The Optimal High Heating Value of the Torrefied Coconut Shells

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Abstract—Coconut is a biomass resource that is abundant in tropical countries. In 2020, the Philippines planted 347 million coconut trees that produced 14.7 million tons of coconuts. The coconut shells (endocarp) are considered a waste material, which comprise 15.18% of each fruit and account for 2.2 million tons. The calorific value of raw coconut shells is 30.79MJ/kg. When torrefied at 275°C for 30 minutes holding time, the calorific value reached the optimal of 34.37MJ/kg, representing an increase of 11.64%. The mass yield (My) was 90.10% and the energy density was 111.64%, resulting in an energy yield of 100.59%.

Keywords—coconut; shells; torrefaction; downdraft; gasifier; gasification; gas synthesis

I. INTRODUCTION

Herbaceous and woody biomasses are used as feedstocks for biomass power plants to produce electricity. Biomass has the potential to replace fossil fuels as a way of fuel-switching to protect the environment [1]. The Philippines, with a total forest land of 15,805,325 hectares [2], is home to various naturally grown trees, such as the Industrial Tree Plantation Species (ITPS) like the paraserianthes falcataria [3], coconut, and agricultural products, like bananas, abaca, corn, rice, sugarcane, pineapple, and many others [4, 5]. In 2020, the Philippines produced 820 thousand cubic meters of logs [2] and 66.30 million tons (MT) of various agricultural products and falcata. Rice contributed by 19.29 MT, corn by 8.12 MT, sugarcane by 24.40 MT, and coconut by 14.49 MT [5].

The coconut tree, which is considered a woody biomass, grows throughout the humid areas of the tropics. Each tree can have an average of 70 nuts and a maximum of 150 nuts every year, and the shell of each fruit accounts for 15.18% of its mass [6]. In 2020, 14.49 MT of coconut fruits were harvested [4, 5] thus producing about 2.20 MT of coconut shells. These coconut shells are also used as activated carbon furniture. They are typically used for cooking briquettes, either as coconut choir with high flexural strength [7] or other biomass feedstock. Coconut trees are widely grown and owned by big companies, individuals, or villagers. There are various methods of changing the thermochemical properties of coconut shells like torrefaction, carbonization, pyrolysis, and combustion [8]. Torrefaction is a burning or combusting process where the raw biomass is heated up at a modest temperature from 200°C to 300°C to dry it or convert it to a coals-like material which eventually improves its properties as a biofuel [9]. Moreover, exposing the materials to a moderately high temperature at an expanded holding time enhances their calorific value [10].

Biomass Gasification Power System (BGPS), is a known and efficient biomass power technology [8]. Biomass gasification is claimed to produce fewer greenhouse gases since it recaptures carbon dioxide and reuses other hazardous gases [8, 11]. The energy conversion efficiency of any biomass power technology depends mainly on the characteristics of the biomass feedstock, especially on its calorific value or High Heating Value (HHV) [8, 12]. HHV can be quantified through proximate analysis where the moisture content (%MC), the volatile matter (%VM), the ash content (ASH), and the fixed carbon (%FC) are measured or with the use of a bomb calorimeter. The calorific value can also be calculated through ultimate analysis using the assessed carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S).

Torrefied Coconut Shells (TCS) are not extensively studied for energy production. In [10], the TCS’s HHV increased from 18.94MJ/kg to 31.23MJ/kg at 250°C, with 30 minutes of holding time, and a size of 15mm×15mm. This indicates that the torrefaction procedure increased the HHV of coconut shells by 64.89%. Also, authors in [13] showed that the HHV of torrefied coconut leaves improved significantly from 17.95MJ/kg (air-dried) to 27.78MJ/kg (torrefied at 295°C), a 54.76% increase. However, despite the demonstrated improved properties of the TCS, the energy density, mass yield, and...
energy yield of the biomass gasification power system utilizing TCS as biomass feedstock is not yet well supported.

To determine if there is an improvement to the calorific value of the coconut shells that are torrefied, the study performed torrefaction to improve the coconut shells’ thermochemical properties. Torrefaction is heating without air using a temperature from 200°C to 300°C, while pyrolysis uses heating temperature above 300°C without the presence of air [8, 14, 15]. The study torrefied the coconut shells using an electric furnace/oven and set the temperatures at 200°C, 225°C, 250°C, 275°C, and 300°C, and holding times of 10, 20, and 30 minutes. Before torrefaction, the coconut shells were ground at an average size of 25mm×25mm.

II. MATERIALS AND METHODS

The study used an experimental research design where the calorific value or HHV of the TCS was determined using proximate and ultimate analyses. The HHV using proximate analysis was compared to the HHV using ultimate analysis. Figure 1 shows the experimental setup of the torrefaction of the coconut shells. A series of experiments and tests was conducted to determine the impact of torrefaction on the coconut shells’ mass yield, energy density, and energy yield when exposed to varying temperatures and residence time. Ensuring the integrity of the experimental results, the samples were sent to the Davao Analytical Laboratory for elemental analysis.

Using a crusher, 15kg of raw coconut shells were ground at approximately 25mm×25mm (see Figure 2). The selected ground coconut shells weighing 1,000 ±0.5%g were placed in a pan for heating at an electric furnace. For each test, the furnace was set to 200°C, 225°C, 250°C, 275°C, and 300°C, for cooking or holding time of 10, 20, and 30 minutes.

After heating, the TCS weighing 500±0.5%g were placed in cellophane and were sealed (Figure 3). For elemental analysis, 16 samples were sent to the Davao Analytical Laboratory, an accredited analytical lab in Davao City, Philippines. The analytical test results for 1 raw and 15 torrefied shells were considered. The resulting %MC, %VM, %FC, %ASH, and S were used in determining the high heating values and applied in assessing H, C, N, and O.

III. RESULT ANALYSIS

A. Proximate Analysis Results

The proximate analysis determines the %MC, %ASH, %VM, and %FC of any biomass feedstock [8]. The Davao Analytical Laboratory uses the ASTM D1762-84 Standard Test Method for Chemical Analysis of biomasses to determine %MC, %ASH, %VM, and %FC [16] and gravimetry to determine the S content of TCS. HHV is the amount of heat released per unit mass of any fuel. To find the calorific value or the HHV, the equation:

\[
HHV = 354.3 \times \%FC + 170.8 \times \%VM
\]

introduced in [17] was used. The result falls not more than 2% relatively to the measured heating values of any biomass feedstock using the bomb calorimeter. Additionally, the calculation can be cross-checked using [18, 19]:

\[
HHV = 0.1846 \times %VM + 0.3525 \times %FC
\]

Table I displays the proximate analyses of the 16 samples, including the HHV. It can be seen that the coconut shells with the lowest HHV are the Raw Coconut Shells (RCS).

![Torrefaction experimental setup.](image1)

![Torrefied coconut shells.](image2)

![Sealed torrefied coconut shells.](image3)

As shown in Figure 4, the optimal HHV is at the temperature of 275°C for holding time of 30min, where the magnitude reached 34.37MJ/kg. At 300°C and holding time of 10min, HHV reduced to 33.08MJ/kg, or by 3.75%. Relatively
to the RCS, the increase was about 11.63%. In [10], the HHV increased by 51.65% when the coconut shells were torrefied at 250°C for a holding time of 15 min. Several studies claim that the torrefaction process improves the HHV of biomass feedstock [20].

The Davao Analytical Laboratory and other Chemical Analytical Laboratories do not offer ultimate analysis services, hence correlation equations were used. To determine the %C, the equation espoused by [24, 25] was used:

$$\%C = 2.1877 \times \text{HHV} + 5.9068$$  \hspace{1cm} (4)

For the determination of the %H, the equation supported by [19] was used:

$$\%H = 0.059 \times \%FC + 0.060 \times \%VM + 0.010 \times \%ASH$$  \hspace{1cm} (5)

The equation introduced in [26] can be used also to determine %H:

$$\%H = \left(3.55 \times (\%C - 232) \times \%C + \text{HHV} + 131 \times \%N + 20600 \right) / (2230 - 51.2 \times \%C) \text{kJ/kg}$$  \hspace{1cm} (6)

Regarding the %N determination, the equation introduced in [27] was used:

$$\%N = 2.6116 \times \text{HHV} - 1.1092 \times \%C + 6.3884 \times \%S$$  \hspace{1cm} (7)

Though these equations may introduce a minute deviation to the measured values, they are widely used in biomass elemental analyses [19, 20].

Table II lists the ultimate analysis and the HHVs for the RCS and TCS. Temperature and residence time affect the calorific value of the biomass [28]. At 275°C and holding time of 30 min, the HHV of the TCS increased to 34.37MJ/kg. Moreover, syngas is highly dependent on H\(_2\) and CO content [28].

### Table II. Coconut Shells Ultimate Analysis

| Type, Temp (°C), Time (min) | C (%) | H (%) | N (%) | S (%) | O (%) | HHV\(_{\text{ULT}}\) (MJ/kg) | HHV\(_{\text{PROX}}\) (MJ/kg) |
|-----------------------------|-------|-------|-------|-------|-------|-----------------------------|-----------------------------|
| RCS 0, 0                    | 73.3  | 5.2   | 0.8   | 0.3   | 19.7  | 30.18                       | 30.79                       |
| TCS 200, 10                 | 76.4  | 5.6   | 0.9   | 0.2   | 16.4  | 31.90                       | 31.79                       |
| TCS 225, 10                 | 75.5  | 5.5   | 0.9   | 0.2   | 16.4  | 31.90                       | 31.79                       |
| TCS 250, 10                 | 74.4  | 5.4   | 0.7   | 0.2   | 18.3  | 30.95                       | 31.32                       |
| TCS 275, 10                 | 76.8  | 5.6   | 0.9   | 0.2   | 16.0  | 32.61                       | 32.41                       |
| TCS 300, 10                 | 75.3  | 5.6   | 0.8   | 0.2   | 18.3  | 31.89                       | 31.70                       |
| TCS 250, 20                 | 77.6  | 5.6   | 1.0   | 0.2   | 13.8  | 32.51                       | 32.78                       |
| TCS 275, 20                 | 81.1  | 5.8   | 1.3   | 0.2   | 9.8   | 35.00                       | 34.37                       |
| TCS 300, 10                 | 78.3  | 5.6   | 1.0   | 0.2   | 13.1  | 32.85                       | 33.08                       |
| TCS 300, 20                 | 76.1  | 5.6   | 0.9   | 0.2   | 15.4  | 31.98                       | 32.08                       |
| TCS 300, 30                 | 76.2  | 5.8   | 0.9   | 0.2   | 15.1  | 32.48                       | 32.15                       |

Milne’s [27] equation was used for ultimate analysis, while the Cordero’s [17] for proximate analysis. Figure 6 shows the graphs and the variation of the HHV using the Milne's equation:

$$\text{HHV} = 0.341 \times \%C + 1.322 \times \%H + 0.0686 \times \%S - 0.12 \times \%O + \%N - 0.0153 \times \%ASH$$  \hspace{1cm} (8)
and provides identical value with:

\[ \text{HHV} = 354.3 \times \% \text{FC} + 170.8 \times \% \text{VM} \]  \hspace{1cm} (9)

introduced in [17]. Note that the optimal HHV for the two equations is at 275°C and 30min. The mean difference on the HHV using the two equations is only ±0.52% or the Mean Absolute Error (MAE) was 0.3388.

**C. Mass Yields, Energy Densities, and Energy Yields**

With the HHV known, Mass yield (M\text{Y}), Energy Density (ED), and Energy yield (E\text{Y}, %) can be determined. M\text{Y} gauges the amount of the torrefaction process. It provides the portion of the mass retained in the biomass after torrefaction [21]. It is the mass produced as a result of the processing of the biomass and is expressed as the ratio between the mass of the torrefied biomass (M\text{TCS}) to the mass of the raw biomass (M\text{raw}) or \((M_{\text{TCS}}/M_{\text{raw}}) \times 100\%\). ED is the amount or quantity of energy stored in a given biomass, which is expressed mathematically as the proportion between the HHV of the torrefied biomass (HHV\text{TCS}) to the HHV of the raw biomass (HHV\text{raw}) or \((\text{HHV}_{\text{TCS}}/\text{HHV}_{\text{raw}})\) [8]. E\text{Y} is the quantity of energy essentially collected from the biomass. It is expressed as the product of the ED and the M\text{Y} or \(M_{\text{Y}} \times (\text{HHV}_{\text{TCS}}/\text{HHV}_{\text{raw}}) \times 100\%\). Though torrefaction causes some losses, it makes biomass to be utilized effectively, especially in energy systems. This loss in energy can be quantified by the E\text{Y} [30]. Table III shows the coconut shells’ M\text{Y}, ED, and E\text{Y}. On average, each sample weighed 500±0.5%g. After torrefaction, the weight of each sample was reduced by an average of 6.27% and the average moisture content was 5.82%.

Figure 7 shows the graphical presentations of M\text{Y}, ED, and E\text{Y}. As the temperature and holding time increase, the M\text{Y}, the ratio between the mass of the TCS and the mass of the RCS, reduce. This is true, since the mass of the TCS becomes lower than the mass of the RCS as the exposure to a high temperature is lengthened. The process also reduces the %MC. Moreover, the ratio between the TCS and the RCS HHV increases while the M\text{Y} decreases. This increase in the ED is a proof that the calorific value of the coconut shells increases at a reduced moisture content of the biomass.

The product of the M\text{Y} and the ED or the ratio between the products of the mass and HHV of the TCS and RCS is the E\text{Y}. Ideally, the value of the E\text{Y} should be greater than 1 (100%). At a temperature of 275°C and resident time of 30min, the E\text{Y} reached 100.59%. This indicates that the torrefaction process improved the value of biomass.

**D. Summary**

1) **Proximate and Ultimate Analysis**

Forest and agricultural resources can be used to produce electricity. One of the available resources is the coconut shell, made at 2.2 MT per year in the Philippines [4, 5, 31]. Its HHV was investigated for the possible use of coconut shells to produce electricity. To improve the HHV of any biomass resource, torrefaction (200°C to 300°C) is a good choice [20]. Coconut shells were torrefied at 200, 225, 250, 275, and 300°C with residence times of 10, 20, and 30min. TCS were sent to an accredited analytical laboratory for proximate analysis. They determined %MC, %VM, %ASH, and %FC using the standard test method for chemical analysis of wood charcoal and other biomasses [8, 16]. The sulfur content (%S) was analyzed using gravimetric analysis. Using (9) [17], the HHV\text{prox} of 15
torrefied shells, including the RCS, were determined. The optimal HHV of 34.37MJ/kg was found for shells torrefied at 275°C for 30min. For the ultimate analysis wherein %C, %H, %N, %S, and %O [21], various known equations were used. Though these equations introduced minor deviations to the measured values, they are widely used in the elemental analyses of biomass and other feedstocks [19, 20]. Table IV lists the equations used in solving the HHV using ultimate analytical elements.

### Table IV. Ultimate Analysis Equations

| Element | Equation | Reference |
|---------|----------|-----------|
| %C      | (4)      | [24, 25]  |
| %H      | (3)      | [19]      |
| %N      | (7)      | [27]      |
| %S      | Laboratory test results | Gravimetric |
| %ASH    | Laboratory test results | ASTM D1762-84 |
| %O      | %O = 100 - %C - %H - %N - %S - %ASH | [32] |

The HHV_{ed} (ultimate analysis) was found using (3) [22, 23]. Comparing the HHV_{prox} and HHV_{ed}, the MAE was ±0.3388.

2) Mass Yield, Energy Density, and Energy Yield

On average, the M_{y}, the ratio between the HHV_{prox} and the HHV_{ed}, was 93.51%, this is what remains in TCS after torrefaction [21]. The higher the temperature and the residence time, the higher the reduction in mass hence reducing the M_{y}, ED, i.e. the ratio between the HHV_{prox} and the HHV_{ed}, is 104.61%. Higher ratio would mean that the TCS had increased their HHV by an immense amount. E_{Y}, i.e. the product of the M_{y} and the ED, was 97.83%. This is the amount of energy that can be potentially collected from the TCS. At the temperature of 275°C and residence time of 30min, the M_{y} was 90.10%, and the ED was 111.64% resulting in an E_{Y} of 100.59%.

### IV. Conclusion

Biomass is a non-fossilized, biodegradable organic substance that can be utilized to supplement other renewable energy technologies and replace fossil fuels. Coconut is woody biomass that grows in abundance in the tropics and is a good alternative energy resource. Ground coconut shells (25mm×25mm) were torrefied to increase their HHV. At 275°C and 30min residence time, the optimal HHV of 34.37MJ/kg was achieved. This suggests an HHV 11.63% higher than the RCS’s HHV of 30.79MJ/kg. This result supports the findings of [10, 13]. The computed calorific value or HHV can be determined with high certainty utilizing a combination of laboratory analyses using established test procedures for chemical analysis and correlative equations developed and extensively used. Since the TCS achieved optimal HHV, they reached an E_{Y} of 100.59%. E_{Y} is the product of the M_{y} at 90.10% and the ED at 111.64%.

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