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Coconut Wastes as Bioresource for Sustainable Energy: Quantifying Wastes, Calorific Values and Emissions in Ghana

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Received: 7 March 2020; Accepted: 26 March 2020; Published: 1 May 2020

Abstract: Coconut husks with the shells attached are potential bioenergy resources for fuel-constrained communities in Ghana. In spite of their energy potential, coconut husks and shells are thrown away or burned raw resulting in poor sanitation and environmental pollution. This study focuses on quantifying the waste proportions, calorific values and pollutant emissions from the burning of raw uncharred and charred coconut wastes in Ghana. Fifty fresh coconuts were randomly sampled, fresh coconut waste samples were sun-dried up to 18 days, and a top-lit updraft biochar unit was used to produce biochar for the study. The heat contents of the coconut waste samples and emissions were determined. From the results, 62–65% of the whole coconut fruit can be generated as wastes. The calorific value of charred coconut wastes was 42% higher than the uncharred coconut wastes. $PM_{2.5}$ and CO emissions were higher than the WHO 24 h air quality guidelines (AQG) value at 25 °C, 1 atmosphere, but the CO concentrations met the WHO standards based on exposure time of 15 min to 8 h. Thus, to effectively utilise coconut wastes as sustainable bioresource-based fuel in Ghana, there is the need to switch from open burning to biocharing in a controlled system to maximise the calorific value and minimise smoke emissions.

Keywords: coconut wastes; bioenergy resource; pollutant emissions; calorific value; biocharing

1. Introduction

Coconut is a perennial fruit that thrives well on sandy soils and mostly grows well on islands and coastal areas in the tropics and rainforest climate, especially along the coastline zones where it enjoys the sun irradiation as well as water [1]. Globally, several million tonnes of coconut are produced annually in Asia, Latin America and Africa. As of the year 2018, the total world production of coconut was 250–300 million tonnes [2]. Every part of the coconut plant is useful with a wide range of products being obtained from it [3–6]. Fresh coconut fruit is appreciated for its juice, food and animal feed; coconut husks are used as raw material supply [7–12] and wall hangings; fibres are used for clothing and bags, among other uses [13]. The shell normally takes a long time to decompose and often becomes a nuisance. Coconut husks with the shells attached and other biomaterials including straw, rice husks, corn stalks, sawdust, cereal husks, sugarcane bagasse and nutshells are a potential bioresource that can be used as domestic fuel [14] in energy-poor communities, such as those found in Ghana where about 73% of households depend on firewood for cooking and water heating [15].

In Ghana, after the edible portions of coconut fruits are consumed, the wastes in the form of husks and shells are usually thrown away or openly burned. The problem is that open burning and improper throwing away of coconut wastes (husks and shells) result in poor sanitation, air pollution and blocked roadside drains that facilitate the breeding of mosquitoes. Local food vendors use either the raw unprocessed coconut wastes or dry them in the open sun for a number of days to reduce the moisture content before employing as fuel for domestic cooking. Lee and Park [16] reported that inefficient combustion of biomass can release a considerable amount of various airborne pollutants, including particulates and carbon monoxide. Exposure to varying concentrations of pollutant emissions can affect people's health as well as the environment. It is reported that exposure to ultra-fine particulates (PM_{01}–$PM_{2.5}$) could increase the risk of severe respiratory diseases [17].

In some Ghanaian communities, coconut sellers at times persuade food vendors to collect the wastes free of charge for use as an alternative to firewood. In the light of these problems, there is the need for continuous research in order to gain insight into the quantity of whole coconut that can be generated as waste, the caloric value and the resulting pollutant emissions.

Parametric data and findings of this study will significantly contribute to the knowledge of the necessity to locally innovate in systems and processes that can be effectively utilised to optimise the waste-to-energy process so as to reach the goal of clean bioenergy production with low carbon emissions. The results of this study will provide data that can be used to estimate the amount of energy that can be produced from known quantities of coconut wastes and several other bioresources such as straw, rice husks, corn stalks, sawdust, cereal husks, sugarcane bagasse, nutshells etc. Such bioresources can be efficiently converted to produce clean biochar briquette fuels for heat and electricity generation in fuel-constraint communities [14,15].

Consequently, this study seeks to achieve the following objectives: 1) quantify the amount of wastes that can be generated from whole coconut; 2) determine the calorific values of raw uncharred and charred coconut wastes; and 3) analyse the moisture content and the resulting carbon monoxide (CO) and particulate matter ($PM_{2.5}$) emissions from the burning of coconut waste for possible emission reduction measures to improve the quality of combustion.

2. Materials and Methods

2.1. Quantifying the Proportion of Waste to be Generated from Whole Coconut

To quantify the proportion of waste that can be generated from whole coconut, fresh coconuts were purchased from a local dealer who obtains his coconuts from the westernmost district located on the coast of Ghana, known as the Jomoro district. In this study, both the pure coconut breed referred to as the local variety and mixed breed referred to as hybrid variety were used. Using an electronic weighing scale CTS 3000 (with 1 g minimum accuracy), a random sample of 50 whole coconuts were weighed to collect data on the individual weights. The fresh coconuts were dehusked using a machete as shown in Figure 1. They were individually weighed to obtain the quantity of husks by weight. The individual shells were also removed, weighed and recorded as quantity of shells by weight. Figure 2 is a half view of a whole coconut showing the skin, husk, shell and copra.

The weight of the fruit (juice and copra) was obtained by finding the difference between the weight of the whole coconut fruit and weight of husk and shell. The percentage composition of the coconut waste (husk and shell) by weight was determined using the formula in Equation (1):

$$\text{Percentage waste} = \frac{\text{sum of waste (husk + shell)weight}}{\text{total weight}} \times 100\% \quad (1)$$

Figure 1. Picture showing the dehusking of fresh coconut fruit.

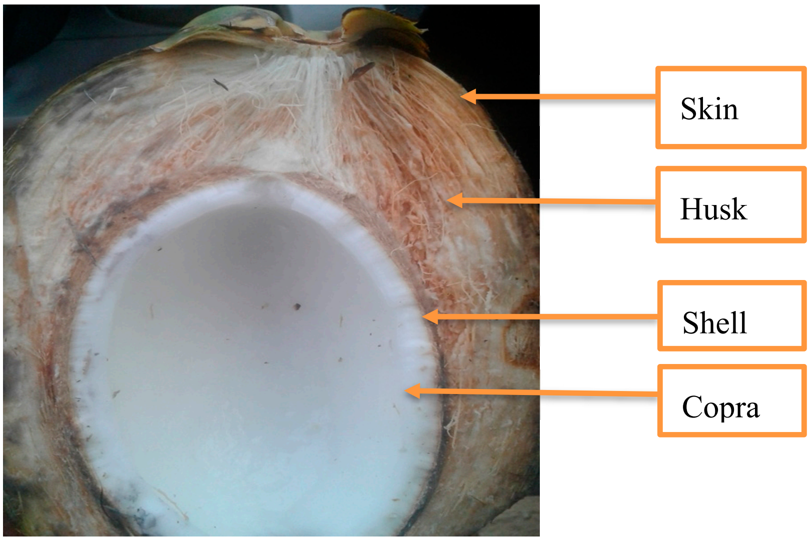

Figure 2. Half view of whole coconut showing the husk, skin, shell and copra.

2.2. Drying and Determination of Moisture Content

The oven-drying method was used to compare the moisture content of the sun-dried coconut wastes that were determined using the pin-type moisture meter (J-2000 Delmhost Instrument type with accuracy of ± 0.2). All things being equal, the moisture contents were determined to understand the influence of moisture content on pollutant emissions produced when coconut wastes are burned raw at the local community level.

Samples of the coconut wastes (husks and shells) were sun-dried for 3 to 18 days. Using the pin-type moisture meter, the moisture contents of randomly sampled coconut wastes were measured for 3 to 18 days as shown in Figure 3.

Figure 3. Field measurement of moisture content using the moisture meter.

Samples of about 200 g of the coconut wastes were also measured using the electronic weighing scale CTS 3000. The coconut wastes samples were then dried in an oven at a temperature of 105 °C for 24 h, then the samples of coconut wastes were weighed, and the moisture losses were determined by subtracting the oven-dry weight from the moist weight. The moisture content (Mc) of the coconut waste samples was determined as the mass of water in the sample expressed as a percentage of the dry mass as shown in Equation (2).

$$\text{Moisture content, Mc} = \frac{\text{MW} - \text{MD}}{\text{MW}} \text{ x } 100\ (\%) \quad (2)$$

where, MW = wet weight and MD = dry weight

2.3. Charring

The charring experiment was carried out at the Food Processing Unit of the Technology Consultancy Centre, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. A top-lit updraft (TLUD) biochar unit of a metallic drum of dimensions (Ø57cm x 85 cm high) was used. It had a chimney dimension of Ø21 cm x 120 cm high attached to a metal lid of Ø54.5cm x 25 cm high as shown in Figure 4. Holes were perforated beneath the reactor and it was mounted on three stones to enhance air flow, while ensuring it is stable. Then 5 kg of coconut waste sample was weighed and poured into the reactor ensuring that the coconut wastes are spread out evenly. A handful of dried leaves were used to kindle the fire from the top to start the combustion process. The metal lid with chimney was then fitted onto the reactor container to stop further entrance of oxygen as well as to provide a channel for the smoke to escape. Temperature of the container was recorded at regular intervals of time using an infrared thermometer. The temperature values measured ranged from 74.2 °C to 406.8 °C. In order to ascertain that the process was complete, drops of water were thrown on the side of the reactor container, when instantaneous puffs of steam close to the bottom were observed, the process was then considered to be completed. The charring test was repeated three times and the average values of the variables were determined. The coconut waste samples were reduced into smaller pieces and crashed using a hammer mill. The milled samples were then sieved using the Tyler sieves to obtain the appropriate particle sizes.

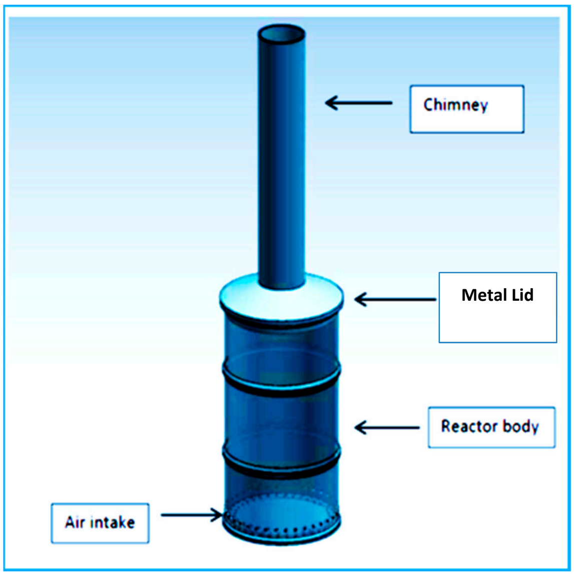

Figure 4. Schematic of top-lit updraft (TLUD) biochar unit.

2.4. Determination of Calorific Value

In this study, a bomb calorimeter SDC311 was used to determine the heat content of the coconut wastes. The bomb calorimeter conforms to ASTMD5865 standard. The specifications of the bomb calorimeter include analysis time of 11 min; precision of RSD< 0.1%; oxygen gas requirement of 99.5% purity etc. The crucible in the bomb calorimeter was placed on the weighing pan of the analytical balance to measure its weight. Using the prongs, one gram of the sample was fetched into the crucible on the analytical balance; the crucible was placed onto the crucible support of the oxygen bomb. Both ends of the firing wire were connected to two electrode rods of the oxygen bomb by bending them in a circular manner for firm contact.

Thereafter, the oxygen bomb core was moved into the oxygen bomb cylinder that had been filled with 10 mL of distilled water earlier on. After that, the oxygen bomb cover was tightly closed. Next, the oxygen bomb was filled with oxygen to about 2.8 to 3.0 MPa of pressure. The oxygen bomb was immersed into a bucket of water to determine the presence of leakage. Being satisfied with the outcome, the oxygen bomb was placed inside the bomb calorimeter and closed, then the system automatically begun the test. After about 10 min when the test was completed, the sample was completely combusted. The bomb calorimeter is instrumented such that after complete combustion of the sample, the calorific value is computed and displayed by running software on the windows-based desktop computer. After taking the readings, the calorimeter was opened to take the sample out. In doing this, oxygen was released using a release valve and then, the crucible taken out, washed in distilled water and cleaned with the bomb towel. To determine the calorific value, the experiment was conducted three times and the average calorific values were computed. The experiment was conducted at the Cookstove Testing and Expertise Laboratory (C-Lab) of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana.

2.5. Determination of Emissions

An indoor air pollution meter (IAP meter 500 series) was used for measuring the emissions. The resulting carbon monoxide (CO) and particulate matter ($PM_{2.5}$) measures (with a site-specific gravimetric calibration) provided an assessment of exposure to emissions. Relative humidity of 60–73% and ambient temperature of 30–34 °C were recorded during the test.

The indoor air pollution meter (IAP 5019)-Aprovecho Research Centre model was used for the emission measurements.

Before the experiment began, the IAP was opened for about 15 min to allow it to get accustomed to the local temperature since the CO sensor is very sensitive to temperature. Slow mode sampling rate was selected owing to the duration of the experiment. Thereafter, the meter was switched on for one hour to activate the system. The IAP was then hung up at the charring site, and the smoke produced from the coconut wastes that were sun-dried for 3 and 15 days is shown in Figure 5a,b. The different time periods were measured. When the charring process began, a few minutes were allowed to elapse to allow the burning to start up well devoid of unnecessary smoke, before timing as "test begins". After charring, the meter was switched off and the time was recorded as the test ends. The IAP was equipped with an SD card that stored the measured data. The data were then processed on a computer using software programmes such as Terreterm and Livegraph for connecting the meter directly to the computer.

(**a**) (**b**)

Figure 5. Smoke emissions from coconut wastes sun-dried for (**a**) 3 days and (**b**) 15 days.

3. Results and Discussion

3.1. Proportion of Whole Coconut Waste

The range, mean and standard deviations of the weights of the whole coconut fruit, husks, shells and copra/juice of the 50 samples of both hybrid and local varieties are presented in Table 1. From the results, an average husk weight of 0.80 ± 0.14 kg and shell weight of 0.25 ± 0.08 kg were determined for the hybrid variety with a total weight of 1.68 ± 0.21 kg. The proportion by weight of the waste husks and shells of the hybrid variety amounted to 62.62% of the whole coconut fruit. In Table 1, an average husk weight of 1.12 ± 0.33 kg and shell weight of 0.34 ± 0.09 kg were determined for the local variety with a total weight of 2.23 ± 0.61 kg. The proportion by weight of both the waste husks and shells of the local variety was about 65.60% of the whole coconut. Overall, a whole coconut fruit can yield husk waste of 47–50% and shell waste of 14–15%. The study results also revealed that 62–66% of the whole coconut is likely to be generated as husk and shell wastes, which can be considered as useful bioresource for sustainable energy production in fuel-constrained communities.

Table 1. Measured values on weight of whole coconut, husks, shells and copra/juice of hybrid and local coconut varieties.

	Whole Coconut Fruit	Husk	Shell	Copra and Juice
	Hybrid Coconut Variety			
Range (min–max) (kg)	1.29–2.11	0.57–1.09	0.13–0.44	0.32–0.97
Mean weight + Std. dev (kg)	1.68 ± 0.21	0.80 ± 0.14	0.25 ± 0.08	0.53 ± 0.18
Weight proportion (%)	100	47.75	14.87	37.38
Husk + shell weight (%)		62.62		
Coefficient of variation (%)	12.5	17.5	32	33.96
	Local Coconut Variety			
Range (min–max) (kg)	1.51–3.53	0.69–2.08	0.20–0.56	0.34–1.55
Mean weight + Std. dev (kg)	2.23 ± 0.61	1.12 ± 0.33	0.34 ± 0.09	0.77 ± 0.29
Weight proportion (%)	100	50.16	15.44	34.41
Husk + shell weight (%)		65.60		
Coefficient of variation (%)	26.35	29.46	26.47	37.66
Sample size (N_1 = hybrid variety; N_2 = local variety)		$N_1 = 25$; $N_2 = 25$		

3.2. Variability in the Various Parts

To find the variation in sizes in regard to the mean weights, coefficient of variation (CV) was used. CV is the ratio of sample standard deviation to the sample mean. According to Kelly and Donnelly [18], lower CV values are more consistent than higher CV values. In Table 1, the hybrid coconut variety shows lower CV values than the local coconut variety, indicating there is less variation in the size of the hybrid coconut variety than the local variety.

Further, Figure 6 depicts graphs that show variability in the weights of both local and hybrid coconut varieties. The trendlines provide a vivid picture and graphical representation of the variability in the weight of the coconuts. It is observed that there is relatively less variation in the weights of the hybrid coconut variety than the local variety. A relatively low degree of variation would mean better uniformity or consistency in the sizes of the hybrid coconut variety. What it means is that the dataset on the local variety of coconut contains values considerably higher and lower than their mean weight when compared to the dataset on the hybrid variety of coconut. In general, coconut hybrids are much preferred by coconut growers. Hence, different forms of varieties are exploited as breeding materials for coconut hybrid production [19].

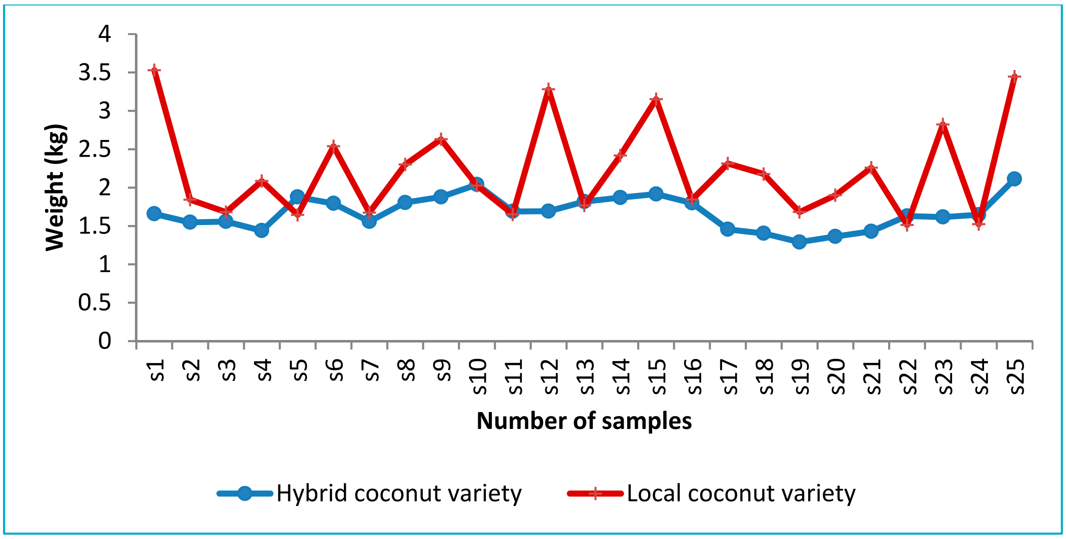

Figure 6. Plot of whole coconut waste samples and their weights.

3.3. Calorific Values of Charred and Uncharred Coconut Wastes

3.3.1. Uncharred Coconut Wastes (Husks and Shells)

The calorific value of the sun-dried coconut wastes (husks and shells) of both the local and hybrid varieties were analysed, and the results are presented in Table 2. The results indicated a mean calorific value of 11.54 ± 1.32 MJ/kg for the local coconut variety and 9.73 ± 0.33 MJ/kg for the hybrid variety. The calorific value, which is also known as heating value (q), is one of the important parameters that are considered when assessing a bioresource as a potential feedstock for fuel [20–23]. It is a measure of the amount of energy per unit mass or volume released on complete combustion. It is the amount of heat produced by the burning of 1 g of a substance and is measured in joules per gram (J/g).

Table 2. Calorific values of local and hybrid varieties of uncharred coconut waste (husk and shell)**.**

Readings	Mass of Sample (kg)	Calorific Value (MJ/kg)
Uncharred coconut waste of the local variety		
1	1.00	12.82
2	1.00	12.82
3	1.00	10.17
		11.63
Mean calorific value +/- Std. dev		11.54 ± 1.32 MJ/kg
Uncharred Coconut Waste of The Hybrid Variety		
1	1.00	9.394
2	1.00	9.762
3	1.00	10.044
Mean calorific value +/- Std. dev		9.73 ± 0.33 MJ/kg

The results indicate a variance in the calorific values obtained. The difference in calorific values is due to the chemical composition of the sample materials, in particular, the varying effect of lignin and extractive content [24]. The biomass of coconut is made up of cellulose, hemicellulose and lignin. There is about 65% cellulose in coconut shells, while lignin in coconut husk is almost 41% [25]. In addition to cellulose and lignin, coconut husk has pyroligneous acid, gas, charcoal, tar, tannin and potassium [26]. Further, with low amount of ash and more volatile matter, the husk make is appropriate for pyrolysis [26].

Amoako and Mensah-Amoah [27] determined the average calorific value of sun-dried uncharred coconut husks and shells to be 10.01 MJ/kg and 17.40 MJ/kg, respectively. These values are generally consistent with the results of 9.73 ± 0.33 MJ/kg to 11.54 ± 1.32 MJ/kg that were obtained in this study. The results also compare favourably with the calorific value of wood of 12–16 MJ/kg [24]. However, coconut waste burns fast, particularly the husk, and can therefore be used as fuel for less energy intense purposes, particularly for small-scale industrial heating, cooking and household applications [27]. Coconut husks and shells can therefore be attractive biomass fuels and are also a good source of charcoal [1,27].

3.3.2. Charred Coconut Wastes (Husks and Shells)

The calorific value of charred coconut wastes (husks and shells) was analysed and the results are presented in Table 3. The results indicated a mean calorific value of 21.307 ± 1.75 MJ/kg for charred coconut wastes of particle size P < 2 mm and 17.471 ± 5.53 MJ/kg for charred coconut wastes of P > 2 mm. From the results, the calorific value of the charred coconut waste is about 42% higher than the calorific value of the uncharred coconut waste. This is particularly significant for charred coconut wastes of particle size of P < 2 mm that are converted into briquettes for sustainable energy applications.

Table 3. Average calorific values of raw charred coconut waste (P < 2 mm, P > 2 mm).

Samples	Average Calorific Value (MJ/kg)
Charred coconut waste (P < 2 mm)	21.307 ± 1.75
Charred coconut waste (P > 2 mm)	17.471 ± 5.53

3.4. Moisture Content, Carbon Monoxide and Particulate Matter Emissions

Figure 7 shows the graph of moisture content and days of drying (sun drying) the coconut wastes. From the graphs, it is shown that as the drying days increased from 3 to 18 days, moisture content reduced as follows: day 3 (36.4%), day 6 (26.1%), day 9 (20.8%), day 12 (17.1%), day 15 (14.5%), and day 18 (10.3%). During drying some of the water in the waste material disappears and hence lessens the wet content. Under actual environmental settings, evaporation can happen because the actual wet content of the waste material is higher than its equilibrium moisture content, which is a factor of the material properties and environmental condition [28].

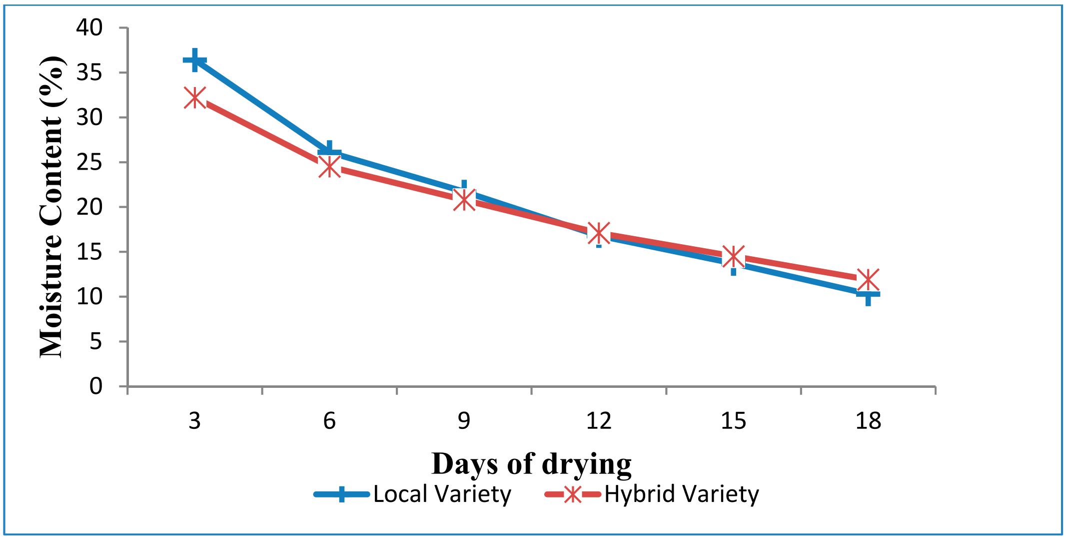

Figure 7. Moisture content of the coconut wastes by days of sun drying.

At harvest, moisture content of fresh coconut husks is around 29–35% [29]. In this study, it was observed that even after nearly one week (6 days) of open sun-drying, the moisture content of the coconut wastes reduced marginally to about 26%. Huda et al. [30] reported that high moisture content of biomass results in poor ignition and reduces the combustion temperature, which in turn affects the combustion of the products and quality of combustion. In general, the moisture content of biomass resources, especially wood, changes the calorific value of the latter by lowering it [31]. The explanation is that part of the energy released during the combustion process is spent in water evaporation. According to Raghavan [28], dry coconut husks with a moisture content of 10% had been used as fuel for the drying of copra in an island community in the Philippines.

Since local food vendors use either the raw unprocessed coconut wastes or dry them in the open sun for a number of days, it was essential to study the moisture content over time in order to understand its effects when coconut wastes are utilized as fuel for domestic cooking in fuel-constraint and energy-poor communities. Properly seasoned firewood has a moisture content below 20% [30]. Now, if we assume this measure for coconut biomass, then we can infer that to use properly seasoned coconut husks and shells with moisture content below 20%, it is likely to take 9 to 18 sun drying days to achieve moisture contents of 10% to 20%.

Figure 8 shows the graphs of carbon monoxide (CO) and moisture content of the hybrid, and local coconut wastes. CO concentrations for coconut wastes sun-dried for 3 days were 7.9 ppm for the local coconut wastes and 12.1 ppm for the hybrid coconut wastes. The values reduced from 7.9 to 7.1 ppm and 12.1 to 10.1 ppm over the 3–18 drying days, resulting in a steady reduction in CO concentration of 10–17% for the studied varieties. The CO concentrations generally decreased with decreasing moisture content over the drying period for both varieties. The smoke produced when burning the husks and shells that were being dried gradually changed from thick white to light smoke in 3 to 15 days. This is an indication of the fact that there was a decreasing amount of volatile gases including water vapour that resulted in the change in the concentration and colour of the smoke (see Figure 5).

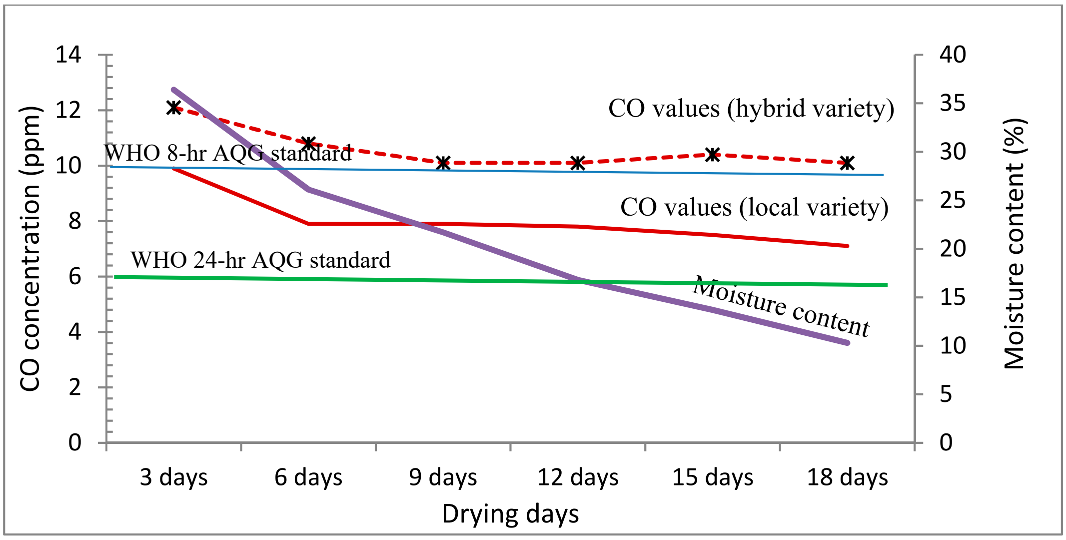

Figure 8. Graphs of CO and moisture content of the hybrid and local coconut wastes.

From the graphs in Figure 8, the CO emissions measured were higher than the World Health Organisation (WHO) indoor air quality guideline (AQG) values at 25 °C, 1 atmosphere. Some suggested tips that are applicable to typical indoor exposure are as follows: 10 mg/m^3 (8.73 ppm) for 8 h (average concentration, low to moderate exercise); and 7 mg/m^3 (6.11 ppm) for 24 h (average concentration, with the assumption that during the exposure people are not sleeping and alert without doing any exercise [32]. However, according to US EPA, outdoor maximum levels should be 35 ppm (1 h averaging) and 9 ppm (8 h averaging), while WHO limits CO concentrations of 90 ppm to 10 ppm based on exposure time of 15 min to 8 h respectively [33].

Overall, the observation is that the burning of fresh unprocessed biomass materials with high moisture levels such as fresh coconut wastes that are used for domestic cooking and other applications are likely to produce higher concentrations of carbon monoxide than charred biomass materials with relatively low moisture content. High moisture levels of fresh biomass materials do not only result in high CO emissions, but also affect the calorific value of the materials.

After sun-drying the coconut waste from 3 to 18 days, data on particulate matter ($PM_{2.5}$) emissions measured are presented in Figure 9. From the graphs, the hybrid coconut wastes showed higher $PM_{2.5}$ values of min = 994 ug/m^3 and max =1 425 ug/m^3 than the local coconut wastes with $PM_{2.5}$ values of min = 933 ug/m^3 and max = 1169 ug/m^3. Comparing the values to [34,35] air quality guidelines (AQG) of $PM_{2.5}$ = 10 µg/m^3 annual mean and 25µg/m^3 24 h mean, it is obvious that the $PM_{2.5}$ from study results were relatively high. The implication is that people who use raw unprocessed waste coconut husks and shells as fuel are under the risks of the adverse effects of $PM_{2.5}$ emissions as a result of the combustion method and conditions. Household combustion methods of biomass are of low energy conversion efficiency and therefore result in high pollutant emissions [36].

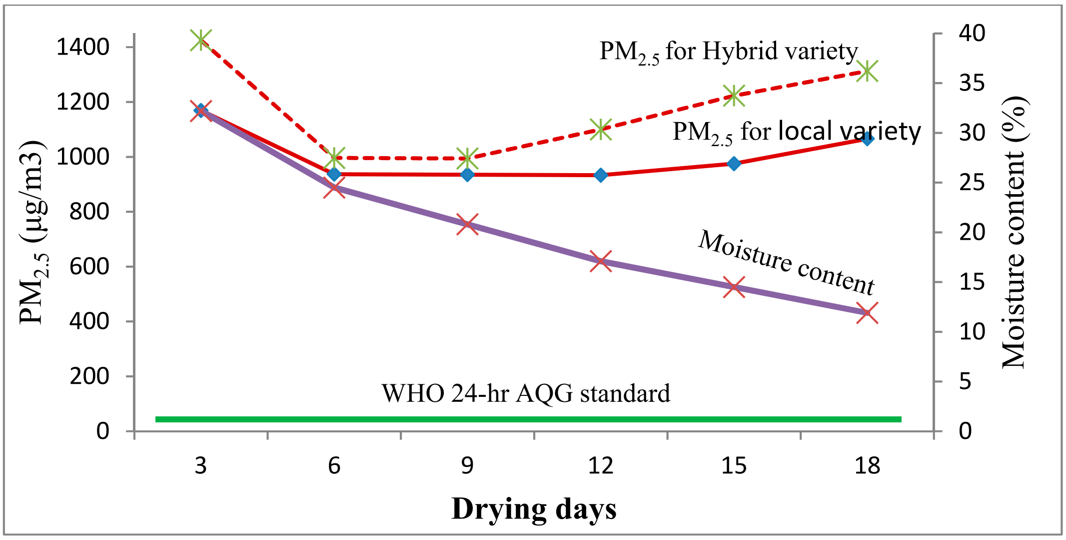

Figure 9. Graphs of PM and moisture content of the hybrid and local coconut wastes.

4. Conclusions and Recommendations

This study assessed the waste proportions, caloric values, and pollutant emissions from the burning of raw uncharred and charred coconut wastes in Ghana.

The results indicate that 62–65% of the whole coconut fruit can be generated as wastes in the form of husks and shells. This amount constitutes a potential bioenergy resource that can be considered as an alternative to firewood and hence can be used as fuel for small-scale electricity production, industrial heating, cooking and household applications.

In this study, the calorific values of the raw uncharred and charred coconut wastes were determined. The average calorific value of the charred coconut wastes was 42% more than that of the uncharred coconut wastes. The moisture content of the raw uncharred coconut wastes might have influenced the relatively low calorific value. The implication is that with relatively high calorific value, charred coconut wastes can be considered to be a better fuel than the raw uncharred coconut wastes that are being burned as domestic fuel, particularly in energy-poor households.

With regard to smoke emissions, the study found that as water evaporated gradually from the raw uncharred coconut wastes during the combustion process, CO emissions generally decreased to a level considered to be within the WHO AQG for 8 h, even though it was above the WHO AQG for 24 h. However, $PM_{2.5}$ pollutant emissions did not meet the WHO 24 h indoor air quality guidelines value at 25 °C, 1 atm. This suggests that charred coconut wastes would likely produce less CO pollutant emissions than the raw uncharred coconut wastes. To effectively utilise coconut wastes as a bioenergy resource for biochar briquette fuel, there is the need to produce biochar for briquettes in a controlled system to maximise the calorific value and minimise smoke emissions.

Author Contributions: Conceptualization, G.Y.O., D.Y.A. and E.M.; Survey, experiments, and data gathering, D.Y.A., G.Y.O. and E.M.; Scientific content and structure—G.Y.O., D.Y.A., E.M. and R.O. Literature review—D.Y.A., G.Y.O. and R.O. Initial draft review—G.Y.O., D.Y.A., R.O., C.K.K.S. and E.A.A. Second draft review and content fine-tuning—G.Y.O., R.O., C.K.K.S., E.A.A. and E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Laboratory equipment used for testing and measurements was financed by UNDP Ghana and supported by the USAID/MIT D-Lab International Development Innovation Network (IDIN) programme. The authors are thankful to the staff of the Cookstove Testing and Expertise Laboratory (C-Lab) of the Technology Consultancy Centre, KNUST for the experimental setup, testing, and data generation that made it possible for us to write the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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