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Potential of Bioenergy in Rural Ghana

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Abstract: Crop residues are common in rural Ghana due to the predominant role agriculture plays in livelihood activities in these communities. In this paper we investigate the prospects of exploiting agricultural crop residues for rural development in Ghana through bioenergy schemes. A theoretical energy potential of 623.84 PJ per year, which is equivalent to 19,781 MW was estimated using crop production data from the Food and Agricultural Organization of the United Nations and residue-to-product ratios. Ghana has a total installed generation capacity of 4577 MW which is four times less the energy potential of crop residues in the country. Cocoa pod husks were identified as important biomass resources for energy generation as they are currently wasted. To further assess the energy potential of cocoa pod husks, different cocoa pod husks samples were collected across the six cocoa growing regions in Ghana and thermo-chemically characterised using proximate and ultimate analysis. The low levels of nitrogen and sulphur observed, together with the high heating value, suggest that cocoa pod husks and for that matter crop residues are eco-friendly feedstock that can be used to power rural communities in Ghana.

Keywords: biomass; bioenergy; agricultural crop residues; conversion technology; cocoa pod husk; thermochemical analysis

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1. Introduction

Agriculture is a predominant livelihood activity for Ghanaians in general but rural communities in particular. One-fifth of Ghana's Gross Domestic Product (GDP) is accredited to the agricultural sector, which employs almost half of the labour pool and provides a livelihood for most of the underprivileged households in Ghana [1]. Millions of tonnes of agricultural residues are produced in Ghana every year. While these agricultural residues are important assets that can be exploited for power production, they are largely under-utilised as current energy uses for them are limited to cooking and heating through inefficient applications. Poverty rate in Ghana has reduced substantially from 56.5% in 1992 to 24.2%; however, high incidence of poverty still lingers in rural areas where the poverty rate is nearly 4 times as high as urban poverty [2]. In spite of the rampant rural-urban migration, most of the poorest households in Ghana will remain rural for years. Since rural poverty far exceeds the national average, and the majority of rural households in Ghana derive their livelihoods from agriculture, it is essential that poverty eradication is linked to agriculture [3].

Ghana heavily depends on wood fuel (charcoal and firewood) as the main cooking fuel for households without modern energy resources. Whiles this practice is unsustainable due to health risk, it also puts the country's declining forest under extreme stress with far-reaching consequences on climate change, crop production and water resources [4,5].

Ghana has subscribed to the United Nations Sustainable Development Goal (UN SDG) number seven which is aimed at ensuring universal access to affordable, reliable and modern energy services to all by 2030. In order for Ghana to achieve its target of universal access by all, biomass energy should be promoted for use in off-grid areas where feedstock are in large abundance [6]. The main problem faced by Ghana's energy sector is the irregular electricity supply which undermines businesses and households. Although electricity access rate in Ghana is 84%, the bulk of the electricity is consumed in cities and urban areas and only less than 30% of rural households are grid-connected [7]. The influx of thermal and hydro sources in Ghana's electricity generation mix means that renewable generation sources only contribute a microscopic 0.2% [8]. By Ghana's current electrification standard, over 50% of rural households that are not grid-connected live in communities that have populations of less than 500. Whiles most rural communities are far away from the national grid, an extension of the grid to these communities is uneconomical as it leads to transmission and distribution losses [9,10]. Although the costs of solar photovoltaics (PV) have gone down significantly, they are only competitive for commercial electricity consumers who use over 600 kWh of electricity a month. Residential consumers would need financial support of up to 90% of its total cost in order to compete with grid electricity [11]. Rural communities are thus major candidates for mini-grid biomass systems due to their remote locations and the enormous proportions of biomass they produce.

There are various energy conversion technologies for converting agricultural crop residues into useful energy forms. Electricity, heat and other energy carriers could be produced from agricultural crop residues through anaerobic digestion, gasification, direct combustion, pyrolysis and fermentation. The suitability of a particular biomass energy conversion technology is dependent on the end-use application (the manner in which the energy is needed) and the biomass feedstock available (type, quantity and characteristics) [12,13]. Anaerobic digestion is used for recycling and treating organic wastes with high moisture content and waste waters [14,15]. About 400 biogas digesters have been built in Ghana, predominantly using the fixed-dome, floating drum and puxin technologies [16]. Nonetheless, the number of biogas systems in Ghana is low compared to the estimated capacity of the country. According to the Netherlands Development Organization (SNV), the technical potential of biogas in Ghana far exceeds 278,000 digesters and has the capability of boosting agriculture by 25% [17,18]. Biogas for electricity generation is competitive with diesel plants if the feedstock is obtained at little or no cost to the site [19]. The Ghana Oil Palm Development Company currently has a 2000 m^3 biogas plant that treats oil palm waste while HPW Fresh and Dry Ltd. has a biogas plant that feeds on fruit processing waste [20].

Biogas production from crop residues can serve a dual function of managing waste and producing power. Even though biogas for cooking could reduce indoor pollution associated with respiratory diseases and eye infections caused by exposure to smoke in the use of wood fuel, inappropriate ventilation and exhaust systems could still cause significant pollution. Since rural households use cheap low quality fuels for cooking, a switch to biogas system may be an expensive investment, as a compatible stove may be needed. Nonetheless, local artisans can be trained to produce compatible biogas stoves at a competitive cost which could provide further employment opportunities. Fermentation of biomass feedstock for ethanol production is a useful way of converting sugars, starches and cellulose materials. While sugars are directly convertible into ethanol, starches must first be broken down to fermentable sugars by the action of enzymes whereas cellulose must also be converted into sugars by the action of mineral acids before enzymes from microorganisms can readily ferment them to ethanol. Fermentation of starch is complex compared to sugar because starch must first be converted into sugar by hydrolysis before ethanol production. This requires high-temperature cooking (140–180 °C) to raise starch saccharification efficiency and increase ethanol yield by sterilising the harmful microbes [21].

Effective pretreatment of biomass feedstock is essential to provide a broad surface area for enzymes to act, improve the feedstock solubility and promote feedstock utilisation to ensure high biofuel yield [22]. Pyrolysis of biomass produces mainly fuel gas, bio-oil and char, which can undergo further processing for power generation [23,24]. Carbon monoxide, hydrogen, methane and other hydrocarbons are also produced from pyrolysis; however, their quantities depend on the biomass type, rate of heating, operational temperature and residence time [25]. Unlike combustion and gasification, pyrolysis produces only a small amount of gas and hence does not require a gas cleaning sub-system [26]. Direct combustion is applicable to any type of biomass; however, combustion is practically feasible for pre-dried feedstock or feedstock with moisture content less than 50% [12]. A modern biomass combustion plant is able to achieve as much as 90% efficiency with minimal environmental effects although significant amounts of pollutants such as carbon monoxide (CO), Soot and Polycyclic aromatic hydrocarbons (PAHs) can be produced when incomplete combustion occurs [27]. Woody biomass is preferred to non-woody biomass for combustion due to its relatively low ash and nitrogen content; nonetheless, non-woody biomass could be used in larger combustion plants with effective flue gas cleaning sub-system to reduce toxic emissions [28]. Biomass gasification is more attractive than ethanol production or anaerobic digestion because it converts the entire carbon content of biomass material into fuel. Due to the diverse range of acceptable reaction conditions for gasifiers, the scale of operation (small, large, centralised, decentralised), feedstock flexibility (size and characteristics) and sensitivity to the amount of ash and tar yield, must be considered before choosing a gasifier [29,30].

While wood fuel (firewood and charcoal) is the most predominantly used biomass in Ghana and the inefficient application for cooking and heating in rural households remains a threat to Ghana's dwindling forest reserves, it is imperative that different sources of biomass that have less impact on forest reserves are exploited. Agricultural crop residues which are in enormous abundance could be utilised to provide modern sources of energy including electricity in rural Ghana. Since electricity coverage in rural Ghana is very low and poverty rate is high, this paper seeks to bridge the gap between rural and urban poverty using agricultural crop residues to expand electricity access to rural households. The paper estimates the energy potential of 15 crop residues in Ghana and further discusses the experimental results of cocoa pod husks from the six administrative cocoa growing regions in Ghana. The analysis of cocoa pod husk and the determination of the higher heating values help to demonstrate the energy potential available in each region.

2. Agricultural Crop Residues

Agriculture is the most important industry in Ghana and major crops like cassava, cocoa, maise, palm oil fruit, yam, plantain, rice, millet, coconut, groundnut, sorghum, sugarcane, coffee, cocoyam and sweet potato are all produced during the farming season. These crops produce tonnes of residues during harvesting and processing. There are two main categories of agricultural crop residues, namely: crop residues and agro-industrial by-products. Crop residues are the materials left on the field after the crops have been harvested while Agro-industrial by-products are derived from crop processing industries [31].

Crop residues produced in Ghana include rice straw, maise/corn stalk and cocoa pod husk, while corn cob, cocoa husk, coconut shell and husk, rice husk, oil seed cake, oil palm empty fruit bunch (EFB) and sugarcane bagasse are examples of agro-industrial by-products. The harvesting and processing of maise produce major residues such as stalk, cob and husk which can be used for biofuel production. While sweet sorghum produces a sugar-rich stalk for ethanol production, coconut produces husk and shells and sugarcane produces bagasse which are all suitable for the production of biochar. Oil palm produces empty fruit bunches (EFB), shells and fronds which compete as fertiliser and as feedstock for activated carbon and mulching. Coffee husk, which is a residue from coffee processing, can be used in biochar production, as fertiliser or for electricity production [31,32]. Rice husk and straw are also a potential feedstock for biofuel generation that are virtually unutilised in Ghana. Traditionally, crop residues are burnt on the farms as a pest control mechanism whiles others are used as substitutes for wood fuel. Cocoa production and processing produce cocoa pod husks (CPH) which at present are left on the farms to decompose.

The trunks, leaves, stems, straws, stalks and peels of cassava, yam and plantain are also potential bioenergy feedstock that have not yet been fully exploited. Effective quantification of agricultural crop residues and assessment of their energy potential has not received much attention in Ghana, which hinders the sustainable use and management of this resource. Quantitative estimation of agricultural crop residues is generally based on statistical data, and it helps in judicious management of the available resources [33].

Table 1 projects the energy potential of crop residues generated in Ghana in 2017. A residue-to-product ratio (RPR) based on [34] and annual crop production data from the Food and Agricultural Organization of the United Nations was used for the estimation. Approximately 50 million tonnes of crop residues were produced, which is equivalent to a theoretical potential of 623.84 PJ of energy. Theoretical potential presumes that all the residues used in the calculation are available. Practically, not all generated residues are available for energy production due to a number of reasons. Firstly, some of the residues may be left on the farmland intentionally to mulch and also for re-fertilisation. Secondly, there may be practical difficulties in collecting some field residues due to bad road conditions notably when it comes to peasants and their farm locations.

Table 1. Crop residues and their energy potential.

Crop	Annual Production (10^3 t) [a]	Residue Type	Residue to Product Ratio (RPR) [b]	Total Residue Produced (10^3 t)	Lower Heating Value (MJ/kg) [c]	Residues Energy Potential (PJ)
Cassava	18,471	Stem/Stalk	1.24	22,904.04	17.50	400.82
Cocoa, beans	884	Husk	1.00	884	15.48	13.68
Coconut	384	Husk/Shell	0.54	207.36	14.71	3.05
Coffee, green	0.73	Husk	2.1	1.53	12.56	0.02
Groundnut	420	Husk/Shell/Straw	2.08	873.6	17.50	15.29
Maize	1965	Stalk/Husk/Cob	0.63	1237.95	18.08	22.38
Millet	167	Stalk	5.53	923.51	15.51	14.32
Oil palm fruit	2470	EFB/Kernel Shell/Fibre	0.44	1086.80	15.23	16.55
Plantain	4051	Trunk/Leaves	0.50	2025.50	15.48	31.35
Rice, paddy	721	Straw/Husk	3.28	2364.88	14.30	33.82
Sorghum	230	Stalk	4.75	1092.50	17.00	18.57
Sugarcane	152	Bagasse	0.2	30.4	13.38	0.41
Sweet potato	146	Straw	0.50	73	10.61	0.77
Cocoyam	1200	Straw	0.50	600	17.70	10.62
Yam	7953	Straw	0.50	3976.50	10.61	42.19

[a] Annual crop production in 2017 [35]; [b] Residue to product ratio (RPR) based on [34]; [c] Lower heating value based on [27,34,35].

In other words, it is not possible for all residues generated to be collected for energy production due to technical hindrances and competing uses such as animal feed, fertiliser and cooking. Utilisation of all these residues in bioenergy production can potentially have adverse impacts on soil fertility [30]. Hence, it is expedient to assume recoverable percentage in order to get the technical potential of generated residues. At 60% recoverable rate of crop residues, Ghana has a technical energy potential of 374.30 PJ per year, which is tantamount to 11,901 MW. There is a huge difference in estimated energy potentials of crop residues between our paper and that of Duku et al. [31] and Mohammed et al. [9] who estimated 75.20 PJ and 91.60 PJ, respectively. The differences in estimated potential can be attributed to the number of crops considered. Whiles the current paper considered 15 crops, the previous research only considered 8–9 crops and left out staple Ghanaian food crops like cassava and yam, which have enormous energy potentials as per Table 1. The RPR values used for the calculation of the total residue generated and energy potential are widely used across sub-Saharan Africa.

According to recent government report, the country has increased its installed generation capacity from 4132 MW in 2016 to 4577 MW [36]. While the increase is welcomed as a step in the right direction, it is reasonably low considering Ghana's energy potential from crop residue is 623.84 PJ per year (19,781 MW).

Figure 1 presents cultivated areas and energy potential of major crops in Ghana while Figure 2 shows trends in land cultivation over the last decade. Cocoa is the most predominantly grown crop in Ghana over the last decade. The predominance of cocoa in terms of cultivation makes it more accessible compared to other crops. Moreover, cocoa is a major foreign exchange earner for Ghana, and its role in the economic development of the country is incomparable. The cocoa sector provides a livelihood for about 800,000 families, which is equivalent to approximately 13% of the country's total population [37]. As the single most important export crop in Ghana, it is expected that it translates into the lives of cocoa farmers as a motivation. However, cocoa farmers who are popularly rural-dwellers continue to live despicable lives without access to electricity and other social services. Admittedly, other crops like cassava, yam and rice possess higher energy potential than cocoa; however, they are not controlled crops and hence can be difficult to quantify their actual availability. The cocoa industry on the other hand is fully controlled by the government of Ghana who has a monopoly over the purchase and export of the cocoa beans. The Ghana Cocoa Board by virtue of its mandate by the government of Ghana monitors and regulates the operations of the cocoa industry in Ghana [38]. As cocoa is a controlled commodity and the main export crop of Ghana, it is easier and convenient to quantify the availability of its residue compared to other uncontrolled crops. In the context of bioenergy production, collection, storage and transportation of biomass are basic operations that characterize the overall design of the supply chain system. For a reliable, long-term and economically sound feedstock supply, the establishment of viable co-operative groups among local farmers is essential [2]. In addition, the scattered geographical distribution of biomass necessitates that a closed type warehouse is located next to the bioenergy plant where feedstock can both be dried and stored to ensure constant supply for the bioenergy plant [3]. Due to the cost of transport, end users of the bioenergy or the collection facility need to be located centrally to boost long-term financial viability.

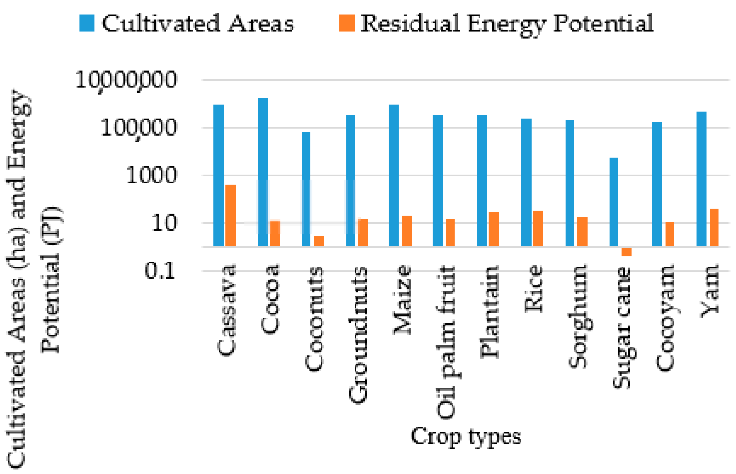

Figure 1. Cultivated areas and energy potential of major crops in Ghana. Data source: [35] and Table 1.

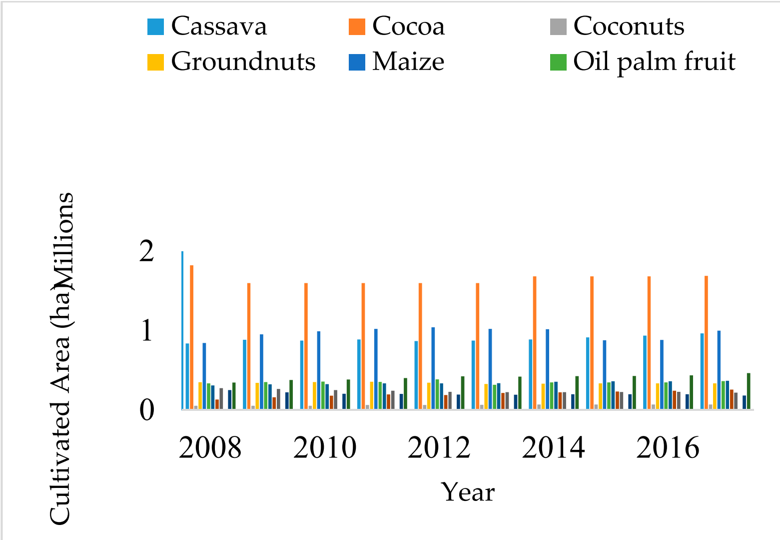

Figure 2. The pattern of cultivation for major crops in the last decade. Data source: [35].

Our feasibility study shows that over 800,000 tonnes of CPH are available every year and yet have not been sufficiently exploited [39]. It is therefore important that CPH and cocoa-growing communities are considered as a priority for any future decentralised bioenergy project. An evaluation of CPH for its thermal and chemical properties could provide a good scientific basis for a prospective integrated bio-rural electric power generation system.

3. Cocoa Pod Husk as a Renewable Source of Energy

In Ghana, cocoa is mainly cultivated for the beans which are used in the production of chocolate, cocoa powder and other similar beverages while the rest of the fruit are discarded. The beans make up about 33% of the size of the fruit, signifying that the cocoa pod husks (CPH) which are usually discarded make up about 67–76% of the fruit by weight [40,41]. By extension, ten tonnes of CPH are produced for every tonne of dry cocoa beans. This poses a genuine disposal dilemma, although the resource is under-exploited. After harvesting the cocoa fruits, the cocoa pod husks which account for up to 76% of the cocoa fruit are left in large piles on the farms to decompose, thereby causing foul odour, soil contamination and black pod rot disease [42]. A total of 20% to 30% of annual yield loss across the globe is caused by black pod rot, with some farmers experiencing up to 90% loss yearly [43]. Ghana produces about 858,720 tonnes of CPH annually, which is equivalent to 19% of the total global production [41]. This abundant potential biomass energy resource is wasted every year as it has not been adequately exploited.

Whiles CPH conversion to useful products such as antioxidants can promote economic development among farmers; it can also boost cocoa production [43]. Recent studies conducted by Syamsiro et al. [44], Tsai et al. [45] and Adjin-Tetteh et al. [46] reveal that CPH has a relatively high heating value of 17–18 MJ/kg. According to Adjin-Tetteh et al. [46], factors such as cultivation methods, environmental influences and differences in soil contaminations can impact greatly on heating value of CPH. Given the high abundance of CPH in Ghana and the fact that cocoa is the major export of the country, any attempt to use CPH for energy generation will not only help to reduce power crisis but also boost cocoa production in Ghana. CPH can be exploited in pellet and briquette production which can serve as an alternative source of cooking fuel to firewood and also for electricity generation [44].

3.1. Thermochemical Characterisation of Cocoa Pod Husk

CPH samples were obtained from the six cocoa growing administrative regions of Ghana: Ashanti, Western, Eastern, Brong-Ahafo, Central and Volta regions. Two common types of CPH samples (Amelonado—the most extensively planted cocoa in Ghana and hybrid—a new high yielding variety) were collected from each of the six regions. The samples were first dried in an oven to achieve a moisture content of about 15% before being crushed using a hammer to obtain a feed size of about 10 millimetres (mm). Retsch Planetary Ball Mill PM 100 was used to grind down the crushed CPH samples at 350 rpm for 3 min and sieved with a vibration pulveriser until a particle size of 212 μm was obtained. The processed samples were stored in airtight plastic sample bottles and labelled for further characterisation experiments (see Figure 3).

Figure 3. (**a**) Retsch Planetary Ball Mill PM 100. (**b**) Retsch Electromagnetic Shaker AS 200. (**c**) Sieve containing milled CPH. (**d**) Packaged CPH sample after milling.

3.1.1. Ultimate Analysis

Basic elemental composition of CPH samples were determined using ultimate analysis. Carbon, hydrogen and nitrogen contents were determined using a LECO CHN628 elemental analyser and sulphur was determined using the LECO CHN628 elemental analyser with a sulphur add-on module (628-S). Oxygen contents were determined by difference. 2, 5-Bis (5-tert-butyl-2-benzo-oxazol-2-yl) thiophene (BBOT) standard was used as the reference for carbon, hydrogen and nitrogen determination and Ref.coal was used as the reference for sulphur determination. All experiments were carried out at least twice to ensure repeatability. A third sample was used if results differed more than 5%.

3.1.2. Proximate Analysis

Proximate analysis was performed on the CPH samples for the determination of moisture, volatile, ash and fixed carbon contents using two methods: thermogravimetric analysis (TGA) and ASTM standards (ASTM E871–82 for moisture, ASTM E1755-01 for ash and ASTM E872-82 for volatile matter). TA Instrument Q500 analyser was employed to carry out TGA using the methodology described by Saldarriaga et al. [47].

Each CPH sample (10 ± 0.5 mg) was placed in a circular platinum crucible 2 mm in height and 5 mm in diameter and inserted into the TGA Q500. The system was initially purged with N_2 for 20 min prior to the beginning of the tests. Once purging had been completed, the sample was raised in temperature from ambient to 110 °C at a constant rate of 10 °C/min under N_2 atmosphere at a volume flow of 50 mL/min. Once the temperature reached 110 °C, the temperature was kept isothermal for 10 min to obtain the change in weight associated with moisture loss. After 10 min, the temperature was increased at a constant rate of 20 °C/min under a N_2 atmosphere until the sample temperature reached 575 °C. Once at 575 °C, the sample was kept isothermal for 20 min to determine the change in weight associated with the loss of volatiles. Following the loss of volatiles, air at a constant flow of 50 mL/min was introduced to the sample for a period of 20 min, so that the char remaining in the sample was oxidised, thus revealing the fixed carbon content. The residue that remained after oxidation was the ash. The proximate analysis experiments were carried out at least twice to ensure repeatability. A third sample was used if results differed more than 5%. Since the analysis method used is ASTM, data in scientific literature that used ISO analysis method may differ from the results of this study.

3.1.3. Assumptions and Potential Limitations of the Analysis

The analysis is limited to the use of CPH as feedstock for electricity generation in cocoa growing communities in Ghana. It is assumed that cocoa growing communities within each region have similar vegetation and hence the regional energy potential is reflective of all other communities.

3.1.4. Results of Cocoa Pod Husk Characterisation

Table 2 shows the basic elemental composition of the twelve CPH samples under investigation. It is evident that all CPH samples studied have homogenous levels of Carbon, Hydrogen and Oxygen. The carbon and oxygen contents were much higher compared to hydrogen. Higher proportions of oxygen in biomass feedstock reduces the heating value of the fuel as it increases the emission of carbon dioxide (CO_2) and water (H_2O) formation. Sulphur and nitrogen contents of all CPH samples were similar and very low. The nitrogen content was found to be 0.77 ± 0.000%–1.63 ± 0.018% as compared to 0.5–3% for coal whereas the sulphur content range was 0.08 ± 0.018%–0.31 ± 0.02% compared to 2–4% for coal. The trace amounts of nitrogen and sulphur observed in the CPH samples allude to the eco-friendly nature of cocoa pod husks.

The atomic ratios H/C and O/C in Table 2 were derived from the elemental analysis. A high H/C ratio means that there is a higher content of hydrogen in the fuel. The higher the H/C ratio, the higher the heating value of the feedstock, since hydrogen has the highest heating value among other fuels. The O/C ratios of the CPH samples are higher than the H/C ratios due to the higher oxygen contents. There is, therefore, a higher possibility of producing more carbon monoxide (CO) than methane (CH4) and hydrogen gas (H_2) in a thermochemical conversion to syngas.

Table 3 lists the moisture, volatile matter, fixed carbon and ash contents of the CPH samples. Apart from two samples from Eastern and Volta regions of Ghana that recorded moisture contents of 10.06 ± 0.47% and 10.35 ± 0.47%, the moisture content of all other CPH samples were less than 10% with the lowest being 6.67 ± 0.05% from the Brong-Ahafo region. The moisture contents reported in Table 3 are lower than those reported in literature; however, the differences can be attributed to the variations in soil composition, cultivation methods and climatic and storage conditions. Moisture content is critical in choosing a biomass conversion technology as it can affect the amount of energy that can be generated from a feedstock. Feedstock with lower moisture content is preferred for thermochemical conversion, whereas higher moisture feedstock is great for biochemical conversion. The low levels of moisture observed in the CPH samples under investigation make them suitable feedstock for thermochemical conversion technologies such as gasification.

Table 2. Ultimate analysis, wt % (dry basis) of cocoa pod husk (CPH) samples from Ghana.

Ultimate Analysis, wt % (Dry Basis)									
Designation	**Area**	**Type**	**C**	**H**	**N**	**S**	**O**	**H/C**	**O/C**
CPH-A1	Volta	Amelonado	41.53	5.81	0.92	0.13	51.61	0.14	1.24
	Standard error		0.072	0.001	0.002	0	NA		
CPH-A2	Volta	Hybrid	40.38	5.89	1.02	0.24	52.47	0.15	1.30
	Standard error		0.081	0.039	0.012	0.05	NA		
CPH-B1	Eastern	Amelonado	39.82	6.11	1.27	0.16	52.63	0.15	1.32
	Standard error		0.003	0.018	0.004	0.004	NA		
CPH-B2	Eastern	Hybrid	41.50	5.86	0.84	0.29	51.81	0.14	1.25
	Standard error		0.0156	0.001	0.01	0.03	NA		
CPH-C1	Western	Amelonado	40.47	5.87	1.63	0.31	51.72	0.15	1.28
	Standard error		0.016	0.02	0.018	0.02	NA		
CPH-C2	Western	Hybrid	42.33	5.98	1.63	0.13	49.94	0.14	1.18
	Standard error		0.022	0.01	0.018	0.015	NA		
CPH-D1	Central	Amelonado	42.78	5.83	1.31	0.14	49.94	0.14	1.17
	Standard error		0.073	0.012	0.01	0.003	NA		
CPH-D2	Central	Hybrid	41.47	5.78	1.14	0.16	51.45	0.14	1.24
	Standard error		0.086	0.01	0.024	0.005	NA		
CPH-E1	Ashanti	Amelonado	43.81	5.79	0.77	0.12	49.52	0.13	1.13
	Standard error		0.03	0.12	0	0	NA		
CPH-E2	Ashanti	Hybrid	42.32	5.76	1.42	0.08	50.43	0.14	1.19
	Standard error		0.16	0.01	0.05	0.01	NA		
CPH-F1	Brong-Ahafo	Amelonado	41.22	5.73	1.13	0.08	51.85	0.14	1.26
	Standard error		0.066	0.105	0.013	0.018	NA		
CPH-F2	Brong-Ahafo	Hybrid	41.45	5.86	1.48	0.12	51.09	0.14	1.23
	Standard error		0.092	0.082	0.01	0.013	NA		

Table 3. Proximate analysis (wt %) of CPH samples from Ghana.

Designation	Area	Type	Moisture	ASH	VM	FC	VM/FC
CPH-A1	Volta	Amelonado	10.35	14	65.24	20.76	3.14
	Standard error		0.47	1.38	1.63	2.43	
CPH-A2	Volta	Hybrid	9.75	13.94	69.05	17.01	4.06
	Standard error		0.46	1.47	1.54	0.33	
CPH-B1	Eastern	Amelonado	9.43	9.45	68.96	21.59	3.19
	Standard error		0.52	0.64	0.23	0.16	
CPH-B2	Eastern	Hybrid	10.06	12.43	64.48	23.09	2.79
	Standard error		0.47	0.54	2.17	0.31	
CPH-C1	Western	Amelonado	7.81	11.84	70.56	17.6	4.01
	Standard error		0.36	0.04	1.21	0.17	
CPH-C2	Western	Hybrid	8.81	11.24	69.23	19.53	3.54
	Standard error		0.44	0.04	0.87	1.86	
CPH-D1	Central	Amelonado	8.65	10.09	66.39	23.52	2.82
	Standard error		0.45	1.78	0.68	1.03	
CPH-D2	Central	Hybrid	9.2	14	66.18	19.82	3.34
	Standard error		0.65	0.12	1.03	0.85	
CPH-E1	Ashanti	Amelonado	7.62	7.87	67.30	24.83	2.71
	Standard error		0.53	0.38	0.28	0.65	
CPH-E2	Ashanti	Hybrid	8.51	9.98	68.65	21.37	3.21
	Standard error		0.61	0.59	1.4	0.82	
CPH-F1	Brong-Ahafo	Amelonado	7.76	12.1	69.96	17.94	3.90
	Standard error		0.32	0.41	1.41	0.79	
CPH-F2	Brong-Ahafo	Hybrid	6.67	11.29	72.44	16.27	4.45
	Standard error		0.05	0.85	0.52	0.28	

The volatile matter content of the CPH samples were reasonably high and comparable to reported literature value such as [4–6]. The higher the volatile matter in biomass feedstock, the faster the ignition potential [7]. Hybrid species from Brong-Ahafo region showed the highest volatile matter of 72.44 ± 0.52% in comparison to the lowest volatile matter of 64.48 ± 2.17% observed for hybrid species from the Eastern region. The fixed carbon content of the CPH samples were between 16.27 ± 0.28% and 24.83 ± 0.65%. The higher the fixed carbon content of a biomass feedstock, the higher the heating value [8]. This is consistent with Table 4 as the sample that recorded the highest fixed carbon content, also recorded the highest higher heating value (19.21 MJ/kg). The highest fixed carbon was recorded by Amelonado species from the Ashanti region (24.83 ± 0.65%).

Table 4. Higher heating values of CPH by ultimate and proximate analysis.

Designation	Area	Type	HHV(MJ/kg) UA	HHV(MJ/kg) PA
CPH-A1	Volta	Amelonado	15.71	17.4
CPH-A2	Volta	Hybrid	15.32	16.67
CPH-B1	Eastern	Amelonado	15.46	18.31
CPH-B2	Eastern	Hybrid	15.78	18.12
CPH-C1	Western	Amelonado	15.46	17.13
CPH-C2	Western	Hybrid	16.41	17.61
CPH-D1	Central	Amelonado	16.42	18.59
CPH-D2	Central	Hybrid	15.67	17.22
CPH-E1	Ashanti	Amelonado	16.82	19.21
CPH-E2	Ashanti	Hybrid	16.12	18.18
CPH-F1	Brong-Ahafo	Amelonado	15.51	17.16
CPH-F2	Brong-Ahafo	Hybrid	15.84	16.96

Higher ash content invariably affects reactor design, leading to blocking problems and also reduces the higher heating value [8]. Power plant maintenance costs could also be increased by high ash content due to increased wear and tear it causes on machinery. However, ash is rich in lime, potassium and other trace minerals and can be utilised as organic fertiliser to improve soil fertility. Ash is also useful in construction industries for improving the durability of concrete. The ash contents of CPH samples measured from 7.87 ± 0.38% to 14 ± 1.38%. The lowest ash content was recorded by the Amelonado species from Ashanti region. Ash contents compared favourably to reported values in literature such as [8,9]. Ash contents less than 10% can be classified as low whereas those less than 25% can be classified as medium [48]. Hence, the CPH samples under investigation can generally be classed as medium ash-content feedstock. The ash content of the CPH samples studied could be a potential drawback that needs to be minimized. High ash content can significantly minimize the energy output from the CPH during thermochemical conversion. Contamination from soil, rocks, metals, plastics, etc. could have caused the high ash content [10]. The ash content of CPH can be highly influenced by the soil type in which it was grown. Crops grown in clay soils are known to produce high ash levels than crops grown in sandy soils [11]. Nutrient deficiency and toxicity could be part of the reasons why some CPH samples recorded higher ash content than the others. Thus, optimum nutrient levels in soil could reduce the ash content of the CPH samples and influence the quality of the CPH fuel. In order to mitigate ash-related issues during CPH conversion, a number of additives can be added via the following means: capturing problematic ash species through chemical adsorption and reactions; physical adsorption and elutriation of troublesome ash species from the gasifier; enhancing the inert compounds in ash residue by increasing CPH ash melting temperature; and finally by using the dilution and powdering effects from the additives to restrain the CPH ash sintering [12].

Based on the data from the proximate analysis, the higher heating value (HHV) was calculated using Equation (1) as:

$$\text{HHV (MJ/kg)} = 0.3536\ \text{FC} + 0.1559\ \text{VM} - 0.0078\ \text{Ash} \quad (1)$$

where FC, VM and Ash are fixed carbon, volatile matter and ash content obtained from the proximate analysis on dry basis respectively (ASH + VM + FC = 100%).

Equation (2) was also used to calculate the higher heating value based on data from the ultimate analysis, thus

$$\text{HHV (MJ/kg)} = 0.3491\text{C} + 1.1783\text{H} + 0.105\text{S} - 0.1034\text{O} - 0.0151\text{N} - 0.0211\text{Ash} \quad (2)$$

where C, H, S, O, N and Ash are percentages of carbon, hydrogen, sulphur, oxygen, nitrogen and ash as determined by ultimate analysis on a dry basis.

Table 4 shows the summary of higher heating values as calculated by ultimate and proximate analysis. The higher heating values predicted by proximate analysis (16.67–19.21 MJ/kg) were higher than those calculated by ultimate analysis (15.32–16.82 MJ/kg). This may be due to the higher oxygen and volatile matter contents of the cocoa pod husks studied.

Figure 4 shows the higher heating values of CPH samples together with the uncertainties in their calculation. Although the higher heating values calculated by the proximate equation were higher than their corresponding values calculated by the ultimate equation, there were comparatively lower prediction errors with the latter. Notwithstanding, the air of uncertainty around both equations was generally minimal and below 5%.

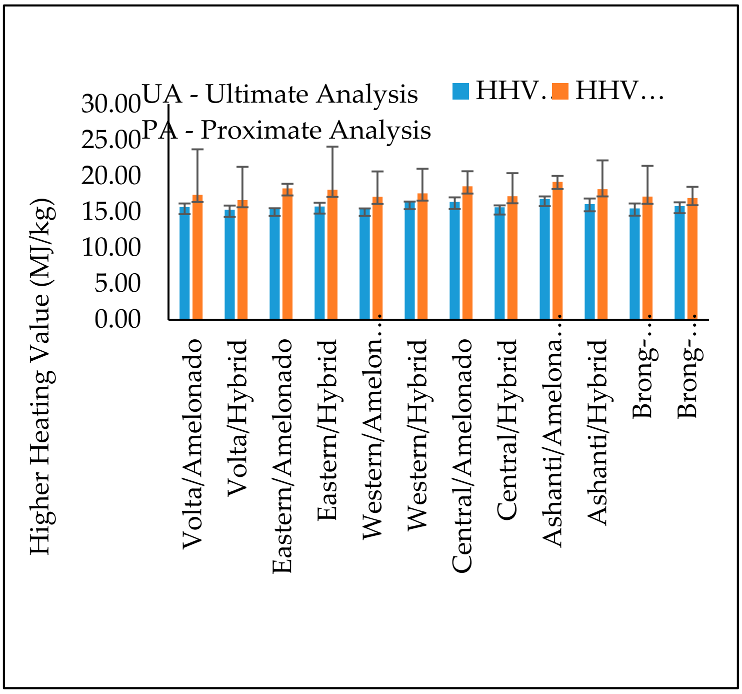

Figure 4. Higher heating values of CPH samples with their absolute errors.

4. Biomass Conversion Technology

One of the objectives of Ghana's Renewable Energy Act, 2011 (Act 832) is to promote the use of renewable energy which includes biomass. However, the use of agricultural crop residue for energy production in Ghana is limited, despite its huge abundance in the country. Biomass such as cocoa pod husk (CPH) can provide a viable renewable energy source for electricity generation especially in local communities close to production areas. CPH is an abundant biomass resource largely available in rural Ghana with enormous quantities of sugar occurring structural polysaccharide-cellulose and hemicelluloses [13].

With over 800,000 tonnes of CPH generated annually in cocoa farms in Ghana, CPH represent an abundantly available energy resource that could be exploited for electricity production to provide economic gains and also environmental solutions for CPH waste disposal problems.

Thermochemical conversion technologies such as combustion, gasification and pyrolysis are appropriate stage processes for CPH conversion due to the low levels of moisture. The high amount of volatile matter observed in the CPH samples suggest that CPH can be used as potential feedstock for combustion, gasification and pyrolysis. The low levels of nitrogen and sulphur in CPH could mean that combustion of CPH and its derived products would be an environmentally friendly exercise. Whiles combustion of CPH would technically be the easiest option; the high ash content (7.87 $\pm$ 0.38% to 14 $\pm$ 1.38%) could potentially be a hindrance. Ash deposition is very critical during biomass combustion as it can reduce burner efficiency due to the agglomeration of the ash particles in the furnace, damage to the burner due to restriction of gas flow and cause maintenance issues such as impulsive shutdowns for cleaning ash deposits [49]. However, operational conditions, regulatory and management systems can be optimised to eliminate excess ash build up [50]. Biomass combustion is a viable power production option in all regions in Ghana especially the rural communities where agricultural crop residues are in enormous abundance.

Pyrolysis of CPH for energy production is also a good option with higher power generating efficiencies at low scales of operation [51,52]. Bio-oils generated from CPH pyrolysis could be burnt directly for heating or converted to electricity.

Gasification is by far the most appropriate technology for converting CPH to electricity. In addition to its ability to utilise low-quality feedstock, it also converts the entire carbon content of the biomass material. Biomass gasification has a varied range of feedstock requirement and could be used to convert CPH into product gas for utilisation in small-to-medium scale decentralised electric power generation system [33]. Since biomass gasification can provide a higher heating value product with better energy capture and lower emissions in comparison to combustion and pyrolysis, it is prudent to use gasification for the conversion of CPH to electricity. For a gasification system, carbon conversion, syngas composition, tars and soot formation and oxidation are important parameters. However, for energy production, it is the nature of the biomass (uniformity, heating value, ash content) together with the local availability of biomass and the end product required (heat, electricity, fuels and chemicals) that makes large-scale implementation of energy production a hectic task [14]. Since CPH is locally available and has moderate amount of ash, gasification of CPH is the most feasible biomass conversion technology for electricity production.

5. Conclusion and Recommendation

In this paper we demonstrated that there is enormous bioenergy potential in agricultural crop residues and a variety of biomass conversion technologies exist to augment their value for rural communities in Ghana. Agriculture crop residues can quadruplicate the total installed generation capacity of the country and bridge the gap in electricity access rate between poor isolated rural communities and urban areas. A mix of biomass conversion technologies could enhance the efficiency in the use of agricultural crop residues with both power and other fuel production emanating simultaneously.

Twelve (12) locally produced cocoa pod husks from the six (6) cocoa-growing regions of Ghana were experimentally investigated for their thermo-chemical properties and energy conversion potential. The results of the study suggest that cocoa pod husk has a higher heating value of 15.32–19.21 MJ/kg which is competitive with firewood, which has heating value of 18 MJ/kg. The volatile matter contents of cocoa pod husk samples studied were reasonably high whiles the moisture contents were low and hence suitable for thermochemical conversion such as combustion, gasification and pyrolysis. Even though combustion, gasification and pyrolysis are appropriate stage procedures, the high ash content (11.52% on average) could be a potential hindrance that needs to be managed, in order to reduce power plant maintenance cost and improve CPH fuel quality and yield. Pre-treatment would therefore be essential which could increase the energy demand and cost of the whole conversion process. Additives can be used to control the ash content and get the best energy output. Notwithstanding, gasification is the best technology for CPH conversion to electricity, as it converts the entire carbon content of the feedstock and provides a better energy capture with lower emissions than other conversion techniques. Gasification of CPH would therefore produce a much cleaner combustion and energy that is more environmentally friendly. The thought of using CPH for electricity production in rural communities in Ghana is contemporary; however, its importance cannot be overemphasized. The use of carbonised and pelletised CPH for gasifiers could also create a secondary market and provide an alternative source of income for farmers. Electric power production from CPH could alter the way of life of rural inhabitants in a very positive way by growing businesses and eradicating poverty. The charred CPH and excess ash can also be used as fertilizer to enhance cocoa growth. The differences in thermal properties observed between the cocoa pod husk samples could be attributed to differences in location, soil contamination, soil types, nutrient deficiency and toxicity, cultivation methods and climatic and storage conditions. Overall, Amelonado from the Ashanti region of Ghana exhibited the highest energy potential at 19.21 MJ/kg and the lowest ash content. The Ashanti region could therefore be prioritised for any future demonstration of a bio-energy plant.

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Nomenclature

MW	Megawatt
PJ	Petajoule
GDP	Gross Domestic Product
UN SDG	United Nations Sustainable Development Goal
CPH	Cocoa pod husk
EFB	Empty fruit bunch
RPR	Residue-to-Product Ratio
MJ/kg	megajoules per kilogram
mm	millimetre
rpm	revolutions per minute
min	minute
μm	micrometre
ASTM	American Society for Testing and Materials
TGA	Thermogravimetric analysis
mg	milligram
N_2	Nitrogen gas
°C	Degree Celsius
°C/min	Degree Celsius per minute
mL/min	millilitre per minute
CO_2	Carbon dioxide
H_2O	Water
wt %	Weighted percentage

HHV	Higher heating value
PA	Proximate Analysis
UA	Ultimate Analysis
FC	Fixed Carbon
VM	Volatile Matter
C	Carbon
H	Hydrogen
S	Sulphur
O	Oxygen
N	Nitrogen
H/C	Hydrogen–Carbon ratio
O/C	Oxygen–Carbon ratio
CH_4	Methane
H_2	Hydrogen gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
m^3	Cubic Metres
PAHs	Polycyclic Aromatic Hydrocarbons
NOx	Nitrogen Oxides

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