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 coal-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

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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 30min for every temperature setting.

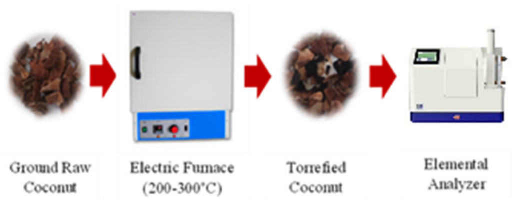

Fig. 1. Torrefaction experimental setup.

Fig. 2. Torrefied coconut shells.

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.

Fig. 3. Sealed torrefied coconut shells.

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:

$$HHV = 354.3\times \%FC + 170.8 \times \%VM \quad (1)$$

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]:

$$HHV = 0.1846 \times \%VM + 0.3525 \times \%FC \quad (2)$$

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).

TABLE I. PROXIMATE ANALYSIS

Type, Temp (°C), Time (min)	%MC	%ASH	%VM	%FC	HHV (MJ/kg)
BCS 0, 0	11.90	0.88	0.63	86.60	30.790
TCS 200, 10	7.40	0.06	3.40	89.10	32.150
TCS 200, 20	6.80	0.54	3.30	89.30	32.200
TCS 200, 30	6.60	1.70	2.40	89.30	32.050
TCS 225, 10	7.60	0.76	3.10	88.50	31.890
TCS 225, 20	6.50	1.50	6.30	86.70	31.790
TCS225. 30	7.20	0.44	6.20	86.20	31.600
TCS 250, 10	8.00	0.97	5.00	86.00	31.320
TCS 250, 20	4.80	0.43	6.40	88.40	32.410
TCS 250, 30	3.60	1.80	9.90	84.70	31.700
TCS 275, 10	7.50	0.10	6.30	86.10	31.580
TCS 275, 20	5.00	0.20	4.40	90.40	32.780
TCS 275, 30	2.00	0.60	0.66	96.70	34.370
TCS 300, 10	4.70	0.95	2.00	92.40	33.080
TCS 300, 20	2.40	2.80	8.20	86.60	32.080
TCS 300, 30	1.10	0.81	14.20	83.90	32.150

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 15min. Several studies claim that the torrefaction process improves the HHV of biomass feedstock [20].

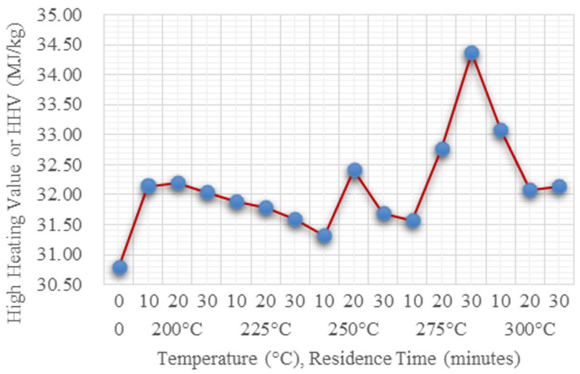

Fig. 4. HHV of coconut shells.

Figure 5 compares the HHV of coconut shells torrefied at various temperature levels and holding times. At a temperature of 275°C and holding time of 30min, the maximum HHV of 34.37MJ/kg was achieved.

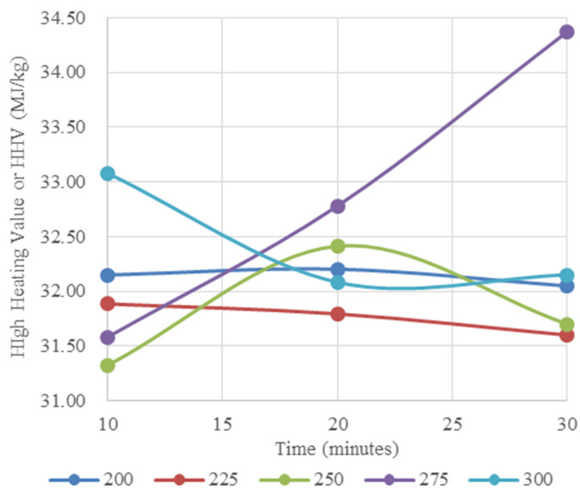

Fig. 5. Torrefied coconut shells proximate analysis.

B. *Ultimate Analysis Results*

The ultimate analysis determines Carbon (%C), Hydrogen (%H), Nitrogen (%N), Sulfur (%S), and Oxygen (%O) [21]. HHV can be measured using the bomb calorimeter or can be calculated using various correlational equations. In the proximate analysis, the value of HHV was determined with an equation using %VM and %FC. For ultimate analysis, the equation [22, 23]:

$$HHV = 0.341 \times \%C + 1.322 \times \%H + 0.0686 \times \%S - 0.12 \times \%O + \% \times N - 0.0153 \times \%ASH \quad (3)$$

was used. This equation differs from that of [17], since it uses the results of the ultimate analysis parameters and %ASH from the proximate analysis. Note that the calorific value of the biomass is highly dependent on %C and %H.

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:

$$\%C = 2.1877 \times HHV + 5.9068 \quad (4)$$

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

$$\%H = 0.059 \times \%FC + 0.060 \times \%VM + 0.010 \times \%ASH \quad (5)$$

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

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

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

$$\%N = 2.6116 \times HHV - 1.1092 \times \%C + 6.3884 \times \%S \quad (7)$$

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 30min, 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_{ULT} (MJ /kg)	HHV_{PROX} (MJ /kg)
BCS 0, 0	73.3	5.2	0.8	0.3	19.7	30.18	30.79
TCS 200, 10	76.2	5.5	0.5	0.2	17.6	31.60	32.15
TCS 200, 20	76.4	5.5	0.6	0.2	16.8	31.88	32.20
TCS 200, 30	76.0	5.4	0.7	0.2	15.9	31.90	32.05
TCS 225, 10	75.7	5.4	0.4	0.2	17.6	31.29	31.89
TCS 225, 20	75.5	5.5	0.9	0.2	16.4	31.90	31.79
TCS 225. 30	75.0	5.5	0.9	0.3	17.9	31.56	31.60
TCS 250, 10	74.4	5.4	0.7	0.2	18.3	30.95	31.32
TCS 250, 20	76.8	5.6	0.9	0.2	16.0	32.61	32.41
TCS 250, 30	75.3	5.6	0.8	0.2	16.3	31.89	31.70
TCS 275, 10	75.0	5.5	0.8	0.2	16.8	30.84	31.58
TCS 275, 20	77.6	5.6	1.0	0.2	13.8	32.51	32.78
TCS 275, 30	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:

$$HHV = 0.341 \times \%C + 1.322 \times \%H + 0.0686 \times \%S - 0.12 \times \%O + \% \times N - 0.0153 \times \%ASH \quad (8)$$

and provides identical value with:

$$HHV = 354.3 \times \%FC + 170.8 \times \%VM \quad (9)$$

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.

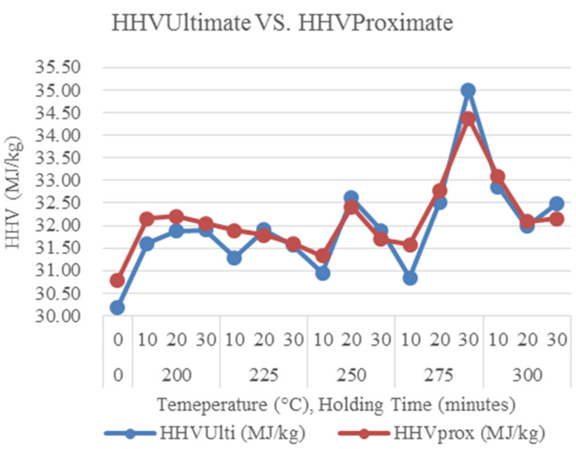

Fig. 6. HHV ultimate vs. HHV proximate.

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

With the HHV known, Mass yield (M_Y), Energy Density (ED), and Energy yield (E_Y %) can be determined. M_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_{torr}) to the mass of the raw biomass (M_{raw}) or (M_{torr}/M_{raw}) × 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_{torr}) to the HHV of the raw biomass (HHV_{raw}) or (HHV_{torr}/HHV_{raw}) [8]. E_Y is the quantity of energy essentially collected from the biomass. It is expressed as the product of the ED and the M_Y or M_Y × (HHV_{torr}/HHV_{raw}) × 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_Y [30]. Table III shows the coconut shells' M_Y, ED, and E_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_Y, ED, and E_Y. As the temperature and holding time increase, the M_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_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.

TABLE III. MASS YIELD, ENERGY DENSITY, AND ENERGY YIELD

Type, Temp (°C), Time (min)	Mass (torr) (g)	Mass (dry) (g)	HHV (MJ/kg)	M_Y (%)	ED (%)	E_Y (%)
BCS 0, 0	500.0	440.5	30.8			
TCS 200, 10	477.5	442.2	32.2	95.5	104.4	99.7
TCS 200, 20	474.5	442.2	32.2	94.9	104.6	99.3
TCS 200, 30	473.5	442.3	32.1	94.7	104.1	98.6
TCS 225, 10	478.5	442.1	31.9	95.7	103.6	99.1
TCS 225, 20	473.0	442.3	31.8	94.6	103.3	97.7
TCS225. 30	476.5	442.2	31.6	95.3	102.6	97.8
TCS 250, 10	480.5	442.1	31.3	96.1	101.7	97.8
TCS 250, 20	464.5	442.2	32.4	92.9	105.3	97.8
TCS 250, 30	458.5	442.0	31.7	91.7	103.0	94.4
TCS 275, 10	478.0	442.2	31.6	95.6	102.6	98.1
TCS 275, 20	465.5	442.2	32.8	93.1	106.5	99.1
TCS 275, 30	450.5	441.5	34.4	90.1	111.6	100.6
TCS 300, 10	464.0	442.2	33.1	92.8	107.4	99.7
TCS 300, 20	452.5	441.6	32.1	90.5	104.2	94.3
TCS 300, 30	446.0	441.1	32.2	89.2	104.4	93.1
Average	469.6	441.9	32.1	93.5	104.6	97.8
Std. Dev.	11.3	0.3	0.8	2.3	2.5	2.2

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

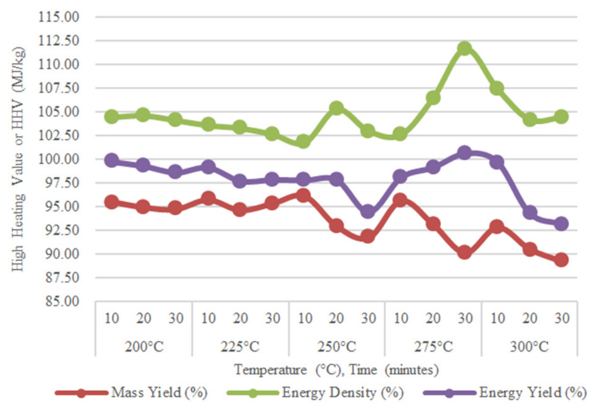

Fig. 7. Mass yield, energy density, and energy yield.

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_{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	(5)	[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_{ulti} (ultimate analysis) was found using (3) [22, 23]. Comparing the HHV_{prox} and HHV_{ulti}, the MAE was ±0.3388.

2) Mass Yield, Energy Density, and Energy Yield

On average, the M_y, the ratio between the HHV_{torr} and the HHV_{raw}, 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 $HHVt_{orr}$ and the HHV_{raw}, 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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REFERENCES

[1] I. Naim and T. Mahara, "Fuel Substitution for Energy Saving: A Case Study of Foundry Plant," *Engineering, Technology & Applied Science Research*, vol. 8, no. 5, pp. 3439–3444, Oct. 2018, https://doi.org/10.48084/etasr.2298.

[2] "Philippine Forestry Statistics." https://forestry.denr.gov.ph/index.php/statistics/philippines-forestry-statistics (accessed Apr. 05, 2022).

[3] Forest Management Bureau, "Philippine Forestry Statistics," Department of Environment Natural Resources, 2020. [Online]. Available: https://forestry.denr.gov.ph/index.php/statistics/philippines-forestry-statistics. [Accessed 7 November 2021].

[4] "Coconut Statistics." https://pca.gov.ph/index.php/resources/coconut-statistics (accessed Apr. 05, 2022).

[5] "Philippine Statistics Authority | Republic of the Philippines." https://psa.gov.ph/ (accessed Apr. 05, 2022).

[6] J. E. G. Van Dam, "Coir processing technologies. Improvement of drying, softening, bleaching and dyeing coir fibre/yarn and printing coir floor coverings," FAO/CFC, Rome, Italy, 2002.

[7] R. Mudiyono and S. Sudarno, "The Influence of Coconut Fiber on the Compressive and Flexural Strength of Paving Blocks," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4702–4705, Oct. 2019, https://doi.org/10.48084/etasr.3008.

[8] P. Basu, *Biomass Gasification and Pyrolysis: Practical Design and Theory*. Burlington, MA, USA: Academic Press, 2010.

[9] M. Wilk and A. Magdziarz, "Hydrothermal carbonization, torrefaction and slow pyrolysis of Miscanthus giganteus," *Energy*, vol. 140, pp. 1292–1304, Dec. 2017, https://doi.org/10.1016/j.energy.2017.03.031.

[10] A. Irawan, L. U. S., and M. D. I. P., "Effect of torrefaction process on the coconut shell energy content for solid fuel," *AIP Conference Proceedings*, vol. 1826, no. 1, Mar. 2017, Art. no. 020010, https://doi.org/10.1063/1.4979226.

[11] B. V. Babu, "Biomass pyrolysis: a state-of-the-art review," *Biofuels, Bioproducts and Biorefining*, vol. 2, no. 5, pp. 393–414, 2008, https://doi.org/10.1002/bbb.92.

[12] A. Bhavanam and R. C. Sastry, "Biomass Gasification processes in downdraft fixed bed reactors: a review," *International Journal of Chemical Engineering and Applications*, vol. 2, no. 6, pp. 425–433, 2011.

[13] L. D. B. Pestano and W. I. Jose, "Production of Solid Fuel by Torrefaction Using Coconut Leaves as Renewable Biomass," *International Journal of Renewable Energy Development*, vol. 5, no. 3, pp. 187–197, Oct. 2016, https://doi.org/10.14710/ijred.5.3.187-197.

[14] W.-H. Chen and P.-C. Kuo, "A study on torrefaction of various biomass materials and its impact on lignocellulosic structure simulated by a thermogravimetry," *Energy*, vol. 35, no. 6, pp. 2580–2586, Jun. 2010, https://doi.org/10.1016/j.energy.2010.02.054.

[15] E. Dahlquist, *Technologies for Converting Biomass to Useful Energy: Combustion, Gasification, Pyrolysis, Torrefaction and Fermentation*. Boca Raton, FL, USA: CRC Press, 2013.

[16] *ASTM D1762-84(2021), Standard Test Method for Chemical Analysis of Wood Charcoal*. West Conshohocken, PA, USA: ASTM International, 2021.

[17] T. Cordero, F. Marquez, J. Rodriguez-Mirasol, and J. J. Rodriguez, "Predicting heating values of lignocellulosics and carbonaceous materials from proximate analysis," *Fuel*, vol. 80, no. 11, pp. 1567–1571, Sep. 2001, https://doi.org/10.1016/S0016-2361(01)00034-5.

[18] S. D. Menon, K. Sampath, and S. S. Kaarthik, "Feasibility studies of coconut shells biomass for downdraft gasification," *Materials Today: Proceedings*, vol. 44, pp. 3133–3137, Jan. 2021, https://doi.org/10.1016/j.matpr.2021.02.813.

[19] M. Hasan, Y. Haseli, and E. Karadogan, "Correlations to Predict Elemental Compositions and Heating Value of Torrefied Biomass," *Energies*, vol. 11, no. 9, Sep. 2018, Art. no. 2443, https://doi.org/10.3390/en11092443.

[20] D. R. Nhuchhen and M. T. Afzal, "HHV Predicting Correlations for Torrefied Biomass Using Proximate and Ultimate Analyses,"

Bioengineering, vol. 4, no. 1, Mar. 2017, Art. no. 7, https://doi.org/10.3390/bioengineering4010007.

[21] P. Basu, "Torrefaction," in *Biomass Gasification, Pyrolysis and Torrefaction*, Second Edition., San Diego, CA, USA: Academic Press, pp. 87–145.

[22] T. A. Mamvura and G. Danha, "Biomass torrefaction as an emerging technology to aid in energy production," *Heliyon*, vol. 6, no. 3, Mar. 2020, Art. no. e03531, https://doi.org/10.1016/j.heliyon.2020.e03531.

[23] T. Milne, A. H. Brennan, and B. H. Glenn, *Sourcebook of Methods of Analysis for Biomass and Biomass Conversion Processes*. New York, NY, USA: Springer, 1990.

[24] D. L. Klass, *Biomass for Renewable Energy, Fuels, and Chemicals*. San Diego, CA, USA: Academic Press, 1998.

[25] T. R. Brown and R. C. Brown, *Biorenewable Resources: Engineering New Products from Agriculture*, 2nd ed. Chichester, West Sussex, UK: Wiley-Blackwell, 2014.

[26] A. Friedl, E. Padouvas, H. Rotter, and K. Varmuza, "Prediction of heating values of biomass fuel from elemental composition," *Analytica Chimica Acta*, vol. 544, no. 1, pp. 191–198, Jul. 2005, https://doi.org/10.1016/j.aca.2005.01.041.

[27] A. Ozyuguran, A. Akturk, and S. Yaman, "Optimal use of condensed parameters of ultimate analysis to predict the calorific value of biomass," *Fuel*, vol. 214, pp. 640–646, Feb. 2018, https://doi.org/10.1016/j.fuel.2017.10.082.

[28] R. P. Bates and K. Dolle, "Syngas Use in Internal Combustion Engines - A Review," *Advances in Research*, vol. 10, no. 1, 2017, Art. no. 32896.

[29] T. A. Milne and R. J. Evans, *Biomass Gasifier "Tars": Their Nature, Formation, and Conversion*. Golden, CO, United States: National Renewable Energy Laboratory, 1998.

[30] P. Basu, *Combustion and Gasification in Fluidized Beds*. Boca Raton, FL, USA: CRC Press, 2006.

[31] S. A. Bellow, J. O. Agunsoye, J. A. Adebisi, F. O. Kolawole, and S. B. Hassan, "Physical properties of coconut shell nanoparticles," *Kathmandu University Journal of Science, Engineering and Technology*, vol. 12, no. 1, pp. 63–79, 2016, https://doi.org/10.3126/kuset.v12i1.21566.

[32] S. H. Solangi, A. Q. Jakhrani, K. C. Mukwana, A. R. Jatoi, and M. R. Luhur, "Investigation of Quantity, Quality and Energy Content of Indigenous Sugarcane Trash in Naoshehro Feroze District, Sindh," *Engineering, Technology & Applied Science Research*, vol. 8, no. 6, pp. 3609–3613, Dec. 2018, https://doi.org/10.48084/etasr.2411.