

**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND
TECHNOLOGY, KUMASI**

**COLLEGE OF ENGINEERING
DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING**

PROJECT REPORT

ON

**PHYSICO-CHEMICAL AND COMBUSTION PROPERTIES OF COCOA POD
HUSK PELLETS**

**DISSERTATION SUBMITTED TO THE DEPARTMENT OF
AGRICULTURAL AND BIOSYSTEMS ENGINEERING IN PARTIAL
FULFILMENT OF
THE REQUIREMENT FOR THE AWARD OF MPhil. AGROENVIRONMENTAL
ENGINEERING**

BY

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NOVEMBER, 2019

DECLARATION

I hereby certify that this submission towards the award of Mphil. Agro-environmental Engineering, is entirely my own work and that it contains no material previously published by another person, except where due acknowledgement has been made in the text.

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ABSTRACT

The increasing bad effects of fossil fuel and traditional biomass (wood) on the environment and the health of individuals has attracted the interest in the search for alternate cleaner source of energy. Attention has therefore been drawn on the utilization of agricultural residues such cocoa pod husk, cassava peels and other residues for energy generation. This study investigates the use of cocoa pod husk to produce pellets which could be used as cooking fuel. Cocoa pod husk (CPH) was sun-dried, charred and crushed to obtain particle size less than 1 mm using a screen. CPH and binder (starch) was pelletized in a proportion of 4:1 (20 % binder), 3:1 (25 % binder), and 7:3 (30 % binder). Proximate and ultimate analysis was performed on the pellets to examine their Physical and combustion characteristics at each binder ratio. Pellets of binder ratio 20 % (4:1) produced compressed and relaxed densities of 1.04 g/cm³ and 0.85 g/cm³, with relaxation ratio of 1.23 lower than all the other binding ratios. Which gives an indication of a more stable pellets for mechanical handling, transportation and storage. Again, 20 % binder recorded the highest durability of 95.63% than 25% and 30% binder which recorded 83.3 and 67.3 respectively. Which implies that pellets produced with lower concentration of binders (starch) are more durable and resistant to mechanical stresses. Calorific values for the 20 %, 25 % and 30 % binder were 13.8 MJ/kg, 13.3 MJ/kg and 13.9 MJ/kg respectively. The result shows that pellets with 30 % binder has the potential to produce high heat energy for domestic purposes, but 20 % binder has much higher potential due to its advantageous physical characteristics. The binder therefore had a high significant effect on the properties of the pellets expect for the calorific value which produced closed values.

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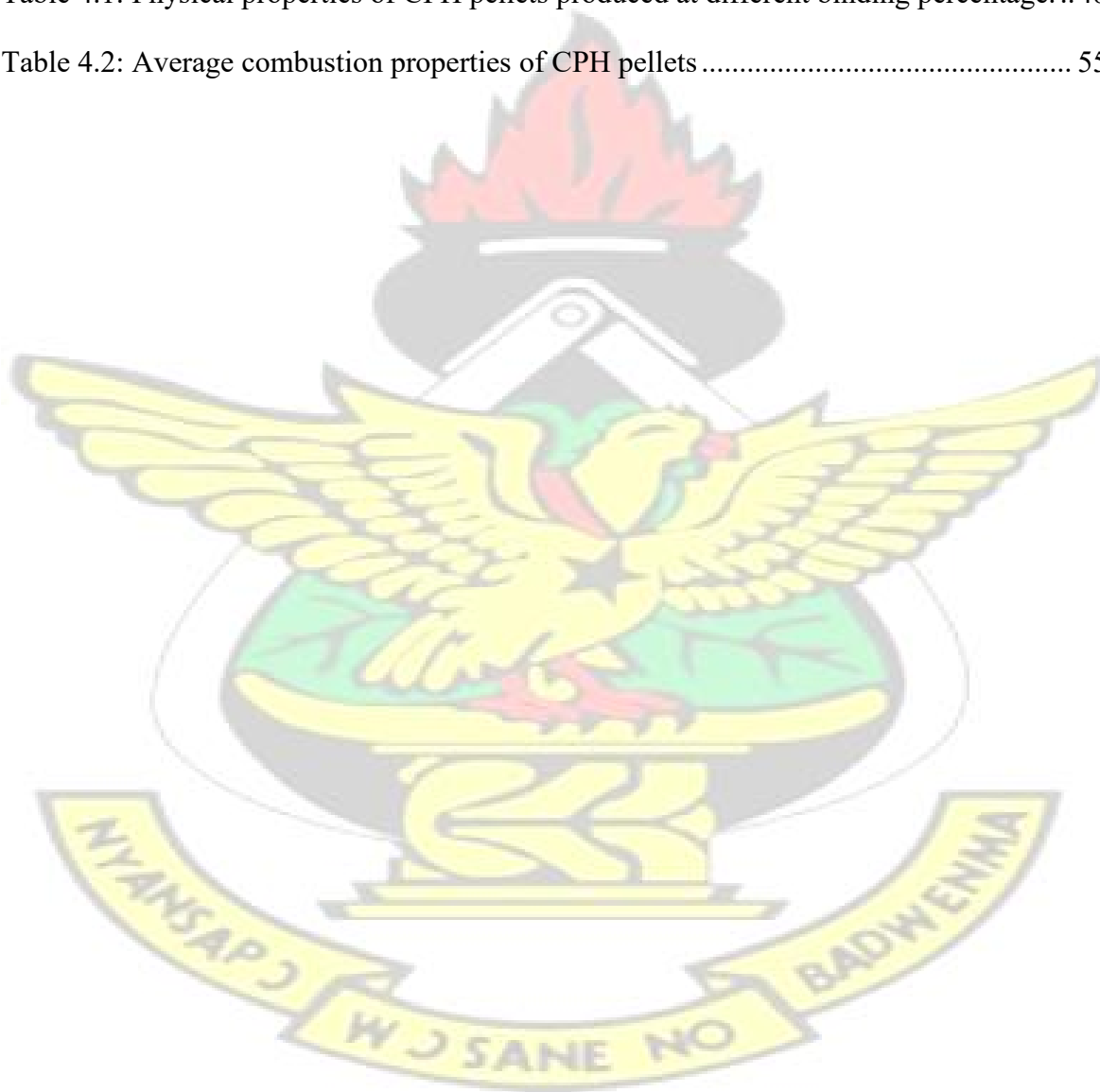
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LIST OF ABBREVIATIONS

AC	Ash content
ANOVA	Analysis of Variance
C	Carbon
$C_6H_{10}O_5$	Diethyl pyrocarbonate
CPH	Cocoa Pod Husk
CO_2	Carbon dioxide
CV	Calorific Value
EUBIA	European Biomass Industry Association
FAO	Food and Agriculture Organization
FCC	Fixed carbon content
GAMA	Greater Accra Metropolitan Area
GDP	Gross domestic products
GEPA	Ghana Export Promotion Authority
GSS	Ghana statistical service
H	Hydrogen
HHV	Higher Heating Value
ICCO	International Cocoa Organization
IEA	International Energy Agency
KNUST	Kwame Nkrumah University of Science and Technology.
LHV	Lower Heating Value
M_{as}	Mass of ash sample
MC	Moisture Content
M_c	Mass of crucible
M_d	Mass of petri dish

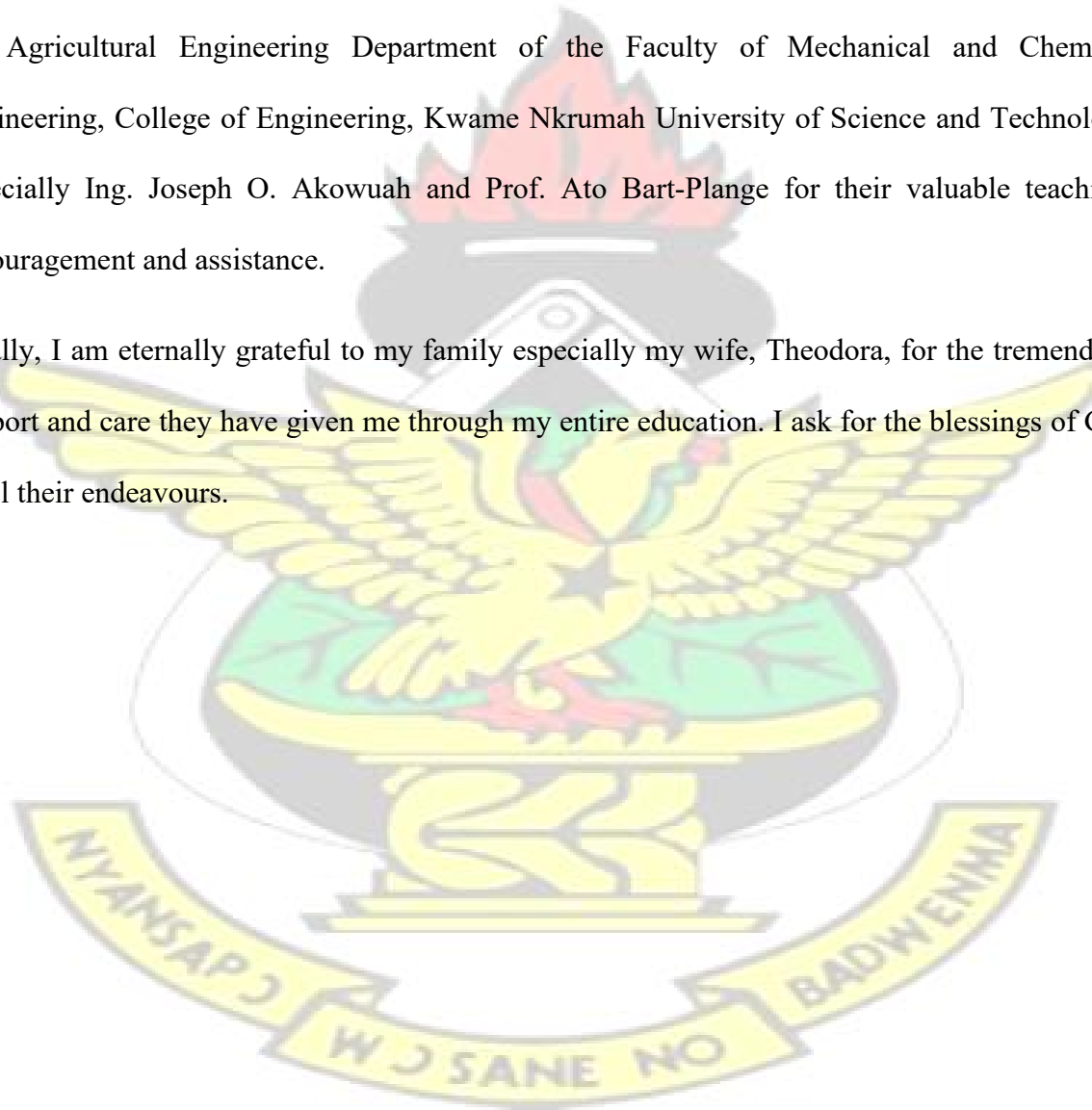
M_{ds}	Mass of petri dish and dried sample
M_s	Mass of sample
M_{sc}	Mass of sample and crucible
Mt/yr	Metric tonnes per year
Mtoe	Million tonnes of Oil equivalent
O	Oxygen,
RE	Renewable Energy
TCC	Technology Consultancy Centre
USA	United States of America
P	Probability
PVM	Percentage Volatile Matter.
PAC	Percentage Ash content.
PFC	Percentage Fixed carbon



ACKNOWLEDGEMENTS

I am very grateful to those who have contributed to the success of my project and academic career. First of all, I thank the Lord Almighty for bringing me this far. My sincerest appreciation goes to my supervisor, Dr. Francis Kemausuor for his advice, supervision and his patience throughout the study. My heartfelt gratitude also goes to my lecturers, friends and the staff of the Agricultural Engineering Department of the Faculty of Mechanical and Chemical Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology especially Ing. Joseph O. Akowuah and Prof. Ato Bart-Plange for their valuable teaching, encouragement and assistance.

Finally, I am eternally grateful to my family especially my wife, Theodora, for the tremendous support and care they have given me through my entire education. I ask for the blessings of God in all their endeavours.



CHAPTER ONE

INTRODUCTION

1.1 Background

Non-renewable energy source, which is viewed as non-sustainable and the primary energy source everywhere throughout the world is decreasing (Saidur *et al.*, 2012; Shafiee and Topal, 2009). In the meantime, the overall fuel request keeps increasing significantly (Saqib *et al.*, 2011). This quick increment in essential primary energy utilization has increase worries about the environmental consequences of continued fossil fuel extraction and use (Luterbacher *et al.*, 2009). Therefore, more consideration has been directed towards energy extraction from alternative cheap and sustainable energy sources with next to zero ecological impact (Peterson *et al.*, 2008). Usage of biomass to substitute non-renewable energy sources for heating and electricity generation can decrease the issue of worldwide CO₂ emissions. CO₂ produced by combustion of biomass makes no net contribution, as it is absorbed by plants, as long as biomass is grown renewably (e.g. without deforestation) (Moran *et al.*, 2004).

Biomass mainly consisting of firewood and charcoal constitute the main cooking fuel for households in rural and semi-rural areas in Ghana (Ghana Statistical Service, 2014). Energy obtained from biomass sources is one of the earliest and now worldwide, the third largest renewable electricity generating source with generation of 493 TWh (Panwar *et al.*, 2011). In 2018, it accounted for close to 41 % of total energy consumed in the country (Ghana Energy commission, 2018). The interesting component of biomass is that, it is the main sustainable energy source which can be changed over into advantageous solid and fluid fuels (Twidell, 1998). However, this pattern of biomass usage present potential health risk and negative

environmental impact coupled with accelerated deforestation due to excessive fuel consumption. The utilization of these materials for energy applications would be a compelling method for dealing with waste, while turning into a helpful asset than a loss under customary administration practices (Klass, 2004). With increasing concern of the negative environmental impact of cutting down trees as fuel source and increasing scarcity of wood, attention has been drawn to the attractive alternative of agricultural and wood waste residues for energy generation. Agricultural residues are potential energy sources and with the right conversion technology, huge quantities of energy can be generated from these resources. This can significantly mitigate the challenges in the energy sector. An example of a crop that can generate significant quantities of residues and also produced widely in Ghana is cocoa.

Currently, Africa is the leading continent in cocoa production, representing 72 % of the all-out worldwide production followed by Latin America and the Asia Pacific. Whereas Europe tops importation and consumption of cocoa followed by North America. Leading cocoa bean trading nations include Cote d'Ivoire, Ghana, Nigeria, Cameroon, Brazil, Ecuador, Colombia, Indonesia and, Malaysia among others (ICCO, 2018). Ghana, second highest exporter of cocoa after Ivory Coast with a record high of 880,000 tons in 2017/2018 (ICCO, 2018). Cocoa is usually cultivated by smallholder farmers and few people on small to large scale; for the most part in Eastern, Ashanti, Brong-Ahafo, Central, Volta and the Western region (Bray, 2014). Cocoa is harvested in two primary seasons in Ghana, the main yield is harvested from October to December and the midcrop is harvested in March (Afoakwa, 2010). The main biomass residue generated from cocoa is the cocoa pod husk (CPH) which is obtained after the cocoa bean is removed from the fruit. Due to Ghana's position as the second highest cocoa producing country in the world there is abundant CPH in the nation that is to a great extent unutilised. The husk

has a high oil content which implies high calorific value and therefore an ideal alternative fuel. In most cocoa farms, few CPH is disposed off at the plantation area so that after disintegration process it turns into a wellspring of compost for the couple of cocoa trees inside that enclave. The CPH are not intentionally spread over the field but deposited within the processing area. However, large portion of the CPH is burnt to provide space to carry out farm activities. One conversion technology that can be used to convert CPH into effective energy source is pelletization.

Pellet is a made by subjecting biomass materials to compression to produce a cylindrical shaped organic fuel (Karkania *et al.*, 2012). Recent interest in biofuel pellets production for domestic and industrial use is on the rise in Europe, Northern America and China over the most recent couple of years (Peksa-Blauchard *et al.*, 2007; Samuelsson *et al.*, 2009). According to Wang *et al.*, (2009), businesses for biofuel in the production of pellets for domestic use is fast increasing due to its advantageous use in furnaces and fluidized bed combustion, its lower pollution, easy storage and transport, lower residue levels and higher calorific values. Moreover, pellets offer indistinguishable favourable circumstances for automation and enhancement from oil inferred fuels, yet with higher ignition effectiveness and a lower measure of burning deposits (Rhen *et al.*, 2007). Pelletizing innovation includes change of biomass into a densified, uniform fuel that is cost-stable, carbon-unbiased, advances an incentive out of waste age, advance monetary advantages, and guarantees energy independence for individual clients and the country. Biomass pellets are substitution to traditional fuels like LPG, Diesel, charcoal and wood. Pellets are generally utilized at homes and factories for cooking and heating purposes.

1.2 Problem statement

Household in rural and semi urban areas of Ghana are highly dependent on traditional biomass for their energy needs. Huge quantities of cocoa pod husks are generated and not utilized. This is mainly due to lack of technical details and a more effective and convenient conversion technology to convert these residues into renewable energy source. Recent studies have mainly focused on utilizing CPH as source of fertilizer. There is however, huge potential to use CPH for pellets for cooking and other heat application especially in rural cocoa producing areas where the residues are in abundance.

1.3 Aim of the study

The aim of this study is to determine the suitability of pellets from CPH as alternative source of energy for cooking.

1.3.1 Specific Objectives of the study

The specific objectives of the study are to:

1. Assess the mechanical properties of pellets produced from CPH;
2. Determine the physical properties of pellets produced from CPH; and
3. Evaluate the thermal properties of pellets produced from CPH.

1.4 Justification of the study

The utilization of cocoa by-product and waste product (cocoa pod husk) has been researched by; Syamsiro *et al.*, (2012), Velazquez-Araque and Cárdenas (2017) and Tsai *et al.*, (2018). However, the above-mentioned studies only concentrated on the chemical composition of CPH and the heating value of CPH pellet value without binder addition. This study however seeks to investigate the potential of using CPH to produce pellets. Pellets can serve as alternative and effective energy for cooking in household especially in the rural areas. Utilisation of such energy source can save cooking time and help prevent health related diseases resulting from smoke inhalation. Moreover, the energy sector has turned out to be more concern in settling on policies and strategies that will address the social, economic and technological issues. In this way, there is therefore the need for approved, updated and logical information and data on ecologically benevolent and waste utilization energy venture such as pellets made from CPH. This study will go a long way to provide alternative uses of CPH for pellet production and subsequently energy generation for daily applications.

CHAPTER TWO

LITERATURE REVIEW

2.1 Sources and current status of energy in Ghana

In Ghana, there are availability of variety of energy resources including biomass, hydrocarbons, hydropower, solar and wind. Among these resources, hydropower and hydrocarbon remains the leading source of energy for the country. Ghana has a total installed power capacity of about 4,132 MW existing plants comprising of 38 % from hydro ,61 % from thermal and less than 1 % Solar (Ministry of Energy Ghana, 2017). Despite these variety of energy resources, the country's energy sector is faced with lots of challenges to meet its demand. Ghana's capacity supply sources are from hydroelectricity and thermal plants which are fueled by crude oil, flammable gas and diesel, solar and furthermore imports from other neighbouring countries. Notwithstanding hydropower, Ghana likewise produces a ton of other sustainable energy sources, these energy sources that produces power in Ghana are biomass, geothermal and wind (Energy Foundation of Ghana, 2013). Natural gas supply began in 2009 with only 5 ktoe and expanded to 292 ktoe in 2013; hydro supply expanded from 609 ktoe to 700 ktoe whiles wood supply decreased from 3,888 ktoe to 3,553 ktoe (Ghana Energy Commission, 2018). This decrease in biomass supply was attributed to Government biomass arrangement which advances the utilization of elective energies, for example, LPG as a substitute for wood fuel and charcoal by tending to the institutional and market imperatives that hamper expanding access of LPG in Ghana. From 2008, oil, natural gas, hydro, solar and biomass energy sources have been the main primary energy supply for power generation in the country.

As at 2017, oil remains the major primary energy supply of 4,086 ktoe (42.5 %), followed by biomass 3,902 ktoe (40.6 %), natural gas 1,146 ktoe (11.6 %), hydro 478 ktoe (5.0 %) with solar being the least of 2.0 ktoe (0.0 %) (Ghana Energy Commission, 2018).

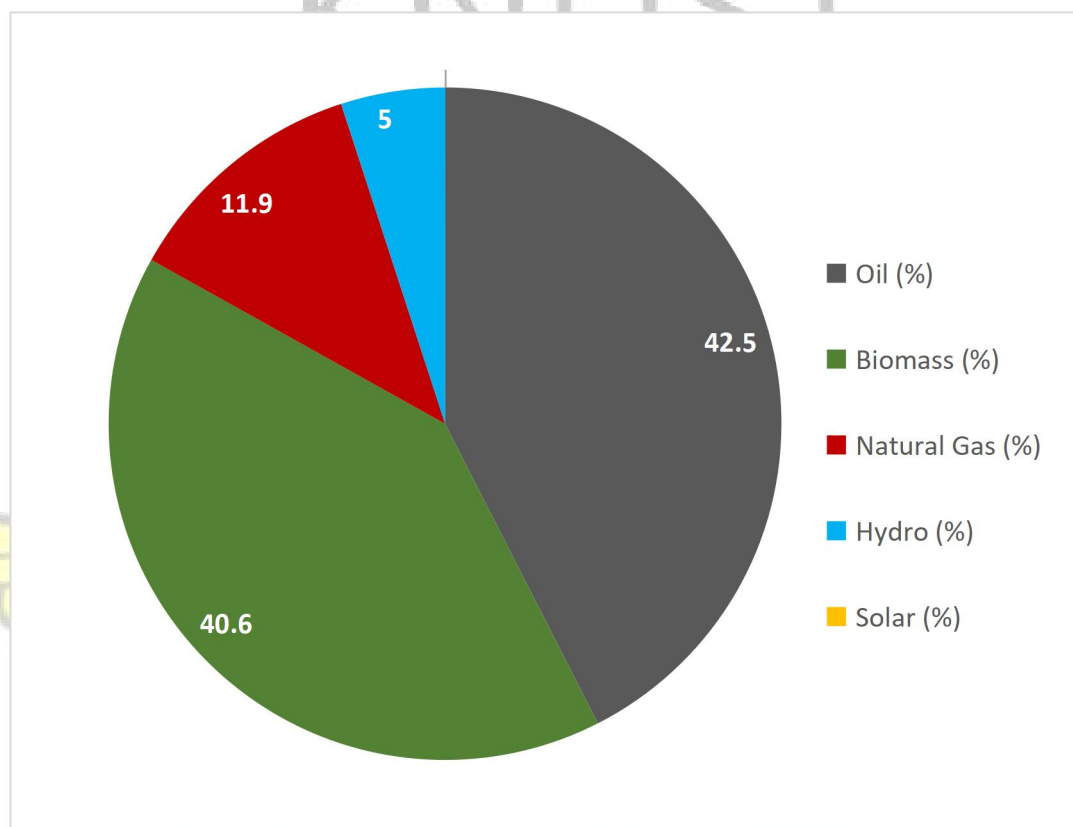


Figure 2.1: Primary energy supply in Ghana, 2017.

Source: Ghana Energy commission (2018).

These primary energy sources are converted and consumed in the form of grid electricity, petroleum and biomass (Ghana Energy commission, 2018). Final energy consumption is the energy which isn't being utilized for change into different forms of energy and it is determined as the aggregate sum of energy required by end-clients as a final product (Asumadu-Sarkodie and Owusu, 2016). These final energies are either transmitted (as in the case of grid electricity) or sold to households, institutions and industries. Significant energy consuming ventures in the

country are: the Volta Aluminum Company (VALCO), Electricity Company of Ghana, and the Northern Electricity Department. Part of power generated in Ghana are exported to its neighbouring countries, specifically Togo, Benin and Burkina Faso (Ministry of Energy Ghana, 2017).

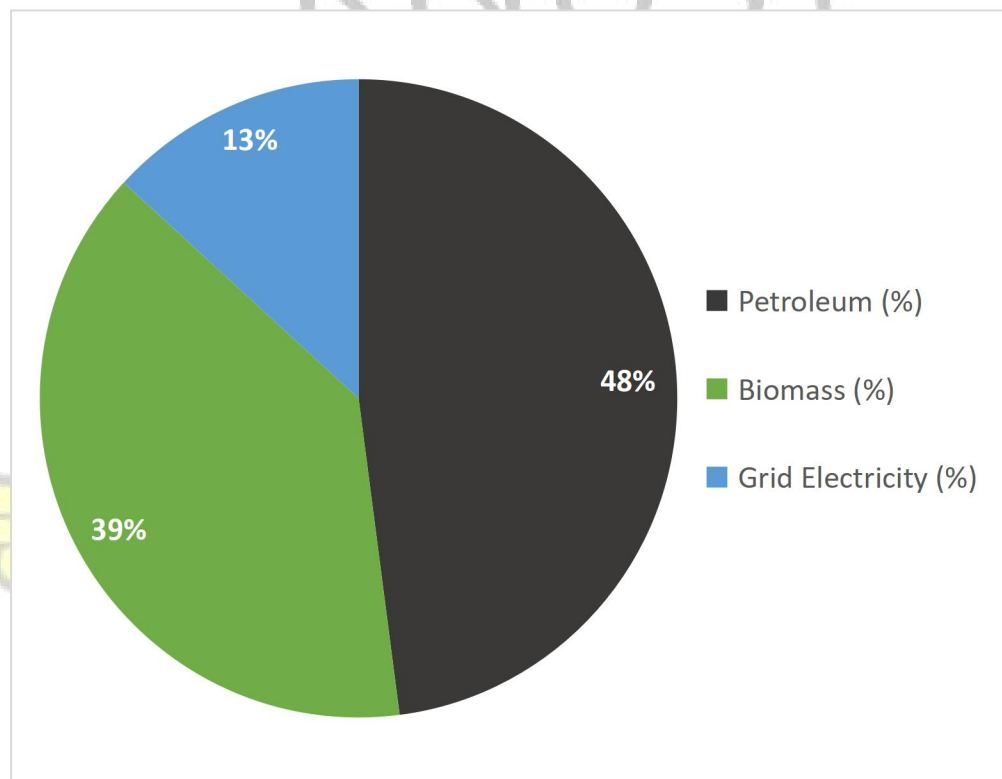


Figure 2.2 Final energy consumption in Ghana, 2017.

Source: Ghana Energy commission (2018).

The percentage consumption of the various final energies in 2017 are presented in Figure 2.2. Petroleum with the highest consumption of 3,115 ktoe (48 %), Biomass 2,829.4 ktoe (39 %) and grid electricity 1,039.8 ktoe (13 %). Out of date transmission lines caused power outages and roughly 4.1 % transmission misfortunes of total energy consumed (Ghana Energy commission, 2018). The demand for petroleum is always high due to its diverse use. Petroleum end products incorporate transportation fuels; that is fuel oils for power generation and heating purposes;

asphalt and road construction oil; and feedstock for making synthetic substances, plastics, and manufactured materials that are in almost all that we use. While biomass is used to generate sustainable power, transportation fuels, thermal energy and forms of fuel products.

According to Thorin (2014), public use of energy is grouped into three segments: energy used in industries, transportation, and buildings, where the energy is consumed as electricity, transportation fuels and for cooling and heating purposes respectively. Energy use in buildings usually constitute the domestic consumption of energy. Domestic energy utilization consists of the aggregate sum of energy utilized in a house for family unit work. Domestic energy utilization consists of the aggregate sum of energy utilized in a house for family unit work. The measure of energy utilized per household varies generally depending upon the way of life of individuals in the country, the weather condition, dimension of innovation, and the age and kind of living arrangement. Domestic energy is utilized for heating and cooling, lighting, washing and drying, cooking and for other different incidental electric burdens.

A household fuel decision is mostly dependent on the availability, moderateness and the convenience the fuel, just as reliant on the financial and specialized choices of a family and the particular social and cultural activities as stated by Sepp, (2014). People living in urban areas could prefer non-fuel wood to fuel wood due to their standard of living and accessibility of wood fuels. In rural areas, most of the inhabitants are farmers so they may rely on wood fuels or other agricultural waste as source of fuel for cooking. Modern fuel used in Ghana are LPG and electricity, whereas solid fuels comprises wood fuel and agriculture waste mostly used in rural areas, and kerosene and charcoal as transition fuels used in towns and cities. Ghana statistical service (2014), pointed that 41.3 % of households in Ghana use wood as their principal source of cooking fuel, while 31.5 % use charcoal and 22.3 % gas. In urban areas, 43.6 % of

households use charcoal and 35.8 % of households use gas as their primary source of fuel for cooking. Among the households in urban areas, 52.7 % of those in Accra use gas contrasted with 28.9 % of households in other urban areas. In rural areas, 74.8 % of household use wood as their primary source of cooking fuel and 16.5 % uses charcoal. In Table 2.1 is the sources and percentage use of household fuels in Ghana.

Table 2.1: Households by source of cooking fuel (%)

Source of Cooking fuel	Locality							
	Urban areas			Rural areas				
	Accra	Other		Rural	Rural	Rural		
None	6.4	4.9	5.4	2.1	2.7	1.3	2.2	3.9
Wood	0.8	20.5	14.3	57.6	72.4	87.4	74.8	41.3
Charcoal	38.9	45.8	43.6	30.0	17.9	7.6	16.5	31.5
Gas	52.7	28.0	35.8	9.5	6.7	1.3	5.5	22.3
Electricity	0.6	0.5	0.5	0.1	0.1	0.1	0.1	0.3
Kerosene	0.5	0.1	0.2	0.3	0.1	0.1	0.1	0.2
Crop residue	-	0.2	0.1	-	0.1	2.2	0.7	0.4
Sawdust	-	-	-	-	-	-	-	-
Animal waste	-	-	-	-	-	-	-	-
Other	-	0.1	-	-	-	-	-	-
All	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Utility	(GAMA)	Urban	All	Coastal	Forest	Savannah	All	Ghana

Source: GSS (2014).

The utilization of wood as cooking fuel is most prevalent in rural savannah (87.4 %) while Accra records the lowest of 0.8 % of households. Only 13.0 % of households in the country's rural savannah uses gas as cooking fuel. This can be attributed to the standards of living of individuals in those areas. Only 0.4 % of households in Ghana use crop residue as their cooking fuel. None of the households uses sawdust, animal waste or other waste products as cooking fuel. This explains the low level of solid agricultural waste utilization in households and the need to develop measures to make waste products useful to curb the high demand of energy in Ghana.

2.2 Biomass utilization in Ghana

Biomass materials are usually raw or waste adaptable material that can be utilized for generation of power, heat and fuels for transport. U.S. Energy Information Administration (2018), defined biomass as waste material from plants or animals that isn't utilized for nourishment or feed; it may be waste from cultivating agriculture, food processing, animal farm, or human waste from sewage plants. Whenever biomass materials are produced and utilized on a feasible basis, it is a carbon-neutral transporter that can make a huge commitment to decreasing ozone harming substance discharges. Biomass materials has so far been Ghana's prevailing source of energy utilization. In 2017, the absolute biomass utilization was 2,829.4 ktoe, which records for 40.5 % of the complete energy consumed (Ghana Energy Commission, 2018). According to Kemausuor *et al.*, (2013), if Ghana would devote more land to energy crops production, it could supplant 17.3 % of transportation fuels by 2020 and 13.3 % by 2030 to satisfy its projections for biofuel need. Like many other developing countries in sub-Saharan Africa, wood fuel and other biomass fuels constitute the main cooking fuel source for households in Ghana. Heft of Ghana's energy supply is met through wood fuels utilization, thus

firewood and charcoal. This is due to the fact that the greater portion of the country's energy consumptions is for domestic use. Biomass is largely used in most Ghanaian homes especially in rural areas for heating, cooking and lighting as shown in Table 2.1. Firewood are usually classified as softwood and hardwood: softwoods burns more rapidly and generate less heat energy compared to hardwood which produces large amount of heat energy per volume for longer period of time (FAO, 2004). The supply of biomass materials from 2000 to 2012 are presented in Figure 2.3, where charcoal supply recorded the highest supply of 1,989 ktoe 2012, firewood, 2,742 ktoe in 2000 and 55 ktoe for any other form of biomass material in 2000. The total biomass supply therefore decreases from 3,891 ktoe in 2000 to 3,554 ktoe in 2012 respectively. The decline can be attributed to the government policy to increase the use of natural gas and LPG for domestic use.

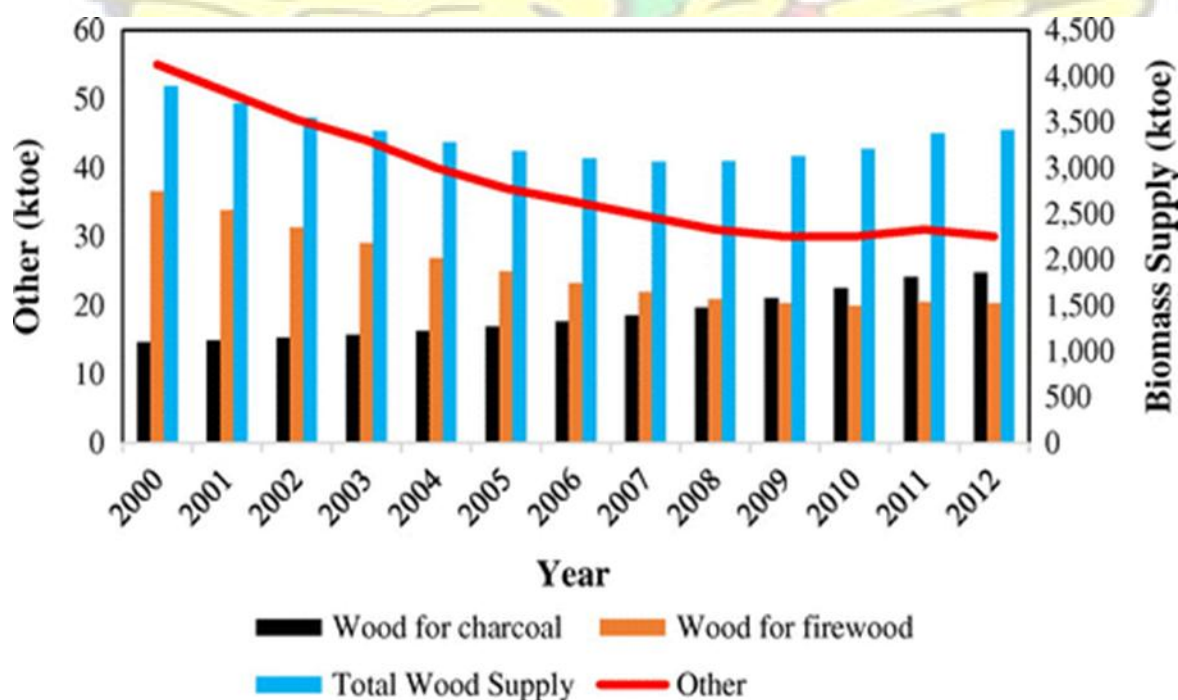


Figure 2.3: Biomass supply.

Source: Asumadu-Sarkodie and Owusu (2016).

Even though biomass provides sustainable and substantial amount of energy, in the long-run it results in deforestation and damages the ecosystem. Uncontrolled discharge of acidic vaporous pollutants of sulfide oxides (SO_x) and nitrogen oxides (NO_x) into the air are later rained back to earth to ferment ineffectively cradled soils and water bodies (Dubey, 2013). Utilization of agricultural waste and waste from other sources is progressively invaluable approach to deliver biofuels with respect to social and ecological advantages. Generally, waste could be liquid or solid waste. The utilization of wood waste can likewise add to an independent, economical and moderate supply of energy in Ghana without felling more trees. There are a lot of unused logging and sawmill wastes produced by the timber industries (World Bank Group, 1988; Duku *et al.*, 2011).

According to Präger *et al.*, (2019), economical and dependable energy blend from local nearby resources can take care of ecological issues like natural waste accumulating and unsafe open sawdust fires. Organic waste is any material that is biodegradable and originates from either a plant or animal sources. This is termed biodegradable waste because it's a natural material that can be broken into CO₂, CH₄ or simple molecules. The wastes are first treated with lime to upgrade reactivity; at that point they are changed to volatile fatty acids, for example, acetic acid, propionic acid, and butyric acid utilizing a blended culture of microorganisms from dairy cattle rumen or anaerobic waste treatment facilities (Demirbas, 2009). The utilization of waste for energy generation likewise overcomes the issues of food and feed grains such as corn for biofuels (Ayamga *et al.*, 2015). Utilization of harvest grains in general increases the cost of food commodities, thereby reducing consumption and nourishment for consumers. This tends to increase pressure on food and feed products, on cultivation soil and the prices of food

commodities worldwide. The objective of accomplishing 10 % biofuels share in transport fuel at the worldwide dimension can be met yet this can cause an increase of 15 % individuals at danger of starving (Fischer *et al.*, 2009). Nilsson *et al.*, (2011) in their study reported that biomass from agricultural waste can be considered as a focused crude material with a lower cost and equivalent fuel properties as the wood-based pellets. These agriculture waste utilizations can take care of energy used at homes and make energy from hydropower plants and fossil fuel available for industrial use. Since industries require more power for manufacturing machines. Kemausuor *et al.*, (2014), confirmed that it is achievable to generate 2700 Mm³/yr of biogas or 2300 ML/yr of cellulosic ethanol from Ghanaian biomass materials such as harvest waste, forest off cuts, animal manure and metropolitan waste. Whenever the procedure has a few difficulties and impediments, which includes transport and handling the biomass waste material, productive pre-treatment techniques and the use of advanced technologies.

2.3 Chemical composition and properties of biomass material

The chemical components of biomass include cellulose, hemicellulose, proteins, lignin, lipids, starches and other compounds, with cellulose, hemicelluloses and lignin being major ones. The chemical composition in a biomass material varies impressively relying upon the kind of species, plant tissue, growing conditions and the stage of growth (Malik *et al.*, 2015).

Cellulose: This is an organic compound with the recipe $(C_6H_{10}O_5)_n$, a polysaccharide comprising of a linear chain of a few hundreds to a large number of $\beta(1\rightarrow4)$ connected D-glucose units (Crawford *et al.*, 1980; Updegraff, 1969). Zandersons *et al.*, (2004) presumed that the coupling quality of wood-based fuels fundamentally depends with respect to changing over the cellulose to an indistinct state.

Hemicellulose: otherwise called polyose, is one of various heteropolymer (network polysaccharides), for example, arabinoxylans, present alongside cellulose in practically all earthly plant cell walls (Scheller and Ulvskov, 2010). Few studies suggest the characteristic holding ability of pellets may happen because of the glue debasement results of hemicelluloses.

Lignin: This is a complex polymer which provides structural integrity in plants. Lignin belong to a class of complex natural polymers that structure key auxiliary materials in the support tissues of vascular plants and some algae (Martone *et al.*, 2009). In pelletization, lignin act as a binding agent to the cellulose fibre, therefore biomass materials with high lignin substance does not require an extra binder. Anglès *et al.*, (2001) reported that lignin grants attachment in the wood structure and goes about as a rigidifying and building specialist.

The properties of biomass materials are determined using proximate analysis. The percentage moisture content, volatile matter, fixed carbon, and ash content are provided through proximate analysis and is subsequently of principal significance for biomass energy use (Brito *et al.*, 1978; Yang *et al.*, 2006). Properties of biomass materials include;

Moisture: moisture content plays a major role in determining energy value of biomass materials. As per the Swedish standard 187170 (1997), estimating the moisture content of biomass materials requires weighing of the sample before and after drying in an oven for 24 h at 105 ± 2 °C. The moisture content is determined by finding the difference in the weight of the biomass sample. Dry biomass materials produce high heating value, as it utilizes little of its energy to evaporate the remaining moisture (Clarke & Preto, 2011).

Volatile matter: Volatile matter is the component of biomass material, with the exception of moisture, which are freed at high temperature in an airtight environment (Osborne, 2013). As

per the procedure laid out in European Standard EN15148 (2009), a carbolite volatile matter furnace and crucible has been designed to fulfill the prerequisites of this method.

Ash content: Ash content is considered to be the proportion of the biomass material that remains after the sample has been incinerated. It therefore has no energy value and is made up of the inorganic elements in the biomass. High ash content is a negative component since it makes the burning procedure of biomass material progressively difficult (Tardenaka and Spince, 2006).

Fixed carbon: This is the carbon content present in a biomass material which is left after combustion after moisture and the volatile matter are driven out. Fixed carbon is the solid ignitable remains part of a heated biomass sample at 900 °C for 7 minutes and the volatile material removed and ash content gathered. This is calculated by determining the difference between 100 and the aggregate of the ash content and volatile matter, on a dry basis (Brockway and Higgins, 1991).

Calorific value: calorific or heating value is the standard for measuring energy content in fuel containing materials. It is the gross heat energy generated by total burning biomass material in the presence of oxygen under standard conditions. As indicated by the Swedish standard SS-ISO 1928, the gross heating value is determined using bomb calorimeter (Malik *et al.*, 2015). Estimation of biomass calorific value specifically depends on the constituents of the biomass material.

2.4 Cocoa Production in Ghana

Cocoa is known to have originated from Southern and Central America and is native to the Amazon and Orinoco valleys of South America (Thompson *et al.*, 2001; Beckett, 2009;

Afoakwa, 2010). It is the main cash crop and agricultural export in Ghana which is cultivated almost every part of the country, most especially in the forest areas. The widespread cultivation of cocoa in the country is ascribed to Tetteh Quarshie, a Ghanaian from Osu in Accra. He worked in Equatorial Guinea (previously Fernando Po) for quite a while and on his arrival to Ghana in 1879, carried with him the Amelonado Cocoa beans. He started a cocoa farm at Akwapim Mampong in the Eastern Region which was later transformed into a nursery for all spearheading Cocoa farmers in the country (Cocobod, 2019). After harvest, the beans are fermented, dried and processed to produce variety of cocoa products. These products include cocoa butter which is mainly used to make chocolate, cocoa powder used with other products to make pastries, and cocoa liquor which is used as flavour in most chocolate flavoured drinks. The husks and pulp, encompassing the beans and the bean shells respectively are utilized in the production of animal feed, fertilizer, beverages, Jam and marmalade. The husks and pulp, encompassing the beans and the bean shells respectively are utilized in the production of animal feed, fertilizer, beverages and soap (Adomako, 1995; ICCO, 2003).

The major varieties of cocoa trees include Forastero, Trinitario, and Criollo. Forastero is the most broadly utilized, containing 80-90 % of the global cocoa production. The beans of the Criollo cocoa are rare and thought to be a delicacy (Spadaccini, 2003). Trinitario variety is a hybrid between the other two varieties. In Ghana, there are other hybrid varieties such as of Amelonado (Tetteh Quarshie cocoa) which is cultivated by most farmers all over the country.

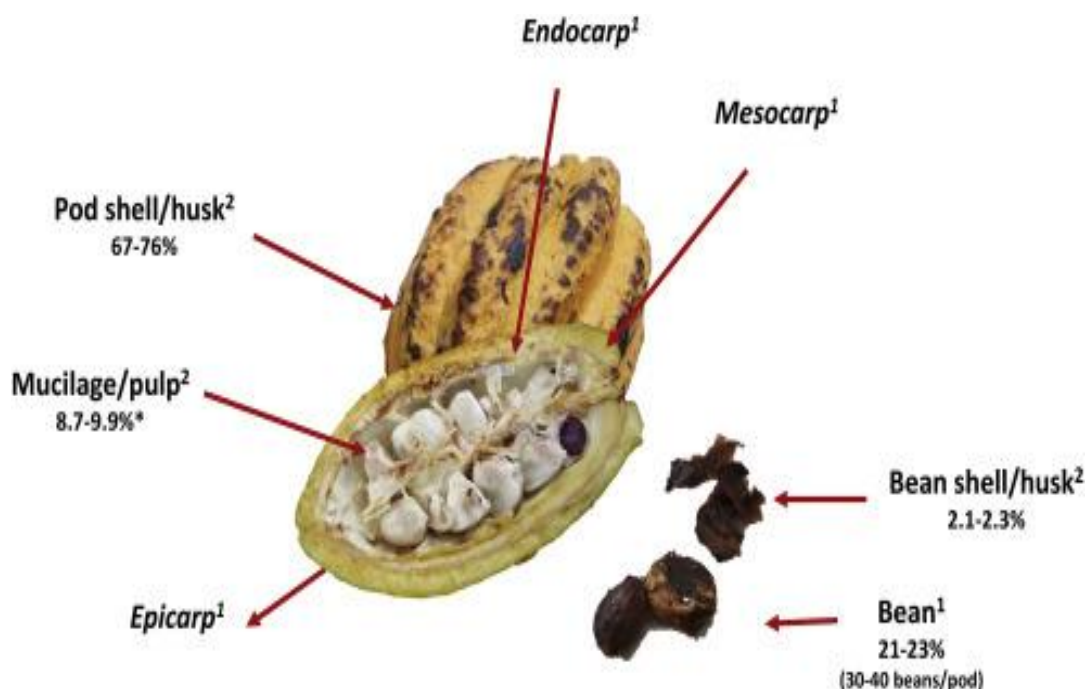


Figure 2.4: Cocoa fruit structures¹ and waste².

Source: Babatope (2005); Oddoye *et al.*, (2013).

Currently, cocoa is cultivated in six regions in Ghana namely; Ashanti, Eastern, Western, Central, Brong-Ahafo, and Volta region. Western region is now the leading producer of cocoa in the country due to the favourable rainfall and soil fertility in the western part of the country (Bray, 2014). The Region covers a territory of 239,221 square kilometers, which account for approximately 10 % of the total area of country. It has about 75 % of its vegetation inside high forest zone described by moderate climate conditions and lies in the equatorial climate zone (MOFA, 2011). Cocoa is cultivated on approximately 1.9 million hectares of land in Ghana by about 800,000 cocoa farmers (Sulaiman and Boachie-Danquah, 2017).

Table 2.2: Annual cocoa production by region (tonnes).

Crop	Ashanti	Brong	Eastern	Central	Western	Volta	Total	Leading
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Year	Ahafo							Producer
2007/08	125270	66921	55916	62378	369458	838	680781	Western
2008/09	110643	61562	63405	60686	413395	951	710642	Western
2009/10	116538	60600	55736	57562	359910	595	650941	Western
2010/11	168916	101302	78928	76863	583589	3241	1012839	Western
2011/12	134295	76511	67713	71760	525237	3833	879349	Western
2012/13	134295	88034	75912	71540	458107	4495	835467	Western
2013/13	156902	87116	80692	85446	483279	3481	896916	Western
2014/15	136134	81896	68415	70690	380469	2690	740254	Western
2015/16	133462	74943	75787	75870	415302	2680	778044	Western
2016/17	173328	101058	96639	95588	496475	6422	969511	Western

Source: GSS (2018).

2.4.1 Economic importance of cocoa

Cocoa is one of the noteworthy commodities that drives Ghana's economy. Ghana isn't just the second highest global cocoa producer; it is the country with the highest cocoa quality in the world. After Ivory Coast, Ghana is the largest producer and exporter of cocoa in the world (Sulaiman and Boachie-Danquah, 2017; Emmanuel and Qineti, 2018). Cocoa business plays significant role in Ghana's economy, as its industry employs about 800,000 citizens in more than six regions in the country. It generates approximately \$2 billion foreign exchange every

year and it's among the main contributors of the country's Revenue and GDP. Chocolate, cocoa powder, cocoa butter and many others are products of cocoa patronized by most Ghanaians (COCOBOD, 2019). The crops sub-sector of which cocoa was part was the highest with a growth rate of 9.4 % in 2017.

Table 2.3: 10-year annual cocoa economic activities.

Year	Production (1,000 tons)	Export (US\$ Million)	GDP (percent)
2007/08	681	1049	2.5
2008/09	711	1180	2.5
2009/10	651	920	3.2
2010/11	101	2300	3.6
2011/12	879	2060	2.6
2012/13	835	1480	2.2
2013/14	897	649	2.2
2014/15	740	643	1.8
2015/16	778	1900	1.7
2016/17	969	2430	1.8

Source: GEPA (2015); COCOBOD (2019); GSS (2018).

Cocoa is a leading commodity that brings income for the nation. An aggregate of 969,511 metric tonnes was created in the 2016/2017 generation season as against 778,044 metric tonnes in 2015/2016 generation season recording a rate increment of 24.6 %. This accomplishment was because of the Government intercession with cocoa mass spraying and manure conveyance program to farmers, presentation of hand fertilization method and successful extension administration service. At any rate 70 % of this volume is relied upon to be sent out to

accomplices for remote trade and farmers gain up to 70 % of the FOB cost of the commodity. For the 2016/2017 season, amount paid to farmers for the price of cocoa increased to GH¢ 7,600 (US\$ 1,914) per ton. This was influenced by the exchange rate at the beginning of the season (Sulaiman and Boachie-Danquah, 2017). Largest portion of Ghana's cocoa production accounting to 67.6 % are exported to Western Europe countries. Netherlands is the highest importer of 33.3 %, followed by U.K (12.1 %), Belgium (8.9 %), Germany (3.6 %), and few others. Aside Europe, Ghana's cocoa is also exported to Japan (7.2 %) and U.S. (3.3 %) (Sulaiman and Boachie-Danquah, 2017).

2.5 Composition of Cocoa pod husk and factors affecting quality standards of pellets

The cocoa fruit is made up of 33 % of its bean (being one third of the fruit) and 67 % CPH as a waste product (Oddoye, *et al.*, 2013). According to Rasjiddin, 2006, CPH contains high amounts of cellulose, hemicellulose and lignin which decompose into carbon after going through calcination. The preeminent mineral in CPH is Potassium, accounting to 7 % (db) of the CPH and approximately 70 % weight of the CPH ash from cocoa produced in Ghana (Donkoh *et al.*, 1991). Other significant CPH minerals include Calcium (0.3-0.8 % db), Magnesium (0.02-0.8 % db), Phosphorus (0.04-0.12 % db), Sulphur (0.02-0.05 % db) and Silicon 0.5 % db together records for 19.9, 21.9 and 27.4 % of the CPH ash weight (Martinez-Angel, 2015).

Table 2.4: Chemical composition of CPH.

Chemical constituent	Percentage constituents (% WT)
Cellulose	35 - 35.8
Hemicellulose	36.5 - 37.5
Lignin	14 - 1
Pectin	6 - 6.2

Source: Aregheore (2002), Daud *et al.*, (2013), Kassim *et al.*, (2014).

The chemical energy stored in biomass is contained in cellulose, hemicellulose and lignin components. CPH has high holocellulose content (hemicellulose and cellulose), with the hemicellulose being greater than cellulose, in contrary to woody biomass (McKendry, 2002).

The epicarp is dominated with high amount of ash (47 %) and minerals (41-66 %) which is the lignified cocoa pod pericarp (Sobamiwa and Longe, 1994). Fresh CPH has about 90 % moisture (Vriesmann *et al.*, 2011), hence fast drying is necessary to forestall deterioration; this is accomplished by cutting the fresh pod, drying to 65 % moisture content, grinding, pelleting and drying the pellets to 10 % moisture before it is stored (Oddeye *et al.*, 2013). Proximate analysis of raw CPH and carbonized CPH are presented in Table 2.2. High heating value (HHV) of 17 and 21.7 MJ/kg for raw carbonized CPH respectively has been reported

Table 2.5: Proximate analysis of raw and carbonized cocoa pod husk (% WT)

Property	Raw CPH	Carbonized CPH
Moisture	16.1	14.3
Volatile matter	49.9	11.4
Fixed carbon	20.5	50.6
Ash	13.5	23.7
HHV (MJ/Kg)	17.0	21.7

Source: Syamsiro *et al.*, (2012).

In comparison to other biomass materials such as bagasse, CPH has higher ash content, however it is lower than rice husk (Mansaray *et al.*, 1999; De Filippis *et al.*, 2004). High ash content is undesirable in biomass fuels since it hinders oxygen penetration in combustion chambers for complete combustion of the biomass material. This therefore decreases the HHV of the biomass material. A good relationship between ash content and HHV can establish to estimate the HHV of biomass materials (Sheng and Azevedo, 2005). According to Demirbas (1997), a function of fixed carbon and volatile matter can also be used to calculate the HHV of biomass materials. In combustion chamber, biomass ash has the ability to store heat for some time so that heat can be brief put away in the combustion chamber. Ignition, combustion and flame stability problems of biomass fuels are usually caused by its high moisture and ash contents. Flame stability can therefore be enhanced by mixing biomass fuels with high quality coal (Demirbas, 2004).

2.6 Production of biomass pellet

Pelleting involves densification of biomass material by compacting it into a much storable size. Biomass materials such as sawdust, woodchips and agricultural residue are usually pelletized and used as fuel. Although these biomass materials can be directly used as fuel, pelletizing changes the properties of the biomass material which increases its fuel energy and storability. Densified biomass fuel has a high density and low moisture content; this lessens the technical constraints related with handling, storage and transportation. One advanced technique is the pelletization of raw biomass materials that upgrades its energy efficiency and empowers the challenge of biomass with other different fuels (Malik *et al.*, 2015). A raw biomass material has certain characteristics properties associated to high bulk volume which add up to high cost of transportation and requires large storage facilities. Such characteristic biomass fuel has high moisture content and usually deteriorate at storage. Biomass, especially waste from agricultural produce has low energy and high moisture content, subsequently treatment process before burning or gasification is a significant method to upgrade thermal efficiency of the systems (Syamsiro *et al.*, 2011). Biomass materials especially agricultural residue has high moisture content and low energy, hence pretreatment before combustion and gasification a significant method to improve its energy for effective heating processes. Biomass materials therefore are made to undergo densification, which involves compressing the materials to achieve a progressively uniform property to overcome the undesirable properties of the material. The technique of compacting biomass materials can likewise be utilized to produce characteristic uniform and environmentally friendly fuel with enhanced handling characteristics, reduced transportation cost and improved heating value (Wilaipon, 2007; Demirbas and Sahin-Demirbas, 2009).

The following are the advantages of densified fuels compared to non-densified fuels;

- Densification increases the bulk density, bringing about easy handling, lower transportation costs and decreased storage capacity.
- Densified fuels have lower moisture content (less than 10 %), which helps in conservation and reduce degradation at storage.
- Densified fuel has high energy density and uniform composition, bringing about better combustion and high energy generation (EUBIA, undated).

High cost of pelleting process is the only disadvantage for this technology, which directly affects price of the fuel product (EUBIA, undated).

2.6.1 Steps in pellets production

The main steps identified by Karkania *et al.*, (2012) in producing pellets from plant biomass are feeding, drying, grinding, conditioning, pelletizing, cooling, screening, distribution and storage.

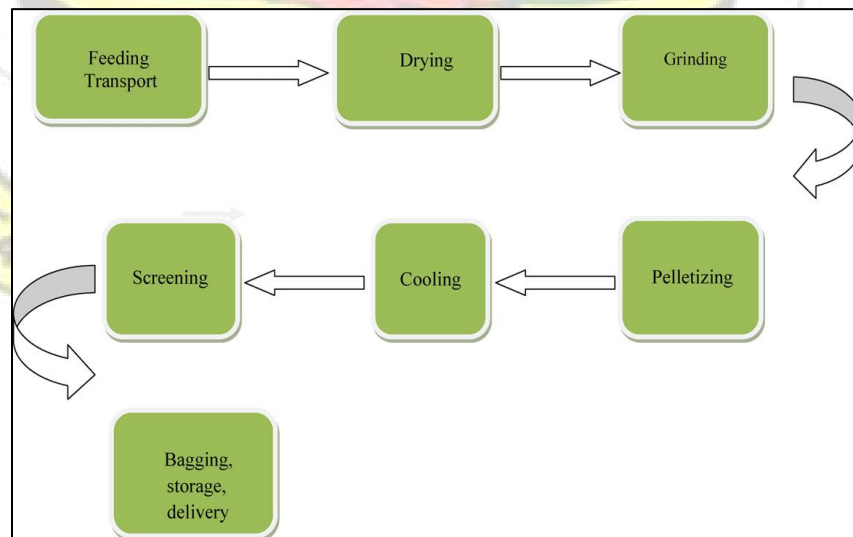


Figure 2.5: Flow chart of pellet production.

Source: Karkania *et al.*, (2012).

2.6.1.1 Feeling

Dealing with the feedstock is one of the best ways of improving pelletizing at facility. Due to the high cost of transportation of raw biomass materials over long distances, it is advantageous to be sourced locally (Peksa-Blanchard *et al.*, 2007).

2.6.1.2 Drying

Drying is an important part of pellets production but consumes a lot of energy. Therefore, the total energy of biomass pellets as a source fuel becomes of major concern. Biomass materials can be pelletized at high moisture content but pelletization at 12 % moisture content or less is optimal if lower moisture content of end product fuel is to be achieved. Biomass materials can likewise be excessively dry to pelletize so finding the optimum moisture content for effective pelletization is very important. To minimize the cost and improve the quality of biomass, it is necessary to do research on effects of drying on pellets for higher income (Peksa-Blanchard *et al.*, 2007).

2.6.1.3 Grinding

Grinding is another form of milling which breaks down the biomass materials into smaller sizes. According to Peksa-Blanchard *et al.*, (2007), material ought not to be ground to a size bigger than the diameter of the pellet (~6 mm) to produce granules with a consistency like that of bread crumbs. Raw material ought to be screened to remove unwanted materials before grinding.

2.6.1.4 Conditioning

Most pelletizing machines has in-built steam conditioning chamber. The chamber has a super-heated steam at temperature over 100 °C (212 F), and it is utilized in softening the biomass material before it undergoes compaction. Steam conditioning is not fundamental procedure however it makes the raw material less abrasive for pelletization (Peksa-Blanchard *et al.*, 2007).

2.6.1.5 Pelletizing

Pelletizing machines, otherwise called extruders, are accessible in a scope of sizes. For most machines, every 100 horsepower gives a limit of around one tonne of pellets for every hour. There are generally two common forms pelletizing machine;

- Flat: where biomass materials are squeezed through the highest point of a horizontal mounted die.
- Revolving: where (at least two) rotating presses drive biomass material from inside a ring die to the outside where it tends to be cut into an ideal length (Peksa-Blanchard *et al.*, 2007).

The two systems make pellet by utilizing a lot of pressure to constrain the biomass material through openings in the die. The temperature of the biomass material increases as the pressure and friction between the materials and the walls of the die increases. This softens the lignin and fibre materials to be shaped into pellet form. (Peksa-Blanchard *et al.*, 2007).

2.6.1.6 Cooling

The cooling procedure is important to the pellet quality and durability. Pellets leave the extruder hot at temperature between 90 °C and 95 °C, and are delicate. Therefore, they are continuously

air cooled, which enables the lignin to harden and reinforce the pellets. Rather than the drying procedure, cooling does not include addition of energy. The three widely known coolers are: horizontal, vertical and continuous flow cooler (Peksa-Blanchard *et al.*, 2007).

2.6.1.7 Screening

After pellets are cooled, they are moved over a vibrating screen to expel any fine material. These expelled fine particles are betokened over into the pelletizing process to guarantee that no raw material go waste. Screening guarantees are fuel source are clean and as close to dust free as could be expected under the circumstances. Once screened, pellets are prepared to be packaged for an ideal end use (Peksa-Blanchard *et al.*, 2007).

2.6.1.8 Distribution and storage

Distribution of pellet are done in bulk, by truck, rail or ship or packed in smaller quantities. Pellets can be obtained either in bagged or bulk and cost can be determined per complete load as per the moisture content (Peksa-Blanchard *et al.*, 2007).

2.6.2 Types of Biomass densification

Due to the non-uniform, low energy density and the handling difficulties of biomass materials, densification seem to be a desirable technique that permit simpler and more economic storage, transportation and energy transformation qualities (Demirbas *et al.*, 2004). Biomass is densified by two primary procedures: mechanical densification and pyrolysis. Mechanical densification is carried out by applying pressure to precisely densify the materials whiles Pyrolysis involves heating the biomass at high temperature without oxygen (Clarke and Preto, 2011). The technique for densification depends on the type of biomass material.

2.6.2.1 Mechanical densification

Pellets are highly densified fuel source. They are simpler to deal with than other densified biomass products. Pellets are framed by an expulsion procedure, utilizing a cylinder press, where finely ground biomass material is constrained through round or square cross-sectional dies the bucket and cut to an ideal length. A standard biomass pellet is uniformly cylindrical in shape, with length less than 38 mm and diameter not above 7 mm. Pellets have varied ash and energy content based on the grades and type of biomass materials used (Clarke and Preto, 2011).

Cubes are typically square fit bigger pellets. They are less thick compared to pellets. Shape sizes go from 25-102 mm in length and 13-38 mm in cross section. The procedure involves compacting the biomass materials with a press wheel and forcing it through dies to create 3D shapes (Clarke and Preto, 2011).

Briquettes are like pellets yet vary in size. It has a diameter of 25 mm (1 in.) and above, and are produced by forcing it through a die under high pressure using piston press. But screw extruder can be used in place of piston press, where the biomass material is extruded through a heated die by a screw. Briquettes made by screw expulsion exhibit higher storability and energy density properties than briquettes made by piston press (Clarke and Preto, 2011).

Pucks are comparable in appearance to a hockey puck, with its density similar to pellets. It is made by a briquetting machine usually 75 mm (3 in.) in width and are flexible to moisture. Pucks production require lower costs compared to pelletization but are moisture resilient (Clarke and Preto, 2011).

2.6.2.2 Pyrolysis

Slow Pyrolysis; Slow pyrolysis involves the slow heating of biomass materials in the absence of oxygen or air. The process takes place at temperature between 350 °C and 500 °C. The end product, which is charcoal, contains 60-70 % of the energy in the biomass material (Clarke and Preto, 2011). The slow pyrolysis process is of special interest because it seems to be able to have greater effect on decreasing the rate of climate change. Higher share of biochar can work as a carbon sink as well as increase the agricultural productivity of soils (Shabangu *et al.*, 2014).

Fast Pyrolysis; It involves high temperature process in which biomass material is quickly heated at high temperature (450 °C and 500 °C) in an airtight environment (without oxygen). Accordingly, the biomass material disintegrates to produce generally vapours, aerosols and charcoal (Bridgwater *et al.*, 1999). This process is primarily use to produce bio-oil and gas.

Another type of pyrolysis is torrefaction. This process also involves decomposition of biomass but at much lower temperature. Biomass torrefaction involves thermal process of converting biomass materials into a high-grade solid fuels or coal-like fuel. It is produced by heating biomass materials at temperatures between 280 °C and 320 °C for a couple of minutes in an inert environment. End products of torrefaction are homogeneous and stable, has high energy density and heating value, resistant to biologically degradation and improved storage characteristics (Clarke and Preto, 2011). Decomposition of biomass materials by torrefaction is mainly reliant on temperature, due to the fact that cellulose ordinarily decays at high temperatures 330 °C and above (Lu *et al.*, 2012; Saadon *et al.*, 2014).

2.7 Pelletizing techniques

Biomass pelletization are grouped into three main techniques; high pressure compaction, medium pressure compaction and low-pressure compaction. Selection of pelletization technique basically depends on type of biomass, the binding agent added and the required pressure to be applied.

2.7.1 High and medium pressure compaction

High and medium pressure compaction technology are typically being termed binderless technology because they do not require binder agent for pelletization. The compaction process is done using a piston press or screw press (Sokhansanj *et al.*, 2005). High pressure densification of biomass brings about strong interlocking and increased adhesion or cohesion between the biomass materials. This create intermolecular bonds between the contact surfaces of the materials. The applied pressure causes interlocking of the fibre materials during the coupling process. The process is increased by the wrapping and overlapping of the solid materials (Tabil *et al.*, 1997). Lignin in biomass material serves as a binding agent. This technology is carried out using pellet mill.

2.7.1.1 Pellet mills

Pelleting process involves squeezing the material through a die, worked in the outskirts of a pivoting ring die. Fitted rolls drives the feed biomass material into the die openings from within the ring towards the outside. The pressure exerted by the rolls causes friction between the materials and the walls of the die, hence compressing the fibre materials against one another inside the die. The friction inside the die causes heat build-up and temperature is elevated to 75-

85 °C as the materials are forced out of die opening. At this point, the lignin is heated and begins to melt, therefore begins streaming off the fibre material. In this state, the lignin is able to bind the fibre materials together (Samson *et al.*, 2000). The compacted feed goes through the die ceaselessly and the extruded pellets are cut into preset lengths with a blade. According to Sokhansanj *et al.*, 2005, the power required to run pellet mills may extend from 15 to 35 kW/t for feed materials. The two most common types of pellet mills are the **flat die mill** and **ring die mills**. The flat die mill operates by rotating the rollers and compressing the feed materials at the same time as the die stays stationary, while the ring die mill operates by rotating the die itself (Chen *et al.*, 2008).

Flat die mill: Flat die mill is the commonest pellet mill in the market. The main parts of flat die pellet are flat horizontal die and the set of rollers. Flat die mill is simpler in structure, less expensive and lighter in weight compared to ring die mill. Flat die mill is further classified into two main types; die-turning type and roller-turning type. Die-turning flat die mill operates by rotating both the die and a set of rollers while roller-turning flat die mill operates by keeping the die stationary and rotating the set of rollers, and it is the popular flat die mill in the market.

Ring die mill: In the assembly ring die mill machine, feed materials are compacted by the rotating rollers and are forced through the openings of the ring die. Pellets discharged out of the extruder are of high quality. Compared to flat die mill, ring die mill has higher efficiency, less energy requirements and longer life span. The only disadvantage is that ring die mill is more convoluted and sophisticated, therefore the cost is generally higher. Ring die mill is generally used in large scale pellet production.

2.7.2 Lower pressure compaction

This technique of pelletization uses low pressure for compaction therefore a binding agent is required to facilitate the bonding formation between the fibre materials. Low pressure compaction is achieved by simple moulded press. Hand mould pelletizer is the least complex devices used to frame pellets on small scale production. This technique of pelleting of mostly used in rural areas in some African countries for small pellet production. The hand moulded pelletizer consist of moulds and pistons which is manually pressed with low pressure to get the cylindrically shaped pellets. Since pressure produced is low, binders are added to give a compacted shape. These binders are either organic (starch, resin, coal tar) or inorganic (cement, clay, lime).

2.8 Storage and consumption of Biomass pellets

Storage of the pellets is given little attention; however, this is utterly crucial to maintain the mechanical properties of pellets for long period of time. Due to seasonal fluctuations with periods of high demand (winter) and periods with moderate or low demand (summer months) pellet producers and intermediate traders need large storage space (Stelte, 2012). According to Stelte (2012), Pellets are stored in either a silo or on a flat storage building Storage. Silo storage is the most widely recognized method of pellet storage for pellet producers, habours and power plants. Silos consumes less space as storage halls and can be filled and emptied easily using screw conveyors. Flat storage building on the other hand are utilized for huge capacity of pellets storage for large scale pellet production. This method of storage is used at the pellet production sites, for wholesale of pellets at harbors and at final consumer. Biomass pellets can easily absorb moisture from the surrounding and deteriorate at storage if the required storage

conditions and practices are not carried out perfectly. This may therefore decrease the calorific value of the fuel pellet. Lee *et al.*, (2015), studied storage of pellets in an open or closed storage configuration. He reported that in open storage, moisture is the main contributing factor to the change in net calorific value. Higher storage temperature decreases moisture content of the wood pellets and hence results in increase in net calorific value. Akowuah *et al.*, (2012), evaluated the physico-chemical characteristics of sawdust charcoal briquette that must be met for potential market. The authors indicated that for potential market, briquettes must have moisture and ash content as low as 5.7 % and 2.6 %, high heating value of at least 4.820 kCal/kg and must be environmentally friendly with sulfur and nitrogen as low as 3.3 % and 0.28 % respectively. Kaliyan and Morey (2009), examined the composition of raw materials of biomass fuels and pointed out that increase in moisture content of pellets and briquettes was as a results of storage conditions such as high relative humidity which eventually reduces the strength and quality of the pellets and briquettes. The storage life of biomass pellets therefore depends on the humidity of the surroundings. A major problem of pellet storage and transport is lost its durability. A critical loss of pellet strength can result in dust buildup, which increases the dangers fire and explosions (Palmer *et al.*, 2011; Hedlund *et al.*, 2014). Pellet is described hygroscopic; thus, whenever it come in contact with water or moist surfaces, it swells up and loose quality. Moist pellets usually self-destruct and causes transport lines blocks and damages (Council, 2012). It is therefore important to consider the storage structure requirements and conditions of pellets for longevity. Optimum moisture content of pellets ought to be 11-13 % for storage over four months (Vladut *et al.*, 2010).

Pellets are utilized in pellet plants for heat and electricity generation by highly efficient and advanced technologies. Pellets are one of the largest globally marketed biomass fuels for energy

generation purposes. Approximately 4 million tonnes of pellets are traded annually and are compared to biodiesel or bioethanol (Heinimo and Junginger, 2009). Of all biomass materials, wood has always been the most popular source of energy used in Europe. In 2016, about 21.7 million tonnes of biomass pellets were consumed in the EU-28, of which 61.7 % was used for heat generation. Biomass pellets used for heat generation is consumed in residential heating, power production, commercial heating and heat generated from combined heat and power (CHP), accounting to 42.6 %, 38.3 %, 11.8 % and 7.3 % respectively. Heat used for power generation is done using combined heat or specialized power plants (Bioenergy Europe, 2017). Due of the accessibility of biomass material, affordability and broadened energy strategies, biomass pellet production is in advance improvement in Europe. Pellet market is in high demand in European countries like Sweden, Germany, Denmark, and Austria. Countries like Italy, France, Belgium and UK as of late developed strong interest for pellet utilization. As at 2006, total pellet production from major producers Sweden, Germany and Austria was estimated to be 4,500,000 tonnes (Peksa-Blanchard *et al.*, 2007). Pellets are utilized generally for little scale private and mechanical warmth in countries like Austria, Germany, Italy, and France (IHB, 2013). In 2016, pellets were generally utilized in Sweden, the largest pellet production country producing approximately 1,458,000 tonnes in 2006, essentially as a choice for heating oil (Peksa-Blanchard *et al.*, 2007; Selkimäki, 2010). The pellets produced in Sweden are primary sold to the Swedish market (PiR, 2009). Pellets plays a major role in fuel utilization Sweden, with practically 60 % being utilized in huge power stations, in region heating, CHP and in residential areas. As at now, industry boilers have been changed over to pellet burning. Biomass specialists have assessed that somewhere in the range of 800,000 and 1,100,000 tonnes of raw material are accessible yearly for pelletizing (Peksa-Blanchard *et al.*, 2007). Pellets

produced in Germany is still moderately small. Be that as it may, positive assessment laws for establishment of biomass pellet combustion frameworks and huge amounts of accessible wood materials make Germany a standout amongst the most potential pellet advertisers in Europe. Over 30 % of the country's land is canvassed in forest. Pellet business has begun in a few areas in Germany in the most recent decade. Distribution of pellets is well settled, with truck transport normal for shorter distance distribution, and sea shipping demonstrating practical for longer distance distribution (Peksa-Blanchard *et al.*, 2007).

Pellet market in Asian shows additionally rapid development, with Japan and South Korea being largest consumers to supplant coal in huge power generation plants. The real interest of pellets is in Europe, the EU as a district is likewise by a wide margin the largest pellet producer of 54 % in 2015, and North America being the second largest of 35 %, which is for the most part trade driven. The remaining 11 % of worldwide pellet production came from minor producers including Asia, Australia, Latin America, and the Russian Federation. In terms of country pellet production, U.S. emerges as the highest producer by a wide margin with 7.4 Mt in 2015 and 6.3 Mt in 2016 (FAO, estimate). Canada is the nation with the most unique growth, having experienced a rapid increase from 1.6 Mt in 2015 to 2.4 Mt in 2015 and 2016 respectively. South Korea is the highest pellet consumer among the Asian countries, principally imported from Vietnam. Notwithstanding, China has defined an objective of utilizing 30 Mt of biomass pellets in 2020 to supplant 15 Mt of coal (Thrän, 2017). In light of ISO 17225-2, two quality divisions are characterized: Pellets for private use and those for industrial use, by studying the market divisions.

Forest area in Africa consist of 16 % of the world's forest area, compared to Europe's 25 %, however larger mass of over-the-ground woody biomass (Hillring, 2006). But Africa makes less

use of the forest resources for energy production. Most of the biomass sources are consumed in its unprocessed state like in the case of firewood, woodchips and charcoal. Few countries like South Africa in the sub-Saharan part of Africa are taking advantage of pellets production though most of their pellet products are exported. According to Ofgem, 2015, South Africa produced 0.1 % (5,160 tonnes) of wood pellets used to generate electricity from April 2013 to March 2014 in UK. Two new technologies to grow South Africa's biomass energy potential; the Howick wood pellet plant, and the Tstsikamma biomass plant failed (Petrie and Macqueen, 2013).



CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter of the study presents materials and methods used in the pellet production process as well as determination of the physical and chemical properties.

3.2 Materials

The materials used for the experiment included: CPH, grinder, analytical balance, calorimeter, binder, sieve, durometer, oven, pelleting machine, digital camera and measuring cylinder.



Figure 3.1: Cocoa pod husk received.



Figure 3.2: Dried cocoa pod husk.

3.3 Methods

3.3.1 Raw material preparation and production of pellets

This study was performed in September 2015, sample of CPH of Amelonado (Tetteh Quarshie cocoa variety) was collected from local cocoa plantation in Ahafo Ano South district in Ashanti

region, Ghana. The CPH was sun-dried for three days. CPH was carbonized at 400 °C for 2 hours using a manually operated biochar kiln to transform the structural molecules of CPH into coal by eliminating water and volatile substances. The charred CPH was crushed, charred, ground and screened to obtain particle size less than 1 mm. Three treatments of varying percentage by mass of CPH and binder (purchased uncooked cassava starch) were applied; 80 % CPH 20 % binder (T₁), 75 % CPH 25 % binder (T₂), and 70 % CPH 30 % binder (T₃) as recommended by Velazquez-Araque and Cárdenas (2017). Cassava starch performs best in uncooked form as a good binder during pelletization (Wood 1987; Suleiman *et al.*, 2009). One kilogram of samples for each treatment was pelletized using a pelleting mould machine at the Technology Consultancy Centre, KNUST. Pellet preparation was repeated three times for each treatment. The samples were then oven-dried at 50 °C for 5 hours. The physical properties and proximate analysis of the pellets were completed using the recorded values. Calorific value of the pellets was determined using bomb calorimeter.

3.3.2 Carbonization and grinding of Biomass Feedstock

The biomass feedstock (cocoa pod husk) was carbonized in a manually operated biochar kiln to obtain a charred biomass. The cocoa pod husk was dried to a moisture content of 10.3 % before it was fed into the biochar kiln. This activity was done in batches. The biochar kiln consists of a firing chamber, air tight carbonizing chamber and a chimney. Fire was set up at the base (firing chamber) of the kiln to heat up the carbonizing chamber to a temperature of 400 °C. At this temperature, the feedstock was fed into the carbonizing chamber and allowed to be carbonized for 2 hours. After 2 hours, the biochar was collected into a basin and allowed to cool to attain

ambient temperature. The cooled biochar samples were crushed in a grinder and screened to obtain 1 mm particle size using a sieve.



Figure 3.3: Cocoa pod husk biochar.



Figure 3.4: Manually operated biochar kiln.

3.3.3 Pelleting of biochar

Pelleting was done using a manually operated 16 mm pelleting mould with at the Technology Consultancy Centre (TCC), KNUST (Figure 3.5). The pelleting mould consist of a steel made hopper, pelleting chamber, removable base plate. One kilogram of samples of each treated feed (grinded biochar mixed with water and starch at percentage of 20 %, 25 % and 30 %) was fed into pelleting chamber through the hopper. The pelleting chamber has a piston which compacts the feed 16 KN load pressure to form a pellet which is extruded at the base of the mould. The base plate was gently removed to prevent breakage of the pellets. The procedure was repeated for all the samples.



Figure 3.5: Pelleting mould.

After pelleting, the dimensions and mass of each extruded sample were recorded according to their binder percentages using Vernier caliper and an electronic balance respectively. The samples were then oven-dried at a temperature of 50 °C for 5 hours. The height and mass of each sample were again recorded after drying.



Figure 3.6: Produced pellets.

3.4 Determining physical and proximate analysis of CPH pellets.

3.4.1 Physical properties

Samples were taken from each batch of treatment and the following physical properties were determined,

- Compressed density
- Relaxed density,

- Moisture content (wet basis)
- Shatter index, were determined.

The detailed description of the methods used in determining the various physical properties are shown in the next section

3.4.2 Compressed and relaxed density

The compressed density of each pellet was determined after extrusion from the pelleting machine. The relaxed density was determined after oven drying at 50 °C for 5 hours to evaporate water from the pellets. Both the compressed and relaxed density were calculated from the ratio of mass of the pellets to its volume using Equation (1). The mass was determined using an electronic balance and the volume was determined from the height and diameter of the pellet. The procedure was repeated for five briquettes and the average value determined.

$$\rho = \frac{M}{V} \dots\dots\dots (1)$$

Where,

ρ = Density of the pellet (g/cm³)

M = Mass of the pellet (g)

V = Volume of the pellet (cm³)

3.4.3 Moisture content of pellets

The mass of the pellet was measured immediately after extrusion from the pelletizer and after sun drying. The moisture content in wet basis was then determined using Equation (2).

$$MC_{wb} = \frac{M_{ib} - M_{if}}{M_{ib}} \times 100 \% \dots\dots\dots (2)$$

Where MC_{wb} is moisture content in percentage wet basis, M is mass measured in grams, and the subscripts ib and fb are pellets initial and final mass respectively.

3.4.4 Shatter index

Shatter index is used to determine the mechanical strength of pellets and its tolerance during handling and at storage. The shatter index is defined as the proportion by weight of standard specimens which is retained by a particular sieve when the specimens have been shattered by falling from a particular height onto a solid plate. In the experiment, five samples of the pellet were put in a polyethylene bag and allowed to fall from a height of about 2 m onto a cemented floor. The samples were passed through 20 mm Tyler sieve and the mass of broken pieces of pellets retained on the sieves were measured using electronic balance. The remaining percentage of the sample on the sieve after the sample has been subjected to a standardized dropping procedure is the shatter index. The shatter index was therefore calculated using Equation (3).

$$R = \frac{M_1}{M_2} \dots \dots \dots (3)$$

Where,

R = Shatter index

M_1 = Mass of pieces of pellet retained (g)

M_2 = Initial mass of pellet before sieving (g)

3.5 Proximate and heating value analysis

Proximate and heating value analysis were performed and the determined components include;

Proximate and heating value analysis were also performed, components determined include:

volatile matter (VM %), ash content (AC %), moisture content by dry basis (MC_{db}), fixed carbon (FC %), and calorific value. Below are detailed descriptions of the methods used in determining these components.

3.5.1 Volatile matter (VM %)

This was determined by pulverizing 2 g of CPH pellet sample in a crucible and oven dried until constant weight is achieved. The pulverized sample were kept in a furnace at 550 °C for 10min and allowed to cool to attained ambient temperature. The sample was weighed using an electronic balance. The volatile matter was calculated using Equation (4).

$$VM = \frac{A-B}{A} \dots \dots \dots (4)$$

Where A, and B are the weight of the sample dried in an oven and weight of samples heated in a furnace at 550 °C for 10 min respectively.

3.5.2 Ash Content (AC %)

Two grams of pellet was oven dried until a constant weight was achieved. The sample was then heated at 550 °C in a furnace for 4 hours and the weight measured after cooling in a desiccator. The ash content was calculated using Equation (5).

$$AC = \frac{C}{D} \dots \dots \dots (5)$$

Where C is the weight of the sample dried in an oven and D is the weight of sample after heating in a furnace at 550 °C for 10min.

3.5.3 Moisture content in dry basis (MC_{db})

Two grams of pellet was placed in a crucible and dried in an oven until a constant weight was achieved. The change in mass after 60 min was used in the determination of the moisture content in dry basis as shown in Equation (6).

$$MC_{db} = \frac{E}{F} \dots \dots \dots (6)$$

Where E is the change in mass after drying and F is the initial mass of the sample which is 2 g in this case.

3.5.4 Fixed carbon (FC %)

The fixed carbon of the pellet was calculated by subtracting the percentage sum of volatile matter (VM %), ash content (AC %) and moisture content (MC_{db} %) from 100 % as shown in Equation (7).

$$FC \% = 100 - ((VM \%) + (AC \%) + (MC_{db} \%)) \dots \dots \dots (7)$$

3.5.5 Calorific value

The calorific value of the pellet was determined using bomb calorimeter. 4 g of pellet was burnt in a bomb calorimeter at maximum and minimum temperatures until complete combustion is achieved. The gross calorific value is calculated from the difference between the maximum and minimum temperatures and the calculated volatile matter and carbon content as shown in Equation (8).

$$Q = 2.326(147.6c + 144v) \dots \dots \dots (8)$$

Where:

Q = calorific value of pellets (kJ/kg)

C = carbon content

V = volatile matter

KNUST



CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Physical properties of cocoa pod husk pellets

In order for CPH pellets to be used as biofuel, it must meet certain standard property values. These property values and their significance to pellets are discussed in this chapter. The compressed density, relaxed density, relaxation ratio, moisture content and durability or shattering resistance of CPH pellets were calculated and presented in Table 4.1. The masses and dimensions (height and diameter) for three (3) samples at different binder percentage of 20 %, 25 % and 30 % were recorded and the average values determined. The mass of pellets immediately after extrusion from the pelleting machine and after drying was also recorded. Dimensions of pellets were also recorded and used to calculate the property values. A one-way independent between-binder percentage analysis of variance (ANOVA) was calculated to determine the significant effect of the various binder percentage on the physico-chemical and combustion properties of CPH pellets. Since there was a need to establish the joint significant between group of variables, F-test was used. The results were analyzed with respect to alpha level of 0.05.

Table 4.1: Physical properties of CPH pellets produced at different binding percentage.

Sample No.	Binding percentage (%)	Compressed Density (g/cm ³)	Relaxed density (g/cm ³)	Relaxation ratio
T ₁	20	1.04	0.85	1.23
T ₂	25	1.10	0.86	1.29
T ₃	30	1.16	0.86	1.36

In Table 4.1, values for compressed densities of pellet at different binder percentage were obtained. Binding percentage 20 %, 25 %, and 30 % produced 1.04 g/cm³, 1.10 g/cm³ and 1.16 g/cm³ compressed density (density immediately after extrusion from the pelleting machine) respectively. Results from ANOVA shows that binder percentage has a significant effect on the compressed density of the pellets, with $F(2, 6) = 162$ ($> F_{\text{critical}} = 5.14$) and $P \text{ value} = 6.01 \times 10^{-6}$ (see Appendix B). This means the results did not happen by chance; hence the null hypothesis can be rejected. The pellet with 20 % binder recorded compressed density of 1.04 g/cm³ which was lower than 25 % (1.10 g/cm³) and 30 % (1.16 g/cm³). The compressed density therefore increased with increase binding percentage. The rise in compressed density with increased binder percentage can be ascribe to the binder (starch) reducing the pores, therefore the volume of the pellet. Variation in compressed density can be attributed to the moisture in the binder (starch) which caused increase in the mass per unit volume of the pellet (Tembe, 2014). After drying of the pellets in an oven, the relaxed densities at different binder percentage was determined. The relaxed density also followed similar trend as compressed density, increasing from 0.85 g/cm³ at 20 % binder to 0.86 g/cm³ at 30 % binder. This observation was similar to that for pellets produced from sawdust, peat shell, palm fibre, rice husk and coconut fibre (Chin and Siddiqui, 2000). But there was no significant difference between the pellets, as $F(2, 6) = 1.50$ ($< F_{\text{critical}} = 5.14$) and $P \text{ value} = 0.30$ (see Appendix C). Comparison between the compressed densities and relaxed densities gives an indication of volume displacement in the pellet after drying. Therefore, the binder percentage with the lowest relaxed density and lowest difference in densities could be more stable, thus 20 % binder.

The relaxation ratio, thus the ratio of compressed density to relaxed density describes the stability of the pellet at various binder percentages. This is used to confirm the values of

compressed and relaxed densities. In Table 4.1, 20 %, 25 % and 30 % binding percentage recorded 1.23, 1.29 and 1.36 relaxation ratios. The analysis of variance shows the binding percentage had a significant effect on the relaxation ratio of the pellet, with $F(2, 6) = 47.63$ ($> F_{\text{critical}} = 5.14$) and $P \text{ value} = 2.08 \times 10^{-4}$ (see Appendix D). A comparative result was made for pellets produced from feed material (hay) which had relaxation ratio of 1.68 to 1.80 which were slightly higher (O'Dogherty, 1989). The least relaxation ratio which approaches 1 gives an indication of pellet with the most stable binder percentage. According to Davies *et al.*, (2013), estimations of relaxation ratio implied that pellets of low relaxation ratio showed low elastic property and much stable pellets than pellets of high relaxation ratio. From the analysis it can be stated that, 20 % binder is the optimum binder percentage required to densify the pellet. Hence, the pellet with this binder percentage has required strength for mechanical handling, transportation and storage.

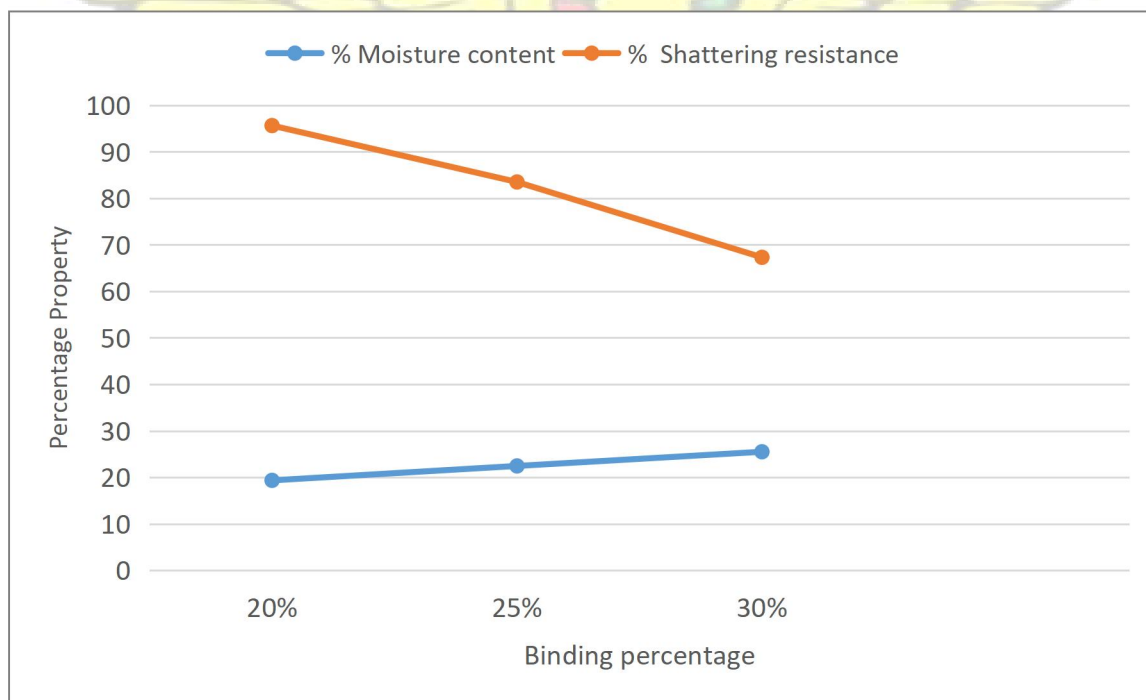


Figure 4.1: Relationship between moisture content and shattering resistance of pellets.

The moisture content by wet basis of pellets after drying was determined for each binder percentage. In Figure 4.1, pellets of binding percentage 20 %, 25 % and 30 % produced moisture content of 19.34 %, 22.44 % and 25.49 % respectively. The moisture content increased linearly with increase in binder percentage. This signifies the effect of the binder on the moisture content of the pellets. Pellets of lower moisture content is desirable since it reduces the rate of deterioration at storage and its weight for transportation. The nature of CPH as a fuel source is considerably influenced by its moisture content. A rise in the moisture content of pellets will cause a reduction in its heating value, which thus decreases the conversion effectiveness in light of the fact that a lot of energy would be utilized to vaporizing the moisture in the fuel (Suarez, 2003). The shattering resistance, which represent the durability of the pellet indicates the tolerance of the pellet utilization, transportation and storage. The shattering resistance decreased with increase binder percentage from 95.6 % at 20 % binder, 83.5 % at 25 % binder to 67.3 % at 30 % binder. It was however analyzed that the binder percentage had a significant effect on the shattering resistance of the CPH pellets, as the analysis of variance produced $F(2, 6) = 62.25 (> F_{critical} = 5.14)$ and $P\text{ value} = 9.72 \times 10^{-5}$ (see Appendix E). Increasing trend of moisture content with decreasing shattering resistance as binder percentage increases could mean that the binder holds the particles together and prevent water loss from the pellets. Pellets with high moisture content therefore becomes susceptible to breakage. Hence increase in binder percentage increased the moisture content in the pellet and decreased the shattering resistance of the pellet. This suggests pellets produced with lower binder (starch) concentration are progressively durable and impervious to mechanical stress.

Comparing the data represented in Figure 4.1, the moisture content of pellets increases with increased binder percentage while the durability of pellets decreases with increasing binder percentage. Hence pellet with optimum binder percentage should have lowest moisture content with highest shattering resistance, thus 20 % binder.

4.2 Proximate and heating value analysis of CPH pellets

4.2.1 Proximate analysis of CPH pellet

After complete combustion of the pellets, component values of the burnt pellets are determined to analyze the combustion characteristics of pellets at different binder percentage. These combustion properties of the pellets are referred to as proximate values, which includes; moisture content in dry basis (MC_{db} %), volatile matter (VM %), ash content (AC %) and fixed carbon (FC %), as shown in Figure 4.2.

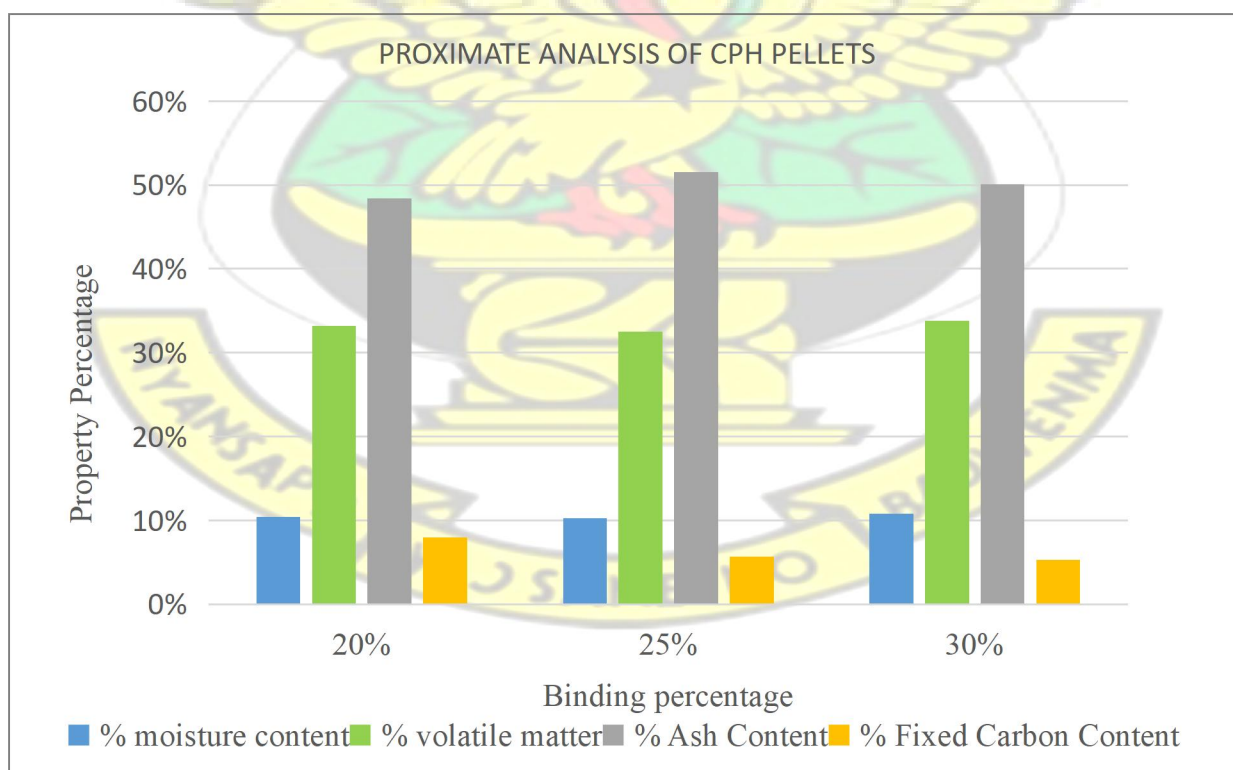


Figure 4.2: Proximate analysis of CPH pellets.

It was observed that pellets with binder percentage 20 %, 25 % and 30 % produced moisture content of 10.4 %, 10.3 % and 10.8 % respectively. Analysis of difference between the binder percentage, $F(2, 6) = 2.21$ ($F_{\text{critical}} = 5.14$) and P value = 0.19 (see Appendix F), shows binder percentage had no significant effect on the pellets. These results are higher than González *et al.*, 2004, who reported 8.8 % moisture content for forest pellet but lower than Syamsiro *et al.*, (2011), who produced CPH pellet with 16.1 % moisture content. High moisture content is undesirable for combustion as it reduces the heating value of pellets. Hence lower binder percentages have positive effect on the combustibility of pellets for heating processes. The percentage volatile matter represents the percentage component of pellets, aside moisture, which are evaporated at high temperature in the absence of air. Pellets of 30 % binder recorded the highest percentage volatile matter of 33.8 %, followed by 20 % binder (33.2 %) while 25 % binder recorded lowest volatile matter of 32.5 %. The analysis shows there was significant difference between the binder percentage, $F(2, 6) = 15.98$ ($F_{\text{critical}} = 5.14$) and P value = 3.95×10^{-3} (see Appendix G). The difference in volatile matter can however be due to the difference in binder percentage. The results are all lower compared to Forero-Núñez *et al.*, (2015), who reported average volatile matter of 58.46 % for CPH pellets. Volatile matter is one of the properties administering the ignition and stability of flame, the reactivity and burnout of biochar, and the measure of unburned carbon in the fly ash (Carpenter, 1998). Hence, the pellets are all expected to generate less smoke and burn with high flame since they have volatile matter less than 100 % (Adekunle *et al.*, 2015). According to Obernberger and Thek (2004), volatile matter determines the combustion ability of biofuels. Pellets with high volatile matter implies easier to ignite, better smoke stability and more heating value discharge in the form of vapour

combustion. There was variation of percentage ash content with binder percentage but did not increase with increasing binder percentage. The pellet with 25 % binder recorded the highest percentage ash content of 51.5 %, followed by 30 % binder which recorded 50.1 %, while 20 % binder recorded the lowest of 48.4 % ash content. Analysis between the binder percentage, $F(2, 6) = 21.20$ ($> F_{critical} = 5.14$) and $P \text{ value} = 1.906 \times 10^{-3}$ (see Appendix H), shows the binder percentage had significant effect on the ash content. Ash content is the non-combustible remains of pellet after being burnt in a furnace (Obi *et al.*, 2013). Hence lower percentage of ash content is desirable as it indicates that higher percentage of the pellet is utilized. The ash content of pellets regularly cause increment in combustion remains as slag which decreases the heating value, pellets of low ash content gives off high heating value (Obi *et al.*, 2013). The 20 % binder is therefore desirable for high heating value and conversion efficiency.

Percentage fixed carbon of the pellets were also recorded at the various binder percentages. Percentage fixed carbon decreased with increase in binder percentage as 20 %, 25 % and 30 % binder recorded 8.0 %, 5.7 % and 5.3 % fixed carbon respectively. Results from the analysis, $F(2, 6) = 13.53$ ($> F_{critical} = 5.14$) and $P \text{ value} = 5.98 \times 10^{-3}$ (see Appendix I), shows the analysis was statistically significant. These results are lower compared to Forero-Nuñez *et al.*, (2015) who reported 16.8 % fixed carbon for cocoa pod husk pellets. Fixed carbon is a proportion of combustible solid in biofuels after expelling the volatile matter; its substance is used as a gauge of measure of coke obtained on carbonization (Diaz *et al.*, 2002). This implies that, pellets of high fixed carbon are favourable for high heating value.

4.2.2 Calorific or heating value analysis of CPH pellets

The gross calorific value (heating value) of pellet is the amount of heat energy discharged when a specified quantity of pellets undergoes complete combustion. For heating processes, calorific value is a significant property of the pellet. The energy output of a pellet is determined using a bomb calorimeter which measures the specific energy output of a pellet during complete combustion. The obtained results are presented in Table 4.2.

Table 4.2: Average combustion properties of CPH pellets

Binder Percentage (%)	MC (db) (%)	VM (%)	AC (%)	FC (%)	GCV (MJ/kg)
20	10.4	33.2	48.4	8.0	13.8
25	10.3	32.5	51.5	5.7	13.3
30	10.8	33.8	50.1	5.3	13.9

The average values of properties the determines the combustion of CPH pellets are shown in Table 4.2. Comparing the heating values of the pellets at different binding percentage, it is observed that 20 %, 25 % and 30 % binder recorded heating values of 13.8 MJ/kg, 13.3 MJ/kg and 13.9 MJ/kg respectively. These results are lower than Syamsiro *et al.*, (2011) and Tembe (2015) who obtained 16.7 MJ/kg and 17.0 MJ/kg for groundnut pellet and Indonesian cocoa pod husk pellet respectively. Analysis of the difference in binder percentage on gross calorific value produced statistically significant results with $F(2, 6) = 39.01$ ($> F$ critical = 5.14) and P value = 3.64×10^{-4} (see Appendix J). The variation of the heating value can be attributed to the difference in density of the pellets, therefore variation of the binder percentage, which had significant

impact on combustion properties of the pellet (Egbewole *et al.*, 2009; Obi *et al.*, 2013). The 20 % and 30 % binder pellets recorded close heating values, which implies that any of the two pellets could be suitable for heating processes. The difference in the heating values could also be linked to the variation in the ash content of the pellets. The low heating value of 25 % can be attributed to the high ash content value which could decrease the heating value by storing some energy.



CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study was conducted to investigate the quality of cocoa pod husk (CPH) pellet as an alternative source of fuel for domestic heating processes. Experimental results for the physico-chemical and combustion properties of pellets at various binder percentage was analyzed. The following conclusions were made;

1. The binding percentage had a significant effect on the physico-chemical and combustion properties of CPH pellets.
2. Results obtained from compressed density, relaxed density and relaxation ratio indicates 20 % binder is appropriate to densify the pellet.
3. The moisture content and shattering resistance or durability analysis of the pellets at different binder percentage shows 20 % binder pellet is advantageous in terms of transportation, mechanical handling and storage.
4. The moisture content, volatile matter, ash content and fixed carbon content was greatly influenced by the binder percentage. Analysis of the values obtained for these combustion characteristics reveals 20 % binder exhibits better burning characteristics, with 25 % binder a close alternative to consider.
5. The gross calorific value varied with binder percentage but did not follow increasing or decreasing pattern. 20 % and 30 % binder produced a close heating values with 30 % binder slightly higher.

6. Though 30 % binder pellets produced heating value closely higher than 20 % binder, 20 % binder pellet is considered the best binder since it exhibits better densification and durability than all the other pellets.
7. Since pellets generally exhibited low heating energy value, it can be concluded that CPH is desirable for cooking and other domestic use.

5.2 Recommendations

The following recommendations should be considered for further studies of this work:

1. Different binder and binding percentage should be used to analyze the physical and combustion characteristics of pellets.
2. Experiments should be conducted to examine the environmental friendliness of the by-products of the CPH pellets.
3. Experiments on different cocoa varieties should be conducted and their physical and combustion properties be compared.
4. Studies should be conducted to determine ways of increasing the heat energy of CPH pellets for higher heating processes.

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APPENDICES

Appendix A

Determination of physical properties of CPH pellets at different binder percentage.

Binding percentage	Sample no.	Mass of pellet before drying (g)	Height (cm)	Diameter (cm)	Volume (cm ³)	Compressed density (g/cm ³)
20%	1	75.5	3.23	5.36	72.99	1.03
	2	77	3.29	5.33	73.44	1.05
	3	76.3	3.26	5.345	73.22	1.04
						1.04
25%	1	76	3.11	5.32	68.98	1.1
	2	75.75	3.10	5.32	68.72	1.1
	3	75.5	3.08	5.32	68.45	1.1
						1.1
30%	1	76.5	2.99	5.28	65.46	1.17
	2	76.5	3	5.29	65.91	1.16
	3	76.5	3	5.285	66.39	1.15
						1.16

Binding percentage	Sample no.	Mass of briquette after drying	Height (cm)	Diameter (cm)	Volume (cm ³)	Relaxed density (g/cm ³)	Relaxation ratio
20%	1	61.5	3.25	5.3	71.83	0.86	1.21
	2	61.5	3.27	5.32	72.65	0.85	1.23
	3	61.5	3.29	5.33	73.46	0.84	1.25
						0.85	1.23
25%	1	57	3.02	5.28	66.12	0.86	1.27
	2	57	2.99	5.3	66	0.86	1.31
	3	57	3.005	5.29	66.06	0.86	1.29
						0.86	1.29
30%	1	59	3.12	5.3	68.83	0.86	1.36
	2	58.5	3.07	5.33	68.5	0.85	1.36
	3	58.75	3.095	5.315	68.665	0.87	1.36
						0.86	1.36

Appendix B

Compressed density of CPH pellets (g/cm³)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
CPH 20%	3	3.12	1.04	0.0001
CPH 25%	3	3.3	1.1	0
CPH 30%	3	3.48	1.16	0.0001

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0216	2	0.0108	162	6.01E-06	5.143253
Within Groups	0.0004	6	6.67E-05			
Total	0.022	8				

Appendix C

Relaxed density of CPH pellets (g/cm³)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
CPH 20%	3	2.55	0.85	0.0001
CPH 25%	3	2.58	0.86	0
CPH 30%	3	2.58	0.86	0.0001

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0002	2	0.0001	1.5	0.296296	5.143253
Within Groups	0.0004	6	6.67E-05			
Total	0.0006	8				

Appendix D

Relaxation ratio of CPH pellets

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
CPH 20%	3	3.69	1.23	0.0004
CPH 25%	3	3.87	1.29	0.0004
CPH 30%	3	4.08	1.36	0

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0254	2	0.0127	47.625	0.000208	5.143253
Within Groups	0.0016	6	0.000267			
Total	0.027	8				

Appendix E

Shattering index of CPH pellets

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
CPH 20%	3	2.869	0.9563	7.93E-05
CPH 25%	3	2.505	0.835	0.000964
CPH 30%	3	2.018	0.672967	0.001878

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.121246	2	0.060623	62.2505	9.72E-05	5.143253
Within Groups	0.005843	6	0.000974			
Total	0.127089	8				

Appendix F

Moisture content of CPH pellets (%)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Row 1	3	0.313	0.10433	1.43333E-05
Row 2	3	0.310	0.10334	2.32318E-06
Row 3	3	0.324	0.10785	6.14305E-06

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.35746E-05	2	1.68E-05	2.208900	0.191	5.1432
Within Groups	4.55991E-05	6	7.6E-06			
Total	7.91738E-05	8				

Appendix G

Volatile matter of CPH pellets (%)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Row 1	3	0.9697	0.32323	0.00010
Row 2	3	1.126	0.37533	0.00045
Row 3	3	0.836130	0.27871	0.00076

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.01403	2	0.00705	15.9782	0.00395	5.143253
Within Groups	0.00264	6	0.00044			
Total	0.01667	8				

Appendix H

Ash Content of CPH pellets (%)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Row 1	3	1.45258	0.48419	5.20189E-05
Row 2	3	1.54486	0.51495	4.79743E-05
Row 3	3	1.50243	0.50081	6.72101E-07

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0014225	2	0.00071	21.1965348	0.0019	5.1433
Within Groups	0.0002013	6	3.36E-05			
Total	0.0016238	8				

Appendix I

Fixed carbon content of CPH pellets (%)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Row 1	3	0.352	0.117333	0.000729
Row 2	3	0.17	0.056667	3.03E-05
Row 3	3	0.099	0.033	0.000499

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.01135	2	0.00567	13.5294	0.005978508	5.14325
Within Groups	0.00252	6	0.00042			
Total	0.01387	8				

Appendix J

Gross Calorific value of CPH pellets (MJ/Kg)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Row 1	3	41.51	13.835	0.00672
Row 2	3	40.01	13.335	0.0121
Row 3	3	41.76	13.92	0.00422

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.599	2	0.29973	39.01145	0.00036	5.143253
Within Groups	0.046	6	0.00768			
Total	0.646	8				