Proximate Analysis of the Torrefied Coconut Shells

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Abstract- Biomass is biodegradable and non-fossilized organic materials derived from abundant, clean, and carbon-neutral plants, algae, and animals that can potentially be used as a bioenergy resource to replace fossil fuels. Coconut is one of the biomass feedstocks that are plentiful in tropical countries. The 347 million coconut trees planted in the Philippines produced 14.7 MT of nuts in 2020. The coconut shells (endocarp) comprise 15.18% of each coconut fruit, accounting for 2.2 MT of the total volume of coconuts. Torrefaction, the slow heating process from 200°C to 300°C, is a vital preprocessing step for improving biomass's physical qualities and chemical content. Coconut shells were torrefied using 200°C, 225°C, 250°C, 275°C, and 300°C at a residence time of 10mins, 15mins, and 30mins. At 275°C and residence time of 30mins, it was found that the moisture content was 2.00%, ash content was 0.60%, the volatile matter was 0.66%, fixed carbon was 96.70%, and the optimal high heating value (HHV) of 34.37 MJ/kg was achieved. The improvement indicates an increase of 11.64% from the heating value of raw coconut shells (RCS) at 30.79 MJ/kg. The study concurs with other researchers on the positive effect of torrefying biomass feedstock, particularly the coconut shells. It is concluded that torrefaction at 275°C and residence time of 30 mins will significantly improve the HHV of the coconut shells.

Keywords Coconut, Shells, Torrefaction, Proximate, Analysis, HHV, Biomass, TCS, RCS.

1. Introduction

Due to the rising population and need for electricity, there is a need to explore alternate sources of electricity as fossil-based fuels are polluting the environment and depleting [1, 2]. Renewable energy technologies like solar, hydro, wind, biomass, and geothermal are gaining attention, sustaining economic growth due to local and natural resources [3]. With the integration of renewable energy technologies into the grid, CO_2 emission may lower due to the less use of fossil fuel-dependent power plants [4]. Biomass is biodegradable and non-fossilized organic material derived from abundant, clean, carbon-neutral plants, algae, and animals. They can potentially be used as a bioenergy resource that will replace fossil fuels in the future [5]. Alternately, with some reforming, livestock manures can be used as biogas to produce electricity [6]. Biogas has several benefits, primarily on managing wastes and the production of electricity [7]. In a way, renewable energy can help reduce CO_2 emissions, provide livelihood, and make energy available to the poor and remote communities [4, 7].

In Europe, about 50% of renewable energy requirements are satisfied using processed and densified forest products and agricultural residues [8]. There are two main biomasses, herbaceous biomass and woody biomass. Due to the relatively higher-high heating value (HHV) of woody biomass, it is identified as a promising resource to address the increasing future demand for electricity [9].

The Philippines has a total forest land of 15,805,325 hectares [10] and is home to a variety of naturally grown trees [11], coconut, agricultural products, and many others [12, 13]. In 2020, the Philippines produced 0.82 million cubic meters of logs [10] and various agricultural products like rice (19.29 million tons or MT), corn (8.12 MT), sugarcane (24.40 MT), and coconut (14.49 MT), which add up to 66.30 (MT) [13]. In this forest land, there are at least twelve (12) herbaceous and woody biomasses being grown or naturally grown. They include cogon grass, corn cobs, peanut shell, rice straw and husks, sugarcane bagasse and leaves, bamboo, coconut shells and leaves, coffee husks and spent coffee ground (SGF), palm oil fiber, shell, Empty fruit bunch (EFB), and bark, acacia, eucalyptus, and woodchips. Of the available biomass resources, only the rice husks (RH) and sugarcane bagasse (SCB), wastes materials of various agricultural companies, are being utilized in the Philippines to produce electricity using biomass thermal power plants.

To increase the contribution of biomass as a renewable resource, coconut shells were investigated as an alternative feedstock. In the Philippines (PH), 347 million fruit-bearing coconut trees were planted on 3.6 million hectares of land, producing 14.7 metric tons of nuts [12]. Every coconut tree may have 70 to 150 nuts annually [14]. Coconut meat (kernel) is a healthy food source and is used to produce oil. The coconut water is suitable for drinking, while the endocarp or the hard shell which surrounds the meat is a good source of carbon [15]. The coconut shell accounts for 15.18% of the nut and is typically used for cooking and producing activated carbon [16]. Nevertheless, coconut shells that account for 2.20 million tons have other uses, especially in producing activated carbon, furniture, and others [12].

Coconut shells and other biomass feedstock have intrinsic high heating value (HHV) but can be improved using various approaches such as torrefaction, carbonization, pyrolysis, and combustion [17]. Torrefaction, which is becoming popular as a vital preprocessing step for improving the physical qualities and chemical content of biomass, is the slow heating of biomass from 200°C to 300°C in an inert or reduced atmosphere to dry or convert the coconut shells to a coal-like material which eventually improves its properties as a biofuel [18, 19]. Moreover, exposing the materials to a moderately high temperature at an expanded residence time enhances their high heating value [20].

There are two known biomass power technology, the biomass gasification power system (BGPS) and the biomass thermal power system (BTPS) [17]. A biomass gasification power system is claimed to produce fewer greenhouse gases since it recaptures carbon dioxide (CO_2) and reuses other hazardous gas [21, 17]. The energy conversion efficiency of any biomass power technology depends on the physical characteristics of any biomass feedstock, especially on its high heating value (HHV) [22, 17, 5]. HHV was quantified through a proximate analysis where the volatile matter (%VM), the ash content (ASH), and the fixed carbon (%FC) were measured using ASTM D1762-84, the Standard Test Method for Chemical Analysis of Wood Charcoal, and other biomasses [23]. The moisture content (%MC) was measured using a gravimetric analytical approach.

Studies showed that biomass feedstocks' high heating value (HHV) improved significantly when torrefied [24]. In the study of Obeng, Amoah, Opoku, Sekyere, Adjei, and Mensah [25], when the coconut wastes were torrefied, their high heating value (HHV) had increased by 42% compared to the uncharred or untorrefied coconut wastes. Pestaño and Jose [26] demonstrated that the high heating value (HHV) of torrefied coconut leaves had substantially improved from 17.95 MJ/kg (air-dried) to 27.78 MJ/kg when torrefied at 295°C or equivalent to an increase of 54.76%. Tumuluru, Sokhansanj, Wright, and Boardman [19] presented that torrefying wood at 290°C and residence time of 30 mins, 82% solid char was achieved. Interestingly, in the study of Irawan, Upe, and Meity [20], at a 250°C, a residence time of 30 minutes, and a size of 15 mm, the HHV of the torrefied coconut shells (TCS) increased from 18.94 MJ/kg to 31.23 MJ/kg. This establishes that the torrefaction process substantially improved the HHV of coconut shells by 64.89%. Nevertheless, despite the evidence that the torrefied coconut shells (TCS) improved biomass feedstock's high heating value (HHV), torrefaction is not yet well-practiced in the biomass gasification power system (BGPS) operation.

With the claims that torrefaction enhanced the high heating value (HHV) of biomass feedstock, the study was conducted to determine the high heating value (HHV) of torrefied coconuts shells (TCS). Further, the study tried to determine the temperature and residence time wherein the optimal high heating value of the torrefied coconut shells was reached. With the findings on the optimal high heating value (HHV) of the torrefied coconut shells (TCS), an immense volume of coconut shells in the Philippines can be used as feedstocks to the biomass gasification power system (BGPS) deployed in remote and unelectrified communities for their sustained use of affordable and relatively clean electricity.

2. Methods and Materials

The study used an experimental research approach where the high heating value (HHV) of the torrefied coconut shells (TCS) was determined using proximate analysis. Figure 1 shows the experimental setup in conducting the torrefaction of the coconut shells. By ensuring the integrity and reliability of the experimental data, samples of torrefied coconut shells were sent to Davao Analytical Laboratory (DAL), a government accredited analytical laboratory, for proximate analysis.

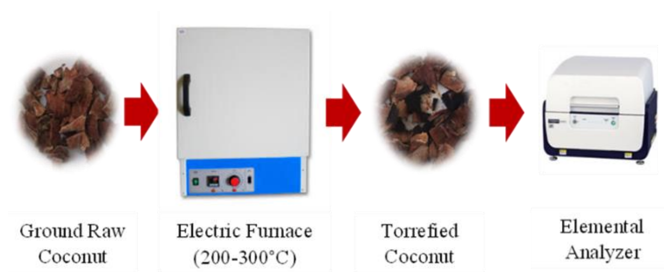

Fig. 1. Torrefaction Experimental Setup

Using a shell crusher, fifteen (15) kgs of raw coconut shells were ground at approximately 25 mm x 25 mm (Figure 2). Selected ground coconut shells weighing 1,000 ±0.5% grams were placed in a pan for heating at the electric furnace. For each test, the furnace was set at 200°C, 225°C, 250°C, 275°C, or 300°C, and a cooking time of 10 mins, 20 mins, or 30 mins.

Figure 2. Torrefied Coconut Shells

After heating, the torrefied coconut shells weighing 500±0.5% grams were placed in cellophane and sealed (**Hata! Başvuru kaynağı bulunamadı.** 3). Sixteen (16) samples were sent to the Davao Analytical Laboratory (DAL), a government accredited analytical laboratory, for proximate analysis.

Figure 3. Sealed Torrefied Coconut Shells

DAL used ASTM D1762-84, a Standard Test Method for Chemical Analysis of Wood Charcoal, and other biomasses, to test approach intends to determine volatile matter (%VM), ash content (%ASH), and fixed carbon (%FC) of wood and other carbonaceous materials [23]. Gravimetric analysis was used in determining the moisture content (%MC). Table 1 shows the analysis conducted by DAL.

Table 1. Proximate Analyses Performed by the DAL

Symbol	Name	Unit	Analytical Method
Ash	Ash Content	%	ASTM D1762-84
FC	Fixed Carbon	%	ASTM D1762-84
VM	Volatile Matter	%	ASTM D1762-84
MC	Moisture Content	%	Gravimetric

ASTM: American Society for Testing and Materials

The analytical test results for one (1) raw and fifteen (15) torrefied shells were analyzed. The resulting moisture content (%MC), volatile matter (%VM), fixed carbon (%FC), and ash content (%ASH) were used in establishing the high heating values of the torrefied coconut shells.

In the study, two groups of samples were made. The first group of samples was composed of a set of 500±0.5% grams ground (25 mm x 25 mm) raw coconut shells. The second sample group was composed of 15 sets of 500 ±0.5% grams ground (25 mm x 25 mm) torrefied coconut shells (TCS). The coconut shells were torrefied in an electric furnace using 200°C, 225°C, 250°C, 275°C, and 300°C with a residence time of 10 mins, 20 mins, and 30 mins.

3 Results and Analyses

3.1 Proximate Analysis

Proximate analysis determines the moisture content (%MC), ash content (%ASH), volatile matter (%VM), and fixed carbon (%FC) of any biomass feedstock [17]. The Davao Analytical Laboratory used ASTM D1762-84, the Standard Test Method for Chemical Analysis of Wood Charcoal, and other biomasses to test approach intends to determine volatile matter (%VM) and ash content (%ASH) of wood and other carbonaceous materials [23]. Gravimetric analysis was used in measuring the moisture content (%MC),

The high heating value (HHV) is the amount of heat released per unit mass of any fuel. To find the high heating value (HHV), the equation HHV = 354.3 x %FC + 170.8 x %VM, introduced by Cordero, Marquez, Mirasol, and Rodriguez [27], was used; the result falls not more than 2% relative to the measured heating values of any biomass feedstock using a bomb calorimeter. Additionally, the calculation was cross-checked using HHV = 0.1846 x %VM + 0.3525 x %FC which was introduced by Menon, Sampath, and Kaarthik [28, 29].

Table 2 shows the proximate analysis results of the sixteen (16) samples—the high heating value (HHV)—is also presented. As shown in the table's 2nd row and 6th column, the coconut shells with the lowest HHV are the raw coconut shells (RCS).

Table 2. Proximate Analysis of Coconut Shells

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

Figure 4 depicts the pattern of the HHV of the raw and torrefied coconut shells (TCS). At 275°C, residence time of 30 minutes, and size of 25 mm, the HHV reached the peak value of 34.37 MJ/kg. At 275°C and holding time of 20 minutes, the HHV was only 32.78 MJ/kg (3.75%), and at 300°C and holding time of 10 minutes, the HHV reduced to 33.08 MJ/kg (3.75%). This shows that the optimal HHV was attained at 275°C and residence time of 30 mins. The increase is primarily due to the fixed carbon (%FC) improvement. Tumuluru, Sokhansanj, Wright, and Boardman [19] showed that 82% solid char was achieved when the wood was torrefied at 290°C and residence time of 30 mins. Interestingly, compared to Irawan, Upe, and Meity [20], the optimal HHV of 31.23 MJ/kg was attained at 250°C and a residence time of 30 minutes. The size of the ground TCS could have contributed to the difference. Irawan, Upe, and Meity [20] use 15 mm sizes, while, in this study, 25 mm size was used.

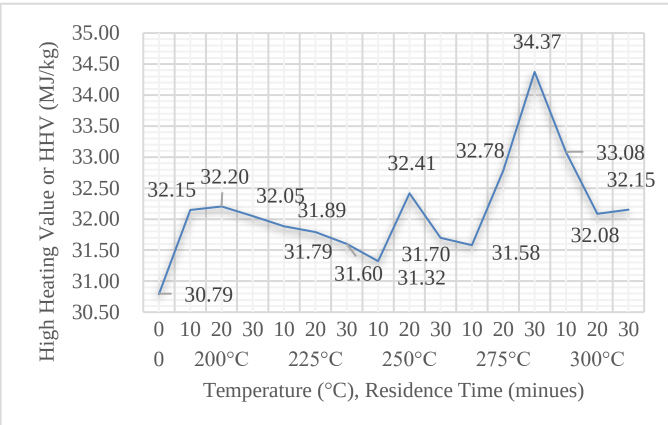

Fig. 4. HHV of Coconut Shells

Figure 5 compares the HHV of coconut shells torrefied at various temperature levels (°C) and holding time (in minutes). At a 275°C, holding 30 minutes, and 25mm size, the optimal HHV of 34.37 MJ/kg was achieved. As presented in Table 3, at a degree of determination (R^2) of 100%, the quadratic equation for the torrefied coconut shells (TCS) at 275°C is $Y = 0.002X^2 + 0.0607X + 30.777$, where Y represents the HHV and X the temperature and holding time. At 275°C, for a residence time of 10 mins, the HHV was lower at 31.58 MJ/kg, and for a residence time of 20 mins, the HHV was 32.78 MJ/kg. And the HHV dropped to 33.08 MJ/kg at 300°C (see Table 2).

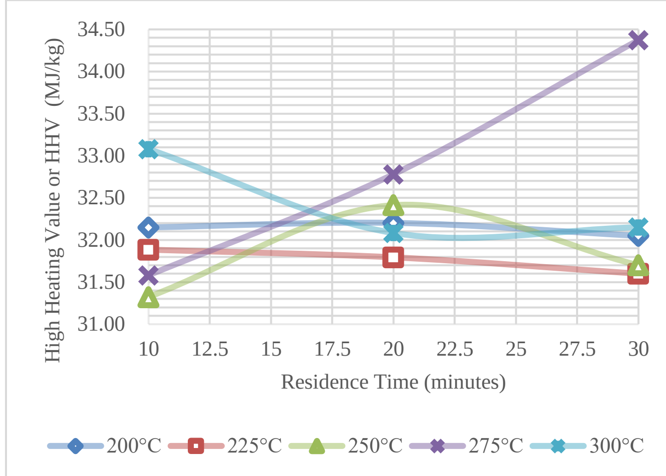

Fig. 5. Torrefied Coconut Shells Proximate Analyses

Table 3 lists the quadratic equations of the torrefied coconut shells (TCS) using the HHV at a holding time of 10 minutes, 20 minutes, and 30 minutes. The equations define the HHV at temperatures from 200°C to 300°C.

Table 3. Torrefied Coconut Shells Proximate Analysis Equations

Temperature (°C)	Equation	R^2
200	$y = 0.0053 x^2 - 0.2592 x + 35.139$	1.000
225	$y = -0.0005 x^2 + 0.0063 x + 31.873$	1.000
250	$y = -0.009 x^2 + 0.3793 x + 28.432$	1.000
275	$y = 0.002 x^2 + 0.0607 x + 30.777$	1.000
300	$y = -0.001 x^2 + 0.0365 x + 31.888$	1.000

With the increase in the HHV of the torrefied coconut shells from 30.79 MJ/kg to as high as 34.37 MJ/kg, the production of electricity using the biomass gasification power system (BGPS) can be increased. Selecting the proper temperature (275°C) and residence time (30 mins), there is an opportunity to increase energy production by 11.63%. Nevertheless, the torrefaction process has challenges, especially on cost and appropriate procedure in maintaining the process. Note that the longer the torrefaction holding time, the higher the chance that the temperature will increase. However, this did not happen with the electric furnace used in the experimentation since the temperature was controllable and time was quickly set. When doing torrefaction in bulk, accuracy is a concern [17]. Also, if implemented in a biomass gasification power system (BGPS), a high cost may be incurred in preparing the torrefied coconut shells (TCS).

3.2 Summary

Biomass is biodegradable and non-fossilized organic material derived from abundant, clean, carbon-neutral plants, algae, and animals. They can potentially be used as a bioenergy resource that will replace fossil fuels in the future [5]. Coconut is a woody biomass feedstock abundant in tropical countries, like the Philippines. There are 347 million coconut trees planted in the Philippines, producing 14.7 MT of nuts in 2020. The coconut shells (endocarp) comprise 15.18% of each coconut fruit, accounting for 2.2 MT of the total volume of coconut shells [12, 16, 13].

Biomass such as forest and agricultural products and residues can be used to produce electricity. For coconut shells, their high heating value (HHV) was investigated for the possibility of using them as feedstock to generate electricity. Torrefaction is a low heating process from 200°C to 300°C, which improves biomass feedstock's physical qualities and chemical content [24]. To improve the HHV of any biomass resource, torrefaction (200°C to 300°C) is a good choice [24]. Coconut shells were torrefied at 200°C, 225°C, 250°C, 275°C, and 300°C with a residence time of 10 mins, 20 mins, and 30 mins.

The torrefied coconut shells (TCS) were sent to an accredited analytical laboratory for proximate analyses. They determined the volatile matter (%VM), ash content (%ASH), and Fixed Carbon (%FC) using ASTM D1762-84, the Standard Test Method for Chemical Analysis of Wood Charcoal, and other biomasses [23, 17]. The moisture content (%MC) was analyzed using the gravimetric method. Using the equation HHV = 354.3 x %FC + 170.8 x %VM, introduced by Cordero, Marquez, Mirasol, and Rodriguez (2001), the high heating values (HHV) of the fifteen (15) torrefied shells (TCS), including the raw coconut shells (RCS), were determined [27].

At 275°C and residence time of 30 mins, the moisture content reduced to 2.00%, ash content lowered to 0.60%, the volatile matter decreased to 0.66%, and fixed carbon increased significantly to 96.70%, which led to reaching the optimal high heating value (HHV) of 34.37 MJ/kg. The change indicates an increase of 11.63% from the heating value of coconut shells (RCS) at 30.79 MJ/kg when not torrefied. The results concurred with the findings of Irawan, Upe, and Meity [20], Obeng, Amoah, Opoku, Sekyere, Adjei, and Mensah [25], Pestaño and Jose [26], and Tumuluru, Sokhansanj, Wright and Boardman [19], that the torrefaction process boosts the HHV of biomass feedstock, specifically of the coconut wastes.

Nonetheless, Irawan, Upe, and Meity [20] got the optimal HHV at 250°C and holding time of 45 mins but using 15 mm size. Obeng, Amoah, Opoku, Sekyere, Adjei, and Mensah [25] increased the HHV by 42% using coconut wastes (husks with shells). Pestaño and Jose [26], the HHV increased by 54.76% using coconut leaves. Tumuluru, Sokhansanj, Wright, and Boardman [19] increased the solid char to 82% at 290°C and holding time of 30 mins. In the study, a fixed carbon of 96.70% was obtained.

4 Conclusion

Biomass is a biodegradable and non-fossilized organic material that can be used as a resource to replace fossil fuels and complement other renewable energy technologies. Coconut is woody biomass that grows abundantly in the tropics. In recent years, the Philippines produced approximately 2.2 MT of coconut shells, considered coconut wastes. Coconut shells were torrefied to enhance their high heating value (HHV). At 275°C and residence time of 30 mins, the optimal high heating value (HHV) of 34.37 MJ/kg was achieved, indicating an HHV improvement of 11.63% compared to raw coconut shells (RCS) with an HHV of 30.79 MJ/kg. Though with some minor variations in the process of producing the HHV and in the use of biomass resources, the result proved the studies of Irawan, Upe, and Meity (2017), Obeng, Amoah, Opoku, Sekyere, Adjei, and Mensah (2020), Pestaño and Jose (2016), and Tumuluru, Sokhansanj, Wright and Boardman (2010) that the torrefaction process improves the HHV of biomass, in particular the coconut wastes.

In comparison, Irawan, Upe, and Meity (2017) attained the optimal HHV at 250°C and holding time of 45 mins using 15 mm size torrefied coconut shells. Obeng, Amoah, Opoku, Sekyere, Adjei, and Mensah (2020) increased the HHV by 42% using coconut wastes (husks with shells). Pestaño and Jose (2016), the HHV increased by 54.76% using coconut leaves. And Tumuluru, Sokhansanj, Wright, and Boardman (2010) increased the solid char to 82% at 290°C and a holding time of 30 mins using wood materials.

The study concludes that torrefying coconut shells at 275°C and residence time of 30 mins will attain the optimal HHV to 34.37 MJ/kg. To further increase the HHV, as demonstrated by Irawan, Upe, and Meity in 2017, performing another study using smaller sizes of ground and torrefied coconut shells is highly recommended,

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