the thermochemical conversion unit

Parameters		Volatile combustible matter, %	Ash, %	Fixed carbon, %
Without Heater	A1-38.8 L/s	40.17	4.46	55.37
	A2-61.3 L/s	26.89	5.94	67.17
	A3-83.8 L/s	33.56	6.23	60.21
With Heater	A1-38.8 L/s	27.06	10.41	62.53
	A2-61.3 L/s	25.98	6.51	67.51
	A3-83.8 L/s	35.20	6.53	58.97

Table 10 Comparison of the elemental properties of corn cobs and bio-char (% wt.)

Elemental Component	Corn Cobs	Bio-char
C	41.15	57.56
H	4.93	2.33
O	37.40	7.18
N	0.18	0.86
S	0.04	0.31

Table 11 Comparison of heating values of corn cob and its by-products

Sample	Heating value (MJ/kg)
Bio-char	26.3
Corn Cobs (air-dried)	17.5
Bio-Oil	26.3
Syngas	10.9

Fig. 3 Energy and mass balance for the newly developed thermochemical conversion unit

Conversion Efficiency = Energy Output / Energy Input

$$\begin{aligned}
 &= \{1.7 \text{ kg (10.0 MJ/kg)} + 0.92 \text{ kg (26.3 MJ/kg)} \\
 &+ 0.19 \text{ kg (26.3 MJ/kg)}\} / \{3 \text{ kg (17.5 MJ/kg)}\} \\
 &= (47.9 \text{ MJ}) / (52.6 \text{ MJ}) \\
 &= 91\%
 \end{aligned}$$

4. Conclusions

A thermochemical conversion unit with a condensing unit for corn residues was designed, fabricated and tested. It consisted of a hopper, modified worm drive, reactor, cyclones separator and syngas condenser. The design incorporated a unique feature that automatically breaks the whole corncob into smaller particles with 50 to 75% size reduction while conveying the feedstock. The study is so unique that all corncob sizes from corn shelling operation could be reduced by 75% upon passing through the newly developed worm gear screw conveyor. This mechanism is such of novelty that it combines particle size reduction and conveyance operation. Therefore, such a mechanism eliminates the need for hammer milling or shredding, thus saving time and energy. Moreover, the system could be operated continuously at 3 kg reactor capacity and a standby hopper capacity of 8 kg.

The highest percentages of biochar, bio-oil and syngas collected using the developed machine were 24%, 37% and 59%. Bio-char contains 33% of volatile combustible matter, 60% of fixed carbon and a heating value of 26.3 MJ/kg. To achieve the highest percent recoveries of bio-oil and syngas, the machine should be operated at an airflow of 84 L/s. On the other hand, to obtain the highest recovery of bio-char, the unit should be operated at lower airflow. The machine has a waste to energy conversion efficiency that could reach as high as 91%.

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