CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Tropical AgriSciences

Utilization of Cocoa Pod Husks for the Generation of Renewable Energy in Ghana

MASTER'S THESIS

Prague 2024

Author: Bc. Faithful Finney Adubofour

Supervisor: doc. Ing. Vladimír Krepl, CSc.

Declaration

I hereby declare that I have done this thesis entitled “Utilization of Cocoa Pod Husks for the Generation of Renewable Energy in Ghana” independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague April 2024

....
Faithful Finney Adubofour

Acknowledgements

I wish to express my profound gratitude to doc. Ing. Vladimír Krepl, CSc.,who has been a pillar at every stage of this study. To Prof. Francis Kemausor whose active consultations birthed this success, I say thank you. I also want to acknowledge the unwavering support of my family especially my mother who is a true example of strength and resilience. To my best friends particularly Bc. Simona Tomanová and Maxwell Asante Danquah who held me accountable at every stage, I am deeply grateful. I say a grand thank you to myself and all my innate avatars who burned the midnight oil for this success.

Finally, my biggest appreciation goes to the communities of Edwenase, Yaw Nkrumah, Oseikrom and CC Krom who opened their arms to me and cooperated in more ways than required. I would hope this study inspires the electrification of their communities in the future.

Abstract

There is a high energy poverty in the rural communities of Ghana. Crop residues are ubiquitous in rural areas of Ghana as agriculture plays a stellar role in livelihood activities in these communities. In this study, the prospects of exploiting agricultural crop residues for rural development in Ghana through bioenergy schemes are investigated. At 70 % recoverable rate of CPHs, Edwenase produces 53 tons of CPHs annually, which can generate 80,772 kWh of electricity each year. CPHs were identified as important biomass resources for energy generation as they are currently being wasted in Edwenase, who have no waste management system for agricultural residues. To further assess the energy potential of CPHs, different CPH samples were collected in the Edwenase community of Ghana and thermo-chemically characterized using UA and PA. An assembly of LBCs and the local farmers was also made to aggregate data on annual cocoa production and other socio-economic factors that may influence the production, availability, and management of the cocoa. The study revealed the CPHs have a HHV of 18.28 MJ/kg which is comparable to widely used feedstock, such as wood, bagasse, rice husk and straw. The low levels of N and S observed, together with the high heating value, suggest that CPHs are eco-friendly feedstock that can be used to power rural communities in Ghana which can help bridge the poverty gap between urban and rural. As low-class users, CPHs produced in Edwenase has 3 times the potential to supply the community with electricity annually since they only need 24,300 KWh at the household level.

It was however recommended that a techno-economic analysis is performed to understand the cost of generating and utilising such biopower in rural communities.

Key words: Valorization, Biochemical Process, Heating Value, Biopower, Agriculture Residues, Proximate Analysis, Ultimate Analysis.

Contents

List of Figures

List of Graphs

List of Tables

List of the abbreviations used in the thesis

ASH	Ash Content
C	Carbon
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon monoxide
CO_2	Carbon dioxide
CPH	Cocoa Pod Husk
DCs	Developing countries
FC	Fixed Carbon
G	Gram
H	Hydrogen
H_2	Hydrogen gas
HDI	Human Development Index
HHV	Higher Heating Value
Hz	Hertz
IGCC	Integrated Gasification Combined Cycle
IRR	Internal Rate of Return
Kg	Kilogram
Kg/m^3	Kilogram per meter cube
KM	Kilometre
KPIs	Key Performance Indicators
kWh	Kilowatt-hour
LBCs	Licensed Buying Companies
MJ/Kg	Megajoule per kilogram
Ml	Millilitre

Mm	Millimetre
N	Nitrogen
NPV	Net Present Value
O	Oxygen
PA	Proximate Analysis
pH	Potential of Hydrogen
RE	Renewable Energy
REPs	Representatives
S	Sulphur
SEE	Social, Economic, and Environmental
UA	Ultimate Analysis
VM	Volatile Matter

1. Introduction

A good energy mix is key to the availability and distribution of energy in any given system and can also shape sustainable pathways for the economy of that system (Akrofi 2021). The heavy reliance on coal, oil and gas is in recent view considered a carbon (C) generating problem. For most developing countries (DCs), an important source of energy is biomass which raises further concerns beyond C emissions. Biomass has been crucial to the development of certain countries as bioenergy has been applied in the execution of basic life activities such as cooking to complicated systems such as biopowered technologies for electrification. Allcott et al. (2016) much like many others have assessed the role of electrification in the development of countries. Although a climbing electrification rate has been said to have increased the Human Development Index (HDI) of countries like Indonesia, China and Ethiopia, the reverse has been observed for countries like Kenya (Lee et al. 2020). The impact of electrification is therefore not straightforward but is predicated on factors like institutions, environmental conditions and approach to electrification. To elicit this point; Tofu et al. (2022) shows that although Ethiopia increased their HDI as their electrification rate increased, the dependency on biomass for this electrification has direly affected the forest areas and land cover especially in northern Ethiopia. This suggests that the energy system for electrification must be built around sustainable models and inputs.

Yalew (2022) reveals that DCs especially need to establish a modern, flexible, reliable, and affordable energy system that is resilient against its fast-growing energy demand due to high growth population growth rates, urbanization, and industrialization. In consideration to the global pursuit of sustainable and renewable energy (RE) sources, the utilization of agricultural residues for electricity generation has emerged as a promising avenue (Pandey et al. 2016). As the world grapples with the challenges of climate change, dwindling fossil fuel resources, and the need for decentralized energy solutions, researchers and policymakers have turned their attention to biomass-based energy alternatives (Johansson 2013). One such biomass feedstock with substantial untapped potential is cocoa pod husks (CPHs), a by-product of the cocoa industry (Ouattara et al. 2021). Cocoa, primarily cultivated for its beans, is a vital agricultural commodity, particularly in West Africa (ICCO 2019). The residues generated from cocoa processing, especially CPHs, represent a significant biomass resource that can be harnessed for electricity generation (Ofori-Boateng et al. 2016).

CPH is a waste by-product of the cocoa industry, obtained after the removal of the cocoa beans from the fruit. Approximately 52–76 % of the weight of the cocoa fruit is pod husk (Oddoye et al. 2013). In addition, CPHs waste is a problem in the cocoa plantations because it is just left as undesirable waste to rot, constituting an environmental menace and a significant source of disease inoculum such as black pod rot due to the presence of Phytophthora spp. (Yapo et al. 2013; Ouattara et al. 2021). To abate the present dilemma, an economical and environmentally friendly way of dealing with the CPH waste menace is to process it to be of economic value.

CPHs, often considered as waste in traditional agricultural practices, possess intriguing properties that make them suitable for energy production (Adjin-Tetteh et al. 2018). In addition to addressing the environmental challenges associated with agricultural waste disposal, the conversion of CPHs into electricity can contribute to the energy needs of cocoa-producing regions (Ramos-Sánchez et al. 2017). This potential aligns with the broader global objective of promoting sustainable energy solutions and reducing the C footprint of energy generation (Yuan et al. 2022).

The global energy landscape is undergoing a paradigm shift towards cleaner and more sustainable alternatives (Jiang et al. 2022). The depletion of fossil fuel reserves, coupled with the environmental impact of their combustion, has led to an increased focus on RE sources (Zhang et al 2023). Biomass, derived from organic materials such as agricultural residues, forestry waste, and organic municipal solid waste, has gained prominence as a viable RE feedstock (Ashokkumar et al. 2022). The utilization of biomass not only provides a sustainable energy source but also offers an opportunity to mitigate the environmental consequences of agricultural waste disposal (Fatma et al. 2018).

Various studies have explored the potential of different biomass feedstocks for energy generation, including agricultural residues such as rice husks, sugarcane bagasse, and corn stover (Koirala et al. 2019). However, the potential of CPHs, a by-product of the cocoa industry, remains largely underexplored (Asomaning et al. 2018). The global cocoa industry, concentrated in regions like West Africa, South America, and Southeast Asia, generates substantial quantities of CPHs as a by-product of cocoa bean processing

(Schutyser et al. 2018). Understanding and harnessing the energy potential of CPHs can contribute to the global transition towards sustainable and RE sources.

Despite the global recognition of the potential of biomass for energy generation, there exists a significant research gap regarding the quantification and characterization of CPHs for electricity generation (Azapagic et al. 2018). This gap can be bridged by providing a comprehensive analysis of the energy content, chemical composition, and combustion characteristics of CPHs (Adanez et al. 2017). By doing so, it aims to contribute valuable insights into the feasibility and sustainability of utilizing CPHs as a biomass feedstock for electricity generation.

Ghana, as one of the leading cocoa-producing countries in the world, serves as an ideal case study for this research (Oreamuno & Croppenstedt 2023). The country's reliance on traditional energy sources, coupled with the challenges of energy access in rural areas, necessitates the exploration of alternative and decentralized energy solutions (Nyasapoh et al. 2022). Here, we attempt to bridge the gap between global energy trends and the local context in Ghana, offering a nuanced understanding of the potential for CPHs in addressing both environmental and energy challenges.

The Edwenase community, situated in the Ashanti Region of Ghana, is one such locality grappling with energy poverty. While cocoa farming is a prominent economic activity in the area, the disposal of CPHs, a byproduct of cocoa production, has become a significant environmental concern. These husks, often seen as agricultural waste, are usually left to decay, or are inefficiently disposed of, contributing to environmental degradation (Cho et al 2020).. This study focuses on addressing two critical challenges faced by the Edwenase community: the need for a reliable source of RE and the proper management of CPHs. By exploring the potential of utilizing CPHs for the generation of RE, this research aims to contribute to a sustainable and environmentally friendly solution while improving the energy situation in Edwenase.

1.1. Problem statement

Many studies have explored the potential of different biomass feedstocks for energy generation, including agricultural residues such as candlenut shell, sugarcane bagasse, and corn stover (Koirala et al. 2019). However, the potential of CPHs, a by-product of the cocoa industry, remains largely underexplored (Asomaning et al. 2018).

Certain regions generate substantial quantities of CPHs as a by-product of cocoa bean processing worldwide (Schutyser et al. 2018). Ghana serves as a good case study as it produces nearly 20 % of the world’s cocoa (Oreamuno & Croppenstedt 2023). The country's reliance on traditional energy sources, coupled with the challenges of energy access in rural areas, necessitates the exploration of alternative and decentralized energy solutions (Nyasapoh et al. 2022). The inappropriate disposal of CPHs exacerbates the environmental problems in the region, causing health issues and deforestation, and emitting greenhouse gases.

The Edwenase community, like many rural areas in Ghana, lacks access to reliable and affordable sources of energy. This energy deficit significantly hampers economic development, access to education, healthcare, and overall quality of life. The extension of electricity into communities has been considered as a non-option for reasons of it being uneconomic. Edwenase has a population of 442 (Municipal Planning Coordinating Unit 2016) which falls under the 500 people minimum criteria for extending a community unto a grid. In fact, over 50 % of rural communities in Ghana have less than 500 inhabitants (Nelson et al. 2021). This makes it economically unviable to also consider solar sourced energy as demands about 90 % financial support and would need a community that consumes over 600 kilowatts-hour (kWh) electricity a month to be sustainable (Quansah et al. 2017). Mensah et al. (2014) observed that less than 30 % of rural communities in Ghana are connected to the grid.

This necessitates this study as a means of providing a baseline for understanding how biopower systems fuelled by agricultural residues can be chosen, designed, and implemented considering social, economic, and environmental (SEE) feasibility factors.

2. Objective and Methodology

2.1. Objectives + Research questions

The primary objective of this research is to explore the utilization of CPHs for the generation of RE in the Edwenase community of Ghana.

To achieve this overarching aim, the study has the following specific objectives:

- To measure the mechanical, physical, and biological properties of CPHs.
- To describe the current waste management practices for agricultural residues and Quantify the CPH produced in Edwenase.
- To measure the energy value of CPHs from the Edwenase community.
- To propose a technology for the utilization of CHPs as a renewable source of energy for the location of Edwenase.

To guide this study, the following research questions will be addressed:

- What is the quantity and quality of CPHs produced in the Edwenase community?
- What are the feasible technologies for converting CPHs into RE in the Edwenase community?
- What are the environmental impacts and benefits associated with the use of CPHs for RE in Edwenase as a way of waste management for this agricultural residue?
- What recommendations can be made to ensure the sustainable utilization of CPHs for RE in Edwenase, taking into consideration socio-economic and environmental factors?

2.2. Methodology

2.2.1. Dry Ashing and Analysis of Plant Tissues

Here, the principle was that plant tissues were ashed or digested to eliminate organic matter and dissolve mineral elements. The material was burned to destroy the organic matter leaving behind mineral elements. In simple steps, the sample was weighed into a crucible and burned to ash in a muffle furnace. The ash sample was cooled and transferred to a centrifuge tube and rinsed with distilled water and aqua regia. It was then analysed for macro- and micro-nutrients. Concentrations of the nutrients analyzed were measured. This was done according to the protocols of Ayo-Omogie & Osanbikan (2019); Hunter et al. (1984).

2.2.2. Determination of Organic Carbon

The Walkley-Black method was used to quantify the organic C by oxidizing it with potassium dichromate in the presence of sulfuric acid. Elaborately, the sample was digested with sulfuric acid and potassium dichromate. The excess dichromate was titrated with ferrous S. Organic C content and total organic matter were then calculated against the Van Bemellean factor. This was done according to the protocols of Ayo-Omogie & Osanbikan (2019); Heanes (1984).

2.2.3. Determination of Total Nitrogen

The total nitrogen (N) was measured using the Kjeldahl method by digesting samples with sulfuric acid and catalysts, then titrating the liberated ammonia. This was done according to the protocols of Bremner & Mulvaney (1982).

2.2.4. Determination of Hydrogen

The titratrimetric method was used to determine the hydrogen (H) content by titrating digested samples with sodium hydroxide. Samples were first digested with acid and catalysts. The digested sample was then titrated with sodium hydroxide to a pink endpoint. Based on the titration volume, the hydrogen content was calculated. The protocols observed here were according to Mclean (1965).

2.2.5. Determination of Total Sulphur

Total Sulphur (S) was estimated turbidimetrically using a spectrophotometer after digesting with acids and barium chloride. To elaborate, the standards were prepared and same was done for unknown samples. Reagents were added and the samples then incubated. The turbidity was measured, and the S concentration was calculated using a calibration curve. The observed protocols were according to Singh et al. (1999).

2.2.6. Moisture Content Determination

Moisture content was determined by simply drying samples in an oven and calculating the weight differences pre and post to know the weight loss. This was done according to the protocol of AOAC (1990).

2.2.7. Volatile Matter Determination

Volatile matter (VM) was determined by heating the samples to release the volatile components. Similar to the moisture content determination, the weighed sample was heated in a furnace. The VM was then calculated based on weight loss. The observed protocols were in accordance with ASTM (2014).

2.2.8. Information Collection from Assemblies

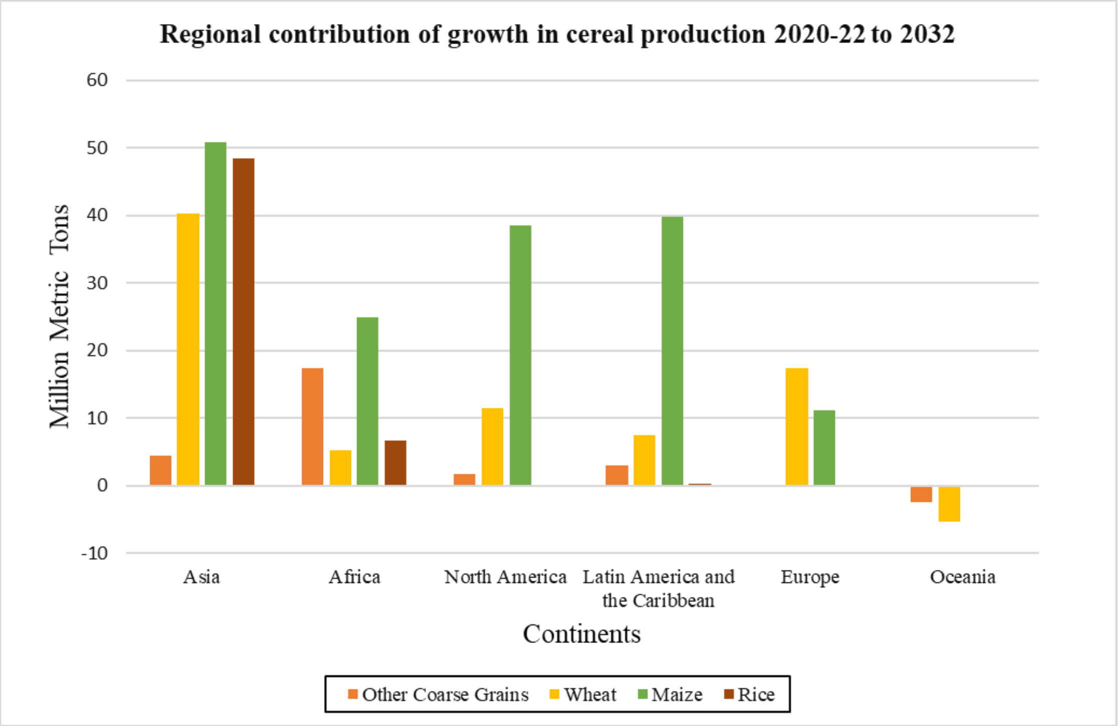
Two assemblies were made during the study. The first assembly comprised of the farmers delegated by the community itself. The second assembly comprised of the delegated farmers and the LBCs. Informal interviews were made at both assemblies and data was gathered.

3. Literature Review

3.1. Global Agricultural Production and Agricultural Residues

Agricultural activities play a key role in global economic growth, food security, and rural development. However, the scale of agricultural production brings a substantial generation of agricultural residues – by-products left after harvesting or processing crops (Shinde 2022).. This section delves into the literature surrounding global agricultural production, the magnitude of residues produced, and the potential of utilizing these residues for various applications, with a particular focus on biomass energy.

Global agricultural production has experienced unprecedented growth to meet the demands of a growing population and changing dietary preferences (FAO 2017). As reported by the FAOSTAT (2021), agricultural production increased at a rate faster than the rate of population growth. This may be one of the indicators of the fact that we produce 1.5 times more food than we need (Holt-Gimenez 2012). There was a general agricultural production of 9.5 billion tons of primary crops between 2000 and 2021 which represents a 54 % growth. The distribution of this global production was exactly 32 % cereals, 22 % of sugar crops, 12 % vegetables and oil crops, 10 % fruits and 9 % root and tuber crops. There was a 53 % growth in animal production and a 58 % increase in milk production.



Graph 1: Regional contribution of growth in cereal production 2020-22 to 2032.

Source: data elaborated from FAOSTAT 2021

The growth across board can be attributed to the increase in cultivated area, adoption and use of technology, increased use of pesticides and fertilizers, scientific breakthroughs, and more investment opportunities (FAO 2017). This growth is earmarked to further increase. Commodity groups like cereals are projected to increase from 320 million tons to 3.1 billion tons as Graph 1 shows. This surge in production, while crucial for sustaining populations, has led to a parallel increase in agricultural residues. Residues encompass various materials, including crop stalks, husks, straw, and other biomass derived by-products. Understanding the dynamics of residue generation is crucial for devising sustainable strategies to manage and utilize these materials.

The magnitude of agricultural residues varies across regions and crops. For instance, rice production contributes to vast quantities of rice husks, wheat cultivation generates straw, and sugarcane processing yields bagasse. These residues often represent an underutilized resource that can be harnessed for multiple purposes, including bioenergy production (Fatma 2018).

Using agricultural residues for bioenergy production has gained traction as a sustainable solution to address energy demands while mitigating the environmental impact of residue disposal (Johansson 2013). Various studies have explored the conversion of agricultural residues into biofuels, such as bioethanol, biogas, and solid biomass for combustion (Chen et al. 2019; Gnansounou et al. 2019). The energy potential of these residues is substantial, offering an alternative to conventional fossil fuels.

In addition to direct energy production, the application of agricultural residues extends to biochar production and soil amendment. Biochar, derived from the pyrolysis of residues, has been recognized for its potential to enhance soil fertility, C sequestration, and overall soil health (Zhang et al. 2018).

While using agricultural residues presents promising opportunities, several challenges hinder their widespread adoption. Logistic issues, economic feasibility, and competition with traditional uses of residues for animal bedding or soil mulching are among the challenges faced in many regions (Haque et al. 2019). Furthermore, the heterogeneity of residue composition demands tailored processing methods for optimal energy extraction, posing technological challenges (Sharma et al. 2018).

However, numerous success stories highlight the potential benefits of effectively managing agricultural residues. The experiences of countries like China, which has successfully implemented bioenergy projects utilizing agricultural residues, serve as valuable case studies for others aiming to develop sustainable bioenergy strategies (Huang et al. 2020).

3.2. Global Energy Situation on Prospects for Green Energy

The global energy landscape is undergoing a transformative shift, driven by increasing concerns about climate change, resource depletion, and the need for sustainable development. This section explores the literature on the current global energy situation, emphasizing the challenges posed by conventional energy sources and the prospects for integrating green energy solutions into the global energy mix (IPCC 2018).

As of the most recent assessments, the world continues to rely heavily on fossil fuels, with coal, oil, and natural gas accounting for the majority of energy consumption (Holechek 2022). This dependence raises serious environmental and geopolitical concerns, including greenhouse gas emissions, air pollution, and energy security issues (World Energy Council 2019).

The uneven distribution of fossil fuel resources and their finite nature necessitate a transition towards more sustainable and diversified energy sources. The literature highlights the urgent need for a paradigm shift to mitigate the adverse impacts of conventional energy use on both the environment and human health (IPCC 2018).

Conventional energy sources, despite their proven reliability, come with significant drawbacks. The combustion of fossil fuels contributes to climate change through the release of greenhouse gases, with severe consequences for global ecosystems and weather patterns (Hossain et al. 2020). Additionally, the extraction and transportation of fossil fuels pose environmental risks, and their finite nature raises concerns about long-term energy security (Kumar & Chandra 2019).

The literature underscores the economic and geopolitical challenges associated with fossil fuel dependency, including price volatility, geopolitical tensions over resource access, and the social costs of environmental degradation (Sovacool 2016; Stern 2016).

In response to the challenges posed by conventional energy sources, the prospects for green energy as a sustainable alternative are highlighted. Green energy, including renewable sources like solar, wind, hydropower, and biomass, has gained momentum globally (IRENA 2021). The decreasing costs of renewable technologies, advancements in energy storage, and supportive policies contribute to the growing potential of green energy solutions (Jacobson et al. 2017).

Solar and wind energy, in particular, have experienced rapid growth, with increasing investments and technological advancements enhancing their efficiency and affordability (IRENA 2021). It is suggested that these renewable sources have the potential to play a crucial role in achieving a low-C and resilient energy future (Proskuryakova 2023).

While the prospects for green energy are promising, challenges persist in its widespread adoption. The intermittent nature of renewable sources, energy storage limitations, and the need for a resilient and flexible energy infrastructure are among the challenges (Jacobson 2019). Additionally, the transition to green energy requires substantial investments, policy support, and societal acceptance (Baldwin et al. 2020).

The literature also discusses the socio-economic opportunities associated with the green energy transition, including job creation, improved energy access, and the potential for decentralized energy systems in remote or underserved regions (Carley & Lane, 2019; Sovacool et al. 2017).

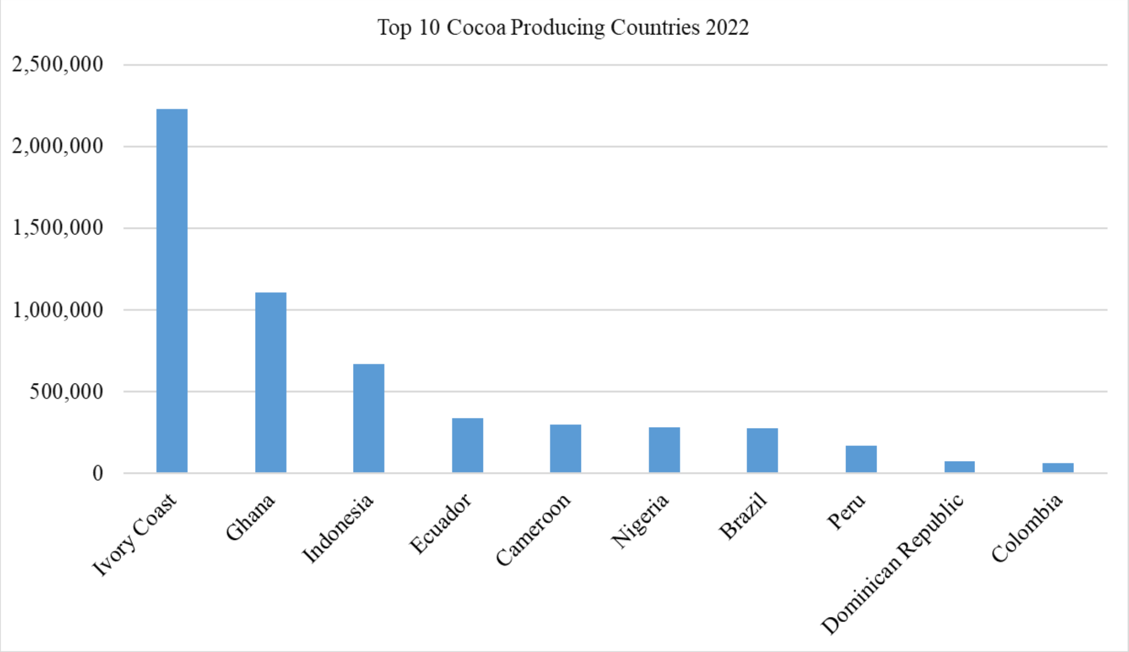
3.3. Cocoa Pod Husk Generation, Composition and Energy Value

CPHs, a by-product of the cocoa industry, have garnered attention as a potential biomass feedstock for energy generation. This section delves into the existing literature to explore the generation, composition, and energy value of CPHs, providing insights into their potential as a sustainable source for electricity production (Figure 1).

Figure 1: A sectional view of an open Cocoa fruit with seeds.

Source: Field observation

CPHs are generated during the processing of cocoa beans, a vital agricultural activity predominantly found in West Africa, South America, and Southeast Asia (Ouattara et al. 2021). Graph 2 shows, Ghana and Cote d'Ivoire produce the greatest number of cocoas in the world. They are trailed in terms of importance to the cocoa industry by Nigeria and Cameroon who can approximate about 6 % and 5% respectfully of the world´s cocoa production (ICCO 2019). Ghana, a major contributor to the cocoa industry is the only cocoa producer which a centrally controlled marketing system.



Graph 2: Top 10 Cocoa Producing Countries 2022.

Source: data elaborated from World Population Review 2024

Reforms in the 1990s paved way for the liberation of the internal market, privatization of the input market and restructuring of the extension services. All external marketing of cocoa in Ghana however are controlled by the Cocoa Marketing Board (Yahaya et al. 2015). In terms of employment, the cocoa sector provides a livelihood to about 6 million Ghanaians which is about 25-30 % of the population (Amponsah-Doku et al. 2022). Selten (2015) followed up with their work which revealed about 67 % of the household income of cocoa-producing households were from their farming of cocoa. The production of cocoa is therefore economically relevant to producer regions like

Ghana. In recent academic parlances, much work is being poured into the use of CPHs for the generation of RE.

The global cocoa industry contributes significantly to the production of CPHs, creating a substantial waste stream that, if harnessed effectively, could serve as a valuable resource for energy generation (Ingram et al. 2018).

The generation of CPHs presents both an environmental challenge, given the need for proper waste management, and an opportunity for sustainable utilization in the context of biomass energy (Ofori-Boateng et al. 2016). Understanding the scale and characteristics of CPH generation is crucial for assessing their potential as a RE feedstock.

CPH exhibit a complex composition, comprising cellulose, hemicellulose, lignin, and various other organic compounds (Olabinjo et al. 2017). The chemical composition plays a crucial role in determining the energy content and combustion characteristics of CPHs. Several studies have investigated the elemental composition and structural features of CPHs to better understand their suitability for energy applications (Ademiluyi et al. 2019).

The high lignocellulosic content in CPHs suggests their potential as a biomass feedstock for energy conversion processes, such as combustion, gasification, or pyrolysis (Ofori-Boateng et al. 2015). The heterogeneity of the composition, however, necessitates thorough characterization for optimal energy extraction.

The energy value of CPHs is a critical factor in evaluating their suitability for electricity generation. Various studies have employed calorimetric analyses to determine the calorific value, heating value, and energy density of CPHs (Owusu et al. 2019; Ramos-Sánchez et al. 2017). These investigations provide valuable insights into the potential energy yield and efficiency of utilizing CPHs as a biomass feedstock.

The calorific value of CPHs is influenced by factors such as moisture content, ash content (ASH), and the proportion of VM. Understanding the energy value do not only aid in assessing the feasibility of energy conversion processes but also informs the design and optimization of biomass energy systems (Ofori-Boateng et al. 2016).

While the literature highlights the potential of CPHs for energy generation, challenges exist in their effective utilization. Logistics, storage, and transportation issues, as well as competition with other uses of CPHs (e.g., as organic fertilizer), present challenges to large-scale implementation (Ingram et al. 2018). Additionally, the economic viability of CPH utilization depends on factors such as energy market dynamics and technological advancements in biomass conversion processes.

Opportunities, however, arise in the form of sustainable practices within the cocoa industry, circular economy approaches, and the potential for decentralized energy solutions in cocoa producing regions (Ouattara et al. 2021). Collaborative efforts between the agricultural and energy sectors can lead to innovative solutions that maximize the value of CPHs while addressing environmental and energy challenges.

3.4. Technologies for Cocoa Pod Husk-Based Energy Generation

As the potential for CPHs as a biomass feedstock gains recognition, the next critical aspect is the exploration of technologies for efficient energy generation. This literature review delves into existing studies to analyze various technologies employed for CPHs-based energy generation, evaluating their efficiency, environmental impact, and applicability in the context of sustainable energy solutions.

3.4.1. Direct Combustion

Direct combustion of biomass, an established technology embraced across various sectors, including the utilization of CPHs, stands as a pivotal pathway for energy generation (Owusu et al. 2019). This method orchestrates the incineration of biomass, yielding substantial heat that can be harnessed for diverse applications ranging from electricity generation to industrial processes. A myriad of studies has meticulously scrutinized the combustion attributes intrinsic to CPHs, with a keen focus on parameters such as calorific value, combustion efficiency, and emissions (Ofori-Boateng et al. 2016).

CPHs, as a biomass feedstock, present a promising avenue for energy production due to their abundance and relatively high energy content. However, the direct combustion of these husks entails confronting a spectrum of challenges, necessitating innovative solutions for optimal energy extraction. Foremost among these challenges is the accumulation of ash, a by-product of combustion that can impede the efficiency of energy generation processes. Additionally, managing emissions from combustion, including pollutants such as particulate matter, nitrogen oxides, and sulphur dioxide, poses a significant concern, especially in light of stringent environmental regulations.

Incomplete combustion further compounds the challenge landscape, leading to suboptimal utilization of the energy potential inherent in biomass. Addressing these obstacles requires a multi-faceted approach, encompassing advancements in both combustion technologies and emissions control strategies.

Technological innovations play a pivotal role in surmounting these challenges and unlocking the full potential of biomass combustion for energy generation. Enhanced combustion systems, leveraging cutting-edge designs and engineering principles, offer the promise of improved efficiency and energy extraction rates. These systems can optimize combustion parameters such as temperature distribution, residence time, and turbulence, thereby minimizing energy losses and enhancing overall performance.

Furthermore, the integration of advanced emissions control technologies is paramount in mitigating the environmental impact associated with biomass combustion. Solutions ranging from electrostatic precipitators to selective catalytic reduction systems hold the potential to substantially reduce emissions of harmful pollutants, safeguarding air quality and ensuring compliance with regulatory standards.

Moreover, the synergy between technological advancements and holistic system optimization approaches can yield synergistic benefits, driving continuous improvement in the efficiency and environmental sustainability of biomass combustion. For instance, the implementation of integrated gasification combined cycle (IGCC) systems, coupled with advanced emissions control technologies, can offer significant gains in energy efficiency while simultaneously minimizing environmental footprint (Osman et al. 2024).

3.4.2. Gasification

Gasification emerges as a compelling alternative technology, offering a transformative approach to harnessing the energy potential inherent in biomass, including CPHs. Unlike direct combustion, which involves burning biomass to produce heat, gasification facilitates the conversion of biomass into a versatile combustible gas known as syngas. This syngas serves as a valuable intermediary, finding applications across diverse sectors ranging from electricity generation to the production of biofuels (Ofori-Boateng et al. 2015).

The allure of gasification lies in its array of advantages over conventional combustion methods. Foremost among these is its superior energy efficiency, owing to the optimized conversion of biomass into gaseous fuels. Additionally, gasification holds promise for cleaner energy production, with reduced emissions compared to traditional combustion processes. These inherent benefits underscore the potential of gasification as a cornerstone of sustainable energy systems.

A wealth of research endeavours has been devoted to exploring the intricacies of CPH gasification, with a particular emphasis on process optimization, syngas composition, and its impact on overall energy yield (Ofori-Boateng et al. 2015; Ademiluyi et al. 2019). These studies delve into the complex interplay of factors influencing gasification performance, ranging from feedstock characteristics to operating conditions and reactor design.

However, the adoption of gasification technology is not devoid of challenges. Chief among these challenges is the design of efficient and reliable gasification reactors capable of accommodating diverse feedstock while ensuring optimal conversion efficiency. The presence of tar compounds in the produced gas poses a significant impediment, necessitating effective tar removal strategies to prevent fouling and ensure downstream process reliability. Furthermore, the need for advanced gas-cleaning technologies to mitigate impurities and contaminants in the syngas adds another layer of complexity to the gasification process (Ofori-Boateng et al. 2015).

Despite these challenges, ongoing research endeavours are poised to overcome barriers and enhance the viability of CPH gasification for sustainable energy generation. Innovative approaches encompassing reactor engineering, catalytic tar reforming, and gas purification technologies hold promise for unlocking the full potential of biomass gasification. Moreover, synergistic integration with complementary technologies such as combined heat and power (CHP) systems and biomass-to-liquid (BTL) conversion pathways can further enhance the economic viability and environmental sustainability of CPH utilization (Ademiluyi et al 2019).

The evolution of gasification technology represents a paradigm shift in the realm of biomass utilization, offering a pathway towards a more sustainable and resource-efficient energy future. By harnessing the inherent energy content of biomass feedstock like CPHs, gasification not only diversifies the energy mix but also contributes to mitigating environmental impacts associated with conventional energy production methods.

3.4.3. Pyrolysis

Pyrolysis, a thermochemical conversion process, holds immense promise in transforming biomass resources like CPHs into a spectrum of valuable energy products, including bio-oil, biochar, and syngas. This process entails subjecting biomass to high temperatures in the absence of oxygen (O), leading to its decomposition into these valuable components. The bio-oil derived from pyrolysis serves as a versatile precursor for liquid biofuels, augmenting the repertoire of RE sources (Owusu et al. 2019).

A plethora of research endeavors has been dedicated to exploring the intricacies of CPH pyrolysis, with a primary focus on optimizing critical parameters such as temperature, residence time, and feedstock characteristics. These studies aim to enhance both the quality of bio-oil and the overall energy yield, thereby maximizing the efficiency of the pyrolysis process (Ademiluyi et al. 2019).

Pyrolysis of CPHs presents a myriad of opportunities for the production of diverse energy products. However, it is not without its challenges. One notable challenge lies in the inherent variability of bio-oil composition, which can significantly impact its properties and suitability for various applications. Additionally, efficient separation techniques are imperative to isolate and purify bio-oil from the pyrolysis product stream, ensuring its usability as a high-quality feedstock for biofuel production (Owusu et al. 2019).

The quest for overcoming these challenges necessitates continued research efforts focused on process optimization and product utilization. Fine-tuning pyrolysis parameters such as heating rate, reactor design, and catalyst utilization can lead to improved bio-oil quality and yield. Moreover, advancements in separation technologies, including solvent extraction and membrane filtration, offer potential solutions for enhancing the efficiency and cost-effectiveness of bio-oil recovery from pyrolysis products.

Furthermore, exploring innovative pathways for bio-oil utilization is essential to unlock its full economic potential. Beyond conventional biofuel production, bio-oil can find applications in sectors such as chemicals, pharmaceuticals, and agriculture, thereby diversifying revenue streams and enhancing the overall sustainability of CPH pyrolysis (Osman et al. 2024).

3.4.4. Biogas Production

Anaerobic digestion stands as a biological marvel, offering a sustainable solution for converting organic matter, including CPHs, into a valuable energy resource known as biogas. This process operates in the absence of O, wherein microorganisms break down organic substrates to produce a mixture of methane (CH_4) and carbon dioxide ($C0_2$), collectively termed biogas. This biogas holds significant potential for diverse energy applications, ranging from electricity generation to heating, and can serve as a renewable alternative to fossil fuels (Ouattara et al. 2021).

A plethora of research endeavors has been dedicated to unravelling the intricacies of CPH biogas production, with a keen focus on factors influencing the process efficiency and gas quality. Studies delve into substrate composition, microbial activity, and digester design, seeking to optimize gas yield and enhance the overall viability of anaerobic digestion as a biomass utilization pathway (ibid p.16)

The utilization of CPHs for biogas production not only offers a RE source but also addresses pressing waste management concerns. By diverting organic waste from landfills and utilizing it as a feedstock for biogas production, anaerobic digestion contributes to mitigating environmental pollution and reducing greenhouse gas emissions. This synergy between energy generation and waste management underscores the environmental sustainability of CPH biogas production (ibid p.24).

However, the widespread adoption of anaerobic digestion technology faces several challenges that warrant attention. One such challenge pertains to the stability of the digestion process, as fluctuations in temperature, potential of hydrogen (pH), and substrate composition can disrupt microbial activity and impede biogas production. Moreover, the heterogeneous nature of CPHs as a feedstock poses challenges in achieving consistent gas yield and quality, necessitating strategies for substrate pre-treatment and process optimization.

Furthermore, scalability emerges as a critical consideration for the commercial viability of CPH biogas production. While laboratory-scale studies demonstrate promising results, translating these findings into large-scale biogas facilities requires overcoming logistical and operational challenges. Factors such as feedstock availability, digester design, and operational efficiency play pivotal roles in determining the economic feasibility and scalability of anaerobic digestion technology for CPH utilization (Maleka 2016).

Addressing these challenges requires a concerted effort encompassing technological innovation, process optimization, and policy support. Advances in digester design, such as the development of hybrid systems combining anaerobic digestion with other biomass conversion technologies, hold promise for enhancing process stability and gas yield. Moreover, integrated approaches that leverage co-digestion with other organic waste streams can diversify feedstock sources and enhance overall process efficiency.

3.4.5. Combined Heat and Power Systems

CHP systems, heralded as a beacon of energy efficiency and sustainability, represent a transformative approach to energy generation by simultaneously producing electricity and useful heat from a single energy source, such as CPH (Ofori-Boateng et al. 2016). This synergy between electricity and heat generation offers a host of advantages, including enhanced overall efficiency and reduced environmental impact compared to separate generation systems.

A wealth of literature has emerged, delving into the intricacies of CPH-based CHP systems, with a particular emphasis on system design, performance optimization, and integration with other RE sources. These studies seek to unravel the complexities of CHP technology, ranging from thermodynamic principles to engineering considerations, with the aim of maximizing energy utilization and minimizing resource wastage (Ofori-Boateng et al. 2016).

The allure of CHP systems lies in their ability to harness the full energy potential of biomass feedstocks like CPHs, thereby maximizing energy efficiency and minimizing greenhouse gas emissions. By utilizing waste heat for thermal applications such as space heating, hot water production, or industrial processes, CHP systems offer a compelling solution for meeting both electricity and thermal energy demands in a sustainable manner.

Despite their inherent benefits, CPH-based CHP systems face a myriad of challenges that necessitate careful consideration and strategic intervention (Ingram et al 2018). One such challenge is the need for integrated infrastructure, encompassing components such as biomass boilers, steam turbines, and heat exchangers, to facilitate seamless energy conversion and distribution. Moreover, the complexity of CHP technology, including control systems, heat recovery mechanisms, and grid integration, poses challenges in terms of system design, operation, and maintenance.

Furthermore, the scalability and adaptability of CHP systems present additional hurdles, particularly in the context of varying feedstock availability, energy demand profiles, and operational conditions. Balancing the competing demands of efficiency, reliability, and flexibility requires innovative approaches that optimize system performance while accommodating dynamic operating environments (Maleka 2016).

Ongoing research endeavors are focused on addressing these challenges and unlocking the full potential of CPH-based CHP systems. Efforts to streamline system design, enhance control algorithms, and integrate advanced monitoring and diagnostic tools hold promise for improving system efficiency, reliability, and flexibility. Moreover, exploring synergies with other RE sources, such as solar and wind power, can further enhance the resilience and sustainability of CHP systems, enabling them to function as integral components of future energy systems.

3.5. Economic Viability of Cocoa Pod Husk-Based Energy Generation

The economic viability of utilizing CPHs for energy generation is a critical aspect in determining the feasibility and sustainability of such initiatives. This literature review explores existing studies to analyze the economic factors, financial considerations, and potential challenges associated with CPH-based energy generation, shedding light on the economic landscape of integrating this biomass resource into the energy sector.

Studies assessing the economic viability of CPH-based energy generation often employ cost-benefit analysis and various financial metrics. Economic evaluations consider factors such as initial capital investment, operational and maintenance costs, revenue generation from electricity sales or other by-products, and potential income from C credits or RE incentives (Ingram et al. 2018; Owusu et al. 2019).

Financial metrics, including the internal rate of return (IRR), net present value (NPV), and payback period, are crucial in determining the project's economic feasibility and attractiveness to potential investors (Ofori-Boateng et al. 2016). Literature suggests that well-designed CPH-based energy projects can yield positive economic returns, especially when considering revenue streams beyond electricity sales, such as C credits or organic fertilizer production (Ingram et al. 2018).

The economic viability of CPH-based energy generation is closely tied to market dynamics and energy pricing. Studies emphasize the importance of understanding local energy markets, policy incentives, and pricing mechanisms for RE sources (Ofori Boateng et al. 2016). Cocoa-producing regions, often characterized by rural communities, may benefit from decentralized energy solutions that cater to local demand and contribute to energy access goals (Ouattara et al. 2021).

Moreover, favourable policy frameworks and incentives, such as feed-in tariffs or RE certificates, can significantly enhance the economic feasibility of CPH-based energy projects (Owusu et al. 2019). The literature underscores the need for a supportive policy environment to stimulate investments and create a conducive market for biomass-based energy.

In addition to financial considerations, the literature emphasizes the importance of conducting social and environmental cost-benefit analyses. Assessing the impact of CPH-based energy generation on local communities, employment opportunities, and environmental sustainability is crucial for achieving holistic economic viability (Ouattara et al. 2021).

Studies suggest that well-managed projects have the potential to generate socio-economic benefits, including job creation, skills development, and improved living standards in cocoa producing regions (Ingram et al. 2018). Environmental benefits, such as reduced greenhouse gas emissions and effective waste management, contribute to the overall positive economic impact of such initiatives.

Despite the potential economic benefits, challenges in the economic viability of CPH-based energy generation exist. Logistic issues, fluctuating biomass prices, and competition with alternative uses of CPHs (e.g., organic fertilizer) can pose economic challenges (Ingram et al. 2018). Mitigation strategies involve optimizing supply chain management, exploring diversified revenue streams, and fostering partnerships with local stakeholders.

Furthermore, technological advancements and process optimization play a crucial role in enhancing the economic feasibility of CPH-based energy generation. Research and development efforts focus on improving conversion efficiencies, reducing operational costs, and exploring innovative applications for by-products (Ofori-Boateng et al. 2016).

3.6. Environmental Impacts and Benefits

As the global focus on sustainable energy intensifies, understanding the environmental implications of utilizing CPHs for energy generation is crucial (Kilama 2019). This literature review explores existing studies to analyze the environmental impacts and benefits associated with CPH-based energy generation, providing insights into the sustainability of integrating this biomass resource into the energy sector.

CPH-based energy generation has the potential to contribute to climate change mitigation by reducing greenhouse gas emissions associated with traditional waste disposal methods. Studies indicate that the combustion, gasification, or pyrolysis of CPHs can be a more environmentally friendly alternative to open burning or landfilling, which can release significant amounts of CH_4 and other pollutants (Ingram et al. 2018; Ouattara et al. 2021).

The reduction in net greenhouse gas emissions, particularly when replacing fossil fuels, positions CPH-based energy as a potentially sustainable and climate-smart solution (Ofori-Boateng et al. 2016). However, the extent of this environmental benefit depends on factors such as the efficiency of energy conversion technologies and the overall life cycle analysis of the CPH utilization process.

CPH-based energy generation offers a dual environmental benefit by addressing waste management challenges and positively influencing soil health. Cocoa-producing regions often grapple with large volumes of discarded husks, as seen in Figure 2, posing disposal challenges and potential environmental degradation (Ouattara et al. 2021). Utilizing CPHs for energy not only diverts this agricultural waste from landfills but also provides an opportunity for resource recovery.

Figure 2: CPHs left to rot on farm.

Source: Field observation

Studies suggest that the application of CPH ash as a soil amendment can enhance soil fertility and structure, offering a sustainable alternative to chemical fertilizers (Ouattara et al. 2021). This dual-purpose utilization aligns with circular economy principles, promoting both waste reduction and soil health improvement. In the Edwenase community in particular, the CPHs were used as an organic source of fertilizer, but most households took interest in the use of the cocoa placenta for animal feed. It was gathered from the field, that the farmers first unhinged this placenta from the cocoa after removing the beans, dried them on raised dying beds in the open sun and then used them as animal feeds. In other cases, the farmer separated the placenta from the cocoa fruit and dried it on the ground.

While CPH-based energy generation can be considered a cleaner alternative, the combustion process may still emit pollutants that can impact air quality. Studies emphasize the importance of implementing emissions control technologies to minimize the release of particulate matter, nitrogen oxides, and other pollutants during combustion (Owusu et al. 2019). Incorporating advanced combustion technologies, such as fluidized bed reactors or gas cleaning systems, can significantly mitigate the environmental impact of CPH combustion (Owusu et al. 2019). Research in this area focuses on improving the efficiency of energy conversion processes while minimizing emissions to ensure a balance between energy generation and environmental sustainability.

CPH utilization can positively influence biodiversity conservation and ecosystem services. Studies indicate that composting CPHs can enhance soil biodiversity and contribute to the overall health of agroecosystems (Ouattara et al. 2021). Additionally, sustainable practices in cocoa cultivation, including responsible waste management, can reduce the ecological footprint of the cocoa industry and support biodiversity conservation efforts (Ingram et al. 2018).

The integration of CPH-based energy generation into agro-industrial landscapes can contribute to a more sustainable and harmonious coexistence between agriculture and the environment. This aligns with broader goals of achieving sustainable development and preserving biodiversity in cocoa-producing regions.

Despite the potential environmental benefits, challenges exist in maximizing the positive impact of CPH-based energy generation. Issues such as the potential release of pollutants, land-use conflicts, and the need for integrated waste management strategies warrant further investigation (Ingram et al. 2018). Future research should focus on optimizing the entire value chain, from cultivation and processing to energy generation, to ensure holistic environmental sustainability.

3.7. Gaps in Existing Literature

As the research on CPH-based energy generation progresses, it is crucial to identify gaps and areas where further investigation is needed. This literature review examines existing studies to highlight gaps in the current understanding of CPH utilization for energy generation, providing insights into potential avenues for future research.

3.7.1. Limited Focus on Community-Specific Dynamics

While studies acknowledge the importance of community engagement and socio-economic considerations, there is a notable gap in the detailed examination of community-specific dynamics, especially in the context of the Edwenase community in Ghana. Future research should delve deeper into the nuances of local cultures, values, and social structures to tailor CPH-based energy projects more effectively. This includes a comprehensive analysis of gender dynamics, cultural practices, and community-specific preferences that can influence the acceptance and success of such initiatives.

3.7.2. Lack of Longitudinal Studies

The majority of existing literature provides snapshots of CPH-based energy projects at specific points in time. Longitudinal studies that track the evolution of these projects over extended periods are scarce. Future research should incorporate longitudinal approaches to assess the long-term impacts, challenges, and benefits of CPH-based energy generation. This could include monitoring changes in community dynamics, project sustainability, and the adaptation of technologies over time.

3.7.3. Inadequate Assessment of Environmental Footprint

While there is recognition of the environmental benefits associated with CPH-based energy generation, there is a gap in comprehensive assessments of the environmental footprint throughout the entire life cycle of these projects. Future research should focus on conducting life cycle analyses, considering aspects such as raw material extraction, transportation, processing, energy generation, and waste management. This holistic approach can provide a clearer understanding of the overall environmental impact and guide improvements in project design and implementation.

3.7.4. Limited Exploration of Technological Innovations

The existing literature predominantly focuses on traditional technologies for CPH-based energy generation, such as combustion, gasification, and pyrolysis. There is a gap in exploring and evaluating emerging technological innovations that could enhance the efficiency, sustainability, and economic viability of these projects. Future research should investigate advancements in biomass conversion technologies, energy storage, and smart grid integration to optimize CPH utilization for electricity generation.

3.7.5. Insufficient Attention to Policy and Regulatory Frameworks

While some studies briefly mention the importance of policy support, there is a gap in in-depth analyses of the policy and regulatory frameworks that can either facilitate or hinder CPH-based energy generation. Future research should delve into the development and effectiveness of policies related to RE, waste management, and rural electrification in cocoa-producing regions. Understanding the regulatory landscape is essential for creating an enabling environment for sustainable energy projects.

3.7.6. Neglect of Socio-Economic Metrics for Success

While socio-economic considerations are acknowledged, there is a gap in the development of standardized metrics for assessing the success of CPH-based energy projects from a socio-economic perspective. Future research should aim to establish key performance indicators (KPIs) that measure the tangible impacts on livelihoods, employment, and community development. This will contribute to a more comprehensive evaluation of the socioeconomic sustainability of such initiatives.

3.7.7. Limited Exploration of Alternative Utilization Pathways

Existing literature primarily focuses on the energy generation aspect of CPH utilization. There is a gap in exploring alternative pathways for utilizing CPHs, such as the production of value-added products, bio-based materials, or other industrial applications. Future research should investigate the feasibility and economic viability of diversifying the use of CPHs beyond energy generation.

3.7.8. Absence of Comparative Analyses

The majority of studies concentrate on individual aspects of CPH-based energy projects. A gap exists in comprehensive comparative analyses that evaluate the performance, benefits, and challenges of different energy conversion technologies, project scales, or community engagement approaches. Future research should undertake comparative assessments to identify best practices and optimize the design and implementation of CPH-based energy initiatives.

3.7.9. Underrepresentation of Developing Regions

Existing literature predominantly focuses on CPH-based energy projects in West Africa, with limited representation from other cocoa-producing regions, particularly in Southeast Asia and South America. Future research should strive for a more geographically diverse representation to account for regional variations in CPH composition, community dynamics, and socio-economic contexts.

4. Materials and Methods

4.1. Area of Study

Edwenase is a rural community with a population of 442 and over 100 households in the Ejisu-Juaben Municipal District in the Ashanti region of Ghana. The 2016 report by Municipal Planning Coordinating Unit (2016) shows there are 202 males and 240 females. It is situated near the communities of Abenase and Onwe. Ashanti's capital, Kumasi, is approximately 24 kilometres (km) away from Edwenase (Figure 3). Edwenase community is located at Latitude 6.68888° or 6° 41' 20" north and Longitude -1.43431° or 1° 26' 4" west with elevation of about 245 meters above sea level.

Figure 3: A map of the Ejisu-Juaben District.

Source: Wiafe & Asamoah 2018

The map of Edwenase community is indicated in Figure 4. The Edwenase community was chosen for the study because the main crop cultivated in the community is cocoa and contributes 2 % of the total 20 % of cocoa produced from the Ashanti region. Their cocoa production has been documented by Licensed Buying Companies (LBCs) who have stations in this area and in nearby zones. This means access to reliable data was possible. The area sits within the wet semi-equatorial zone. It is characterized by a double maxima rainfall in June and October. May to June is the first rainy season and the heaviest rainfall occurs in June while the second rainy season is from September to October with very little variations between the surrounding communities and towns. Temperatures are high in the area and can range from 26 ℃ in August and 30 ℃ in March. The relative humidity throughout the year varies between 70 to 80 % which can be considered to be high. The forest and savannah type of soils are suitable for the cultivation of a variety of crops including cocoa, cola-nuts, citrus, oil palm and staple food crops such as cassava, yam, cocoyam, maize, rice and vegetables. The area contributes immensely to the production of industrial crops such as cocoa, pineapple, pawpaw, and oil palm but is more notable for the substantial contribution to the cocoa production in the Ashanti Region. There is a trace amount of farmers who dabble in the production of exotic crops such as black and sweet pepper, ginger, cashew nuts, Irish potatoes, rubber, and mangoes which are all gaining importance as export commodities (ibid p.35).

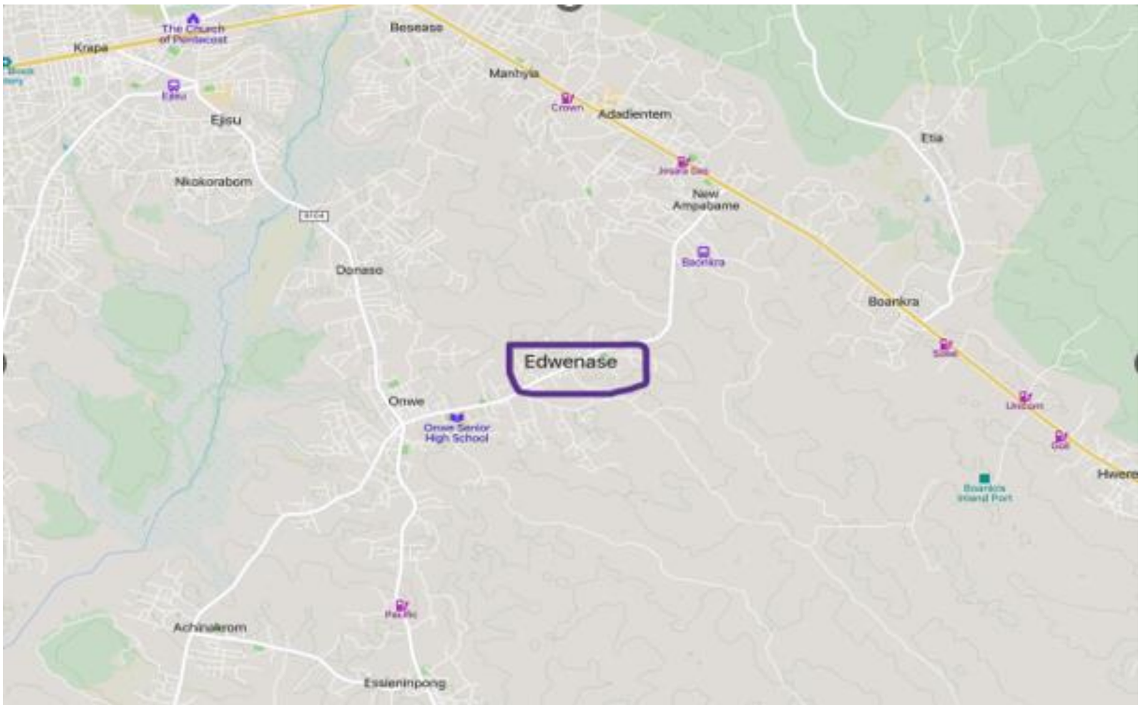


Figure 4: A map of the Edwenase community within the Ejisu Juaben District.

Source: Mapcarta 2024

It was gathered from the field that 60 % of the people of Edwenase were farmers and about 80 % of these farmers engaged in cocoa production. After the harvest and removal of the beans from the pods, the improperly disposed pod husks are left to decay, becoming an environmental menace by the way of the odor, unpleasant sites and the generation and spread of bacteria and fungi (ibid p.35).

4.2. Materials Used

i. CPHs: collected as the biomass fuel source from cocoa plants in the Edwenase community.
ii. Planetary ball mill: used to mill and reduce the size of the dried CPHs samples.
iii. Sieve: was used to size the milled CPH samples to fine particles.
iv. Electronic mass balance: used to weigh the cocoa pods and the husks.

4.3. Collection and Preparation of Cocoa Pod Husks

In this study, four CPHs samples from four different cocoa plant types, Amelonado, Amazonia, Trintario and Hybrid, were obtained from the Edwenase community and analyzed to determine their chemical composition and heating values. These cocoa plant types were chosen for the samples because they are the most types of cocoa plants cultivated in the Edwenase community. An assembly of the Edwenase farmers and LBCs was made to inquire about their current waste management practices for agro-residues (Figure 5). This also allowed us to gather general concerns and suggestions on how they are and can be integrated into this study. Data for the total number of cocoas produced in this area were collected from 2019 to 2023 production season by aggregating all the cocoa purchased from the LBCs and from Legacy farmers.

Figure 5: Assembly of LBC reps and farmers for data aggregations.

Source: Field observation

The data gathered here helped find the annual total energy potential of the area.

Annual Total Energy Potential= Total cocoa produced x Calorific Value..............[1]

The cocoa pods were maintained fresh until the pods were opened to remove the beans. Prior to the cracking of the pods and removal of the beans, the pods were weighed using an electronic mass balance. After the beans were removed, the CPHs were weighed to determine their masses.

The weight % of the wet CPHs that were obtained from the cocoa fruits was determined using the equation [1]; which gives:

$$\mathbf{CPH\%} = \frac{\mathbf{M_h}}{\mathbf{M_p}} \times \mathbf{100\%} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{[2]}$$

Where M_h is the mass of the wet CPH and M_p is the mass of the cocoa pods with the beans before it was removed.

The CPHs were then chopped into smaller pieces for drying. The duration for the drying was 2 hours at a temperature of 50 °C, this was to reduce the moisture content of the husks to 8-12 % of its initial moisture content for accurate determination of the calorific value and also for the proximate and ultimate tests.

The dried CPHs was reduced in size by planetary ball mill and sieved to obtain a uniform size of about 1 millimetre (mm).

4.4. Measurement of Total Cocoa Produced in Edwenase

The total number of cocoa produced in the region was essential to this study. The total figure was necessary for highlighting the magnitude of the potential for renewable energy and the sustainability of such a project which is significantly dependent on the availability of the feedstock. The information was taken from the LBCs and the farmers during the assemblies. The data provided ranged from 2019-2023 because it was the period from which accurate data started been recorded. Majority (98 %) of the cocoa farmers sell everything to the LBCs in this cocoa producing zone. The other data was collected from Legacy farmers. Legacy farmers were farming families who produced the cocoa but did not sell them. They claimed to be keeping the farms alive due to the heritage they came with and must keep them alive for when their children would be interested to having the farms. These constituted only 2 % of the cocoa farmers.

4.5. Measurement of the Chemical Composition of CPHs

Proximate analysis (PA) was used to obtain moisture, VM, fixed carbon (FC) and ASH. Ultimate analysis (UA) was used to determine C, H, N, S and O.

The main factors affecting the quality of the biomass feed stock is the moisture content, ASH, particle size and density. High moisture contents in biomass feed stock reduces the energy value of the feed stock. A reduction in the moisture content of the feed stock increases the energy density and also improves the combustion efficiency of the feed stock. Determining the VM of the CPHs will suggest how easily combustible gases will be released when the CPHs are heated.

The values of C and H which are the main combustible elements will be determined from the UA. Higher % of these elements will indicate a higher heating value (HHV). Levels of N and S which becomes harmful when burned will also be determined, and lastly, the O % of the CPHs.

4.6. Measurement of the Physical Properties of the Cocoa Pod Husks

4.6.1. Moisture content

The quality of the CPH as a source of fuel for energy production is influenced by its moisture content. Higher moisture content reduces the combustion efficiency of the CPH as fuel, thus, it makes the CPH difficult to ignite and sustain combustion. Also, moist CPH is prone to microbial degradation during storage, reducing its fuel quality over time.

To determine the moisture content, a dry and empty aluminium tray was weighed with an electronic balance and the mass recorded as M_T. The chopped wet CPHs were poured into the aluminium tray and was weighed, and the mass was recorded as M_{TW}. The aluminium tray containing the wet CPH were placed in 60 °C oven and dried for 4 hours. This duration of drying was chosen because the aim was to reduce the moisture content of the CPHs and prepare it for the UA and PA. After the 2 hours of drying, the tray with the dried CPHs was removed and left to cool down to room temperature. The mass of the tray with the dried CPHs was weighed and recorded as M_{TD}. With the masses known, mass of wet CPH only M_W and mass of dry CPH only M_D can be calculated for using equation [2] and [3] respectively.

$$\boldsymbol{M_W = M_{TW} - M_T} \ldots\ldots\ldots\ldots \textbf{[3]}$$

$$\boldsymbol{M_D = M_{TD} - M_T} \ldots\ldots\ldots\ldots \textbf{[4]}$$

With the masses known, the moisture content of the CPHs was determined using the equation [4]; which gives:

$$\mathbf{M\%} = \frac{\mathbf{M_W - M_D}}{\mathbf{M_W}} \times \mathbf{100\%} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \mathbf{[5]}$$

Where M_W is the mass of the wet CPH samples and M_D is the mass of the dried CPH samples.

4.6.2. Density

The density of the CPH is another factor that affects its suitability for energy production. Higher densities indicate greater energy content, better heating rates, gas yield and conversion efficiencies in thermochemical processes. Lower densities cause bridging and flow issues, and also occupies more volume per unit energy.

Both the particle and bulk densities of the CPH are to be determined. While the particle density is valuable supplemental information, the bulk density is needed for sizing equipment, logistics, and processing in order to utilize CPH as biomass fuel.

To determine the bulk density, a container of volume 550 millilitres (ml) was weighed, and the mass recorded as M_1. The container was fully filled with the CPH samples without compacting. Ensure the CPH pieces are randomly oriented and loosely filled without gaps. Determine the mass of the container fully filled with CPH samples M_2. Determine the mass of the CPH added using the equation [5].

$$\mathbf{M = M_2 - M_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \mathbf{[6]}$$

With the mass of the CPH sample added known, and the volume of the container also known, equation [6] gives the bulk density of the CPH samples.

$$\textbf{Bulk density} = \frac{\mathbf{M}}{\boldsymbol{Volume\ of\ container}} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \mathbf{[7]}$$

Where M is the mass of the CPH samples.

For the determination of the particle density, a volumetric flask was weighed, and the mass recorded as M_1. The container was then filled with a grounded CPH samples, and the mass weighed as M_2. To make sure the spaces between the grounded

CPHs in the flask is filled, 100 taps are made on the flask. The tapped volume is measured as V_t, which is equal to the volume of the grounded CPHs in the flask.

The particle density is then calculated using equation [7], which gives:

$$\textbf{Particle density} = \frac{\mathbf{M_2 - M_1}}{\mathbf{V_t}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{[8]}$$

Where M_1 and M_2 are the masses of the empty container, and the container with CPH samples respectively. The V_t is the tapped volume of the CPHs samples.

4.7. Measurement of the Mechanical Properties

The only mechanical property that was determined for this study is the hardness of the CPHs. The hardness of CPHs can have some influence of their use as fuel for electricity generation, primarily impacting the handling, processing, and combustion characteristics. Harder cocoa pods may be more resistant to mechanical degradation during transportation and feeding operations. This could reduce dust formation and improve flow characteristics, which is beneficial for handling and feeding the fuel into the combustion systems. The hardness of the CPHs can influence its combustion properties. Harder husks may have a higher bulk density and lower porosity, which can impact the O diffusion and heat transfer during combustion, potentially affecting burnout rates and combustion efficiency.

Methods like the Vickers and Rockwell hardness methods can be used to determine the hardness of the CPHs. But for this study, the idea of the relationship between the hardness, densities and compressibility was used to estimate the hardness of the CPHs. Knowing the particle density and the bulk density from equation [7] and [6] respectively, the compressibility was estimated using equation [8], which gives:

$$\boldsymbol{Compressibility} = \mathbf{1} - \frac{\boldsymbol{Bulk\ density}}{\boldsymbol{Particle\ density}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{[9]}$$

This ratio provides a value greater than 1. The closer the value is to 1, the harder the CPHs and the farther the value is away from 1, the softer the CPHs. For biomass to be considered as a good fuel for power production, moderately hardness is required. Biomass with a hardness value from 1.1 to 1.4 is said to be moderately hard.

4.8. Community Engagement and Perspectives Gathering

Examining community perspectives and socio-economic considerations is essential when implementing RE projects, particularly in regions with unique social and economic dynamics. An assessment had to be gathered on how the local population perceives and is impacted by CPH-based energy generation initiatives.

Community engagement is fundamental to the success and sustainability of any RE project. Studies emphasize the significance of involving the Edwenase community in the decision-making processes, from project planning to implementation and maintenance. Engaging with local leaders, residents, and relevant stakeholders ensures that the project aligns with community needs, values, and expectations. Participatory approaches, such as community meetings, workshops, and collaborative planning sessions, have been shown to foster a sense of ownership and shared responsibility among the Edwenase community members (Ouattara et al. 2021).

Understanding their perspectives, concerns, and aspirations is crucial for establishing a positive and sustainable relationship between the project and the community. The socio-economic impact of CPHs-based energy generation on the Edwenase community extends to livelihoods and employment opportunities. Studies suggest that well-designed projects have the potential to create local job opportunities, particularly in biomass collection, transportation, and facility (Ingram et al. 2018). The cultivation and processing of cocoa pods for energy generation can also contribute to income diversification for local farmers.

However, it is crucial to assess the potential trade-offs and ensure that the introduction of new technologies does not negatively impact existing livelihoods or create economic disparities within the community. Balancing economic development with social equity is essential for garnering community support and ensuring long-term project sustainability.

Improving energy access in the Edwenase community through CPH-based energy generation can have broader socio-economic implications. Reliable and affordable energy contributes to enhanced productivity in various sectors, such as agriculture and small-scale enterprises, thereby fostering economic development (Ouattara et al. 2021). Increased energy access can also facilitate the use of electric appliances, support education through improved lighting, and enhance overall quality of life.

Studies underscore the importance of aligning the project goals with the socio-economic development priorities of the Edwenase community. This may involve tailoring the energy generation system to meet specific local needs, such as powering agricultural processing units or community centres (Ingram et al. 2018). Ensuring that the project addresses identified community needs enhances its acceptance and positive impact.

Cultural considerations and local values play a pivotal role in the acceptance and success of RE projects in the Edwenase community. Studies highlight the need to respect cultural norms, traditional practices, and community values during project implementation (Ouattara et al. 2021). Integrating local knowledge and practices into the design and operation of the CPH-based energy generation system fosters cultural sensitivity and acceptance.

Understanding the cultural dynamics also involves acknowledging gender roles and dynamics within the community. Studies suggest that considering the perspectives and needs of both men and women in the Edwenase community ensures that the benefits of the energy project are equitably distributed (Ingram et al. 2018).

Despite the potential benefits, challenges may arise during the implementation of CPH-based energy generation projects in Edwenase. These challenges could include land-use conflicts, disagreements over resource allocation, or concerns about potential environmental impacts. Establishing effective conflict resolution mechanisms, as identified in the literature, is crucial for addressing disputes and maintaining positive community relationships (Ouattara et al. 2021).

Furthermore, ongoing communication and feedback loops between project developers and the Edwenase community are vital for addressing emerging challenges and adapting the project to evolving community needs and concerns. Against this background, two assemblies were made to engage with the Edwenase farmers and LBC representatives (REPs) (Figure 6).

Figure 6: Meeting with Edwenase farmers about their participation in this study.

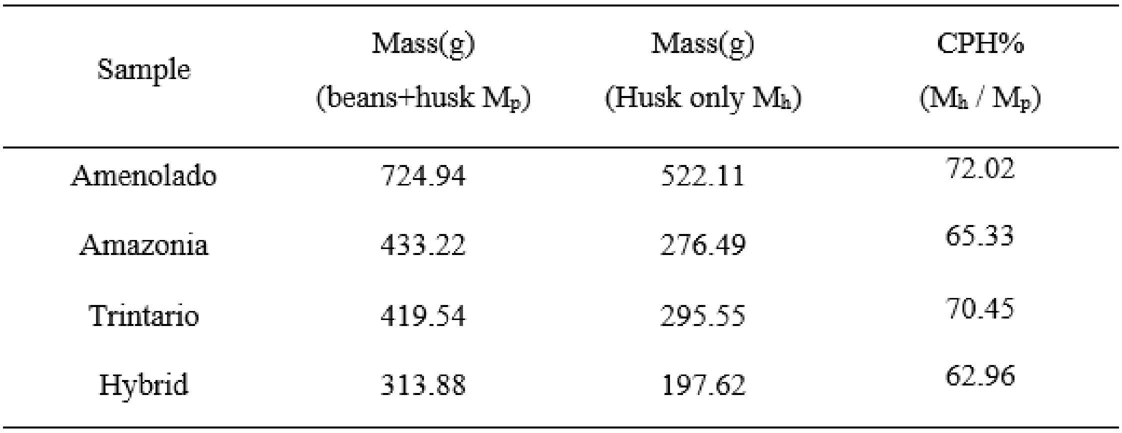
Source: Field observation

5. Results and Discussion

5.1. Thy Physical Properties of the Cocoa Pod Husks

CPHs volumes obtained from the four cocoa plants; Amelonado, Amazonia, Trintario and Hybrid, are shown in the Table 1.

Table 1: Volume percentage of CPHs



Sample	Mass(g) (beans+husk M_p)	Mass(g) (Husk only M_h)	CPH% (M_h / M_p)
Amenolado	724.94	522.11	72.02
Amazonia	433.22	276.49	65.33
Trintario	419.54	295.55	70.45
Hybrid	313.88	197.62	62.96

Source: data of the study

The CPH% values range from 62.96 % (Hybrid) to 72.02 % (Amelonado). This indicates that while CPHs make up a significant portion of the total mass in all samples, there is variation in their relative contribution. In all the samples, the CPH % exceeds 60 %, meaning CPHs are the majority component by mass. This suggests that the properties of the samples, such as density, hardness and combustion behaviour, will be primarily influenced by the characteristics of the CPHs. Despite being the majority component, the CPH % differs among the samples, with Amelonado having the highest at 72.02 % and Hybrid having the lowest at 62.96 %. This variation could lead to differences in the overall properties of the samples, even though CPHs are the dominant component.

Averagely, the CPH % across all the samples is 67.69 %. This relatively high average value suggests that the CPHs have a higher fraction as compared to other components (beans) from the whole cocoa fruits being harvested in Edwenase community. On the impact on fuel properties, a higher CPH % is generally preferable, as it represents a higher fraction of the desirable cocoa husks' properties contributing to the overall fuel characteristics, such as energy content, ash behaviour, and grindability. This proposes that the Amenolado can be the specie zoomed into for future studies of HHV of CPHs in such rural areas.

5.1.1. Particle Density

The particle density, also known as true density, is a fundamental property that characterizes the density of the solid matter in a material, excluding any internal pores or voids. For the CPHs investigated in this study, the particle density was determined to be 394.37 kilogram per metre cube (kg/m^3).

The mass of the volumetric flask (M_1) used in measuring the mass of the grounded husks was measured to be 262.79 grams (g). And the mass of the volumetric flask together with the grounded CPHs (M_2) was measured to be 412.65 g. The tapped volume of the grounded pod husks was recorded as 380 ml, using the equation [7], the particle density was determined.

The particle density of a fuel is often correlated with its calorific value. Generally, higher particle densities correspond to higher energy content per unit volume. With the particle density of 394.37 kg/m^3, the CPHs are expected to exhibit a moderate to good energy density, making them a reasonable solid fuel option for electricity generation applications. The particle density can also influence the combustion behaviour of a fuel, specifically the char burnout rate. Denser particles tend to have slower burnout rate due to limitations in O diffusion and heat transfer. The moderate particle density of 394.37 kg/m^3 for the CPHs may result in reasonable char burnout rates, facilitating efficient combustion and minimizing unburned C losses.

5.1.2. Bulk Density

The bulk density is a key property that describes a material's mass per unit volume, comprising both solid materials and voids or pores. The bulk density of the CPHs examined in this study was found to be 290.4 kg/m^3.

The mass of an empty container with a known volume was weighed and recorded as 343.6 kg/m^3. And the mass of the dry CPHs together with the container was measured to be 503.32 kg/m^3. With the volume of the container known to be 550 ml, the bulk density was determined from equation [6] as 290.4 kg/m^3.

A fuel's energy density, often known as its calorific value per unit volume, is directly proportional to its bulk density. Compared to other biomass fuels, the CPHs should have a modest energy density, with a bulk density of 290.4 kg/m^3. Because of their intermediate energy density, CPHs may be able to produce a respectable amount of energy per unit volume, which will help gasifiers and furnaces operate more efficiently throughout the combustion and heat transfer processes.

5.1.3. Moisture Content

The moisture content of a fuel is a critical parameter that can significantly influence its combustion behaviour and overall performance in electricity generation applications. On a wet basis, the moisture content of the CPHs under investigation in this study was found to be 10.71 %.

The mass of the wet CPHs was measured to be 168.33 g. The CPHs was chopped, and oven dried for 4 hours under 50 °C. The mass of the dried CPHs were measured to be 150.31 g. With equation [4], the moisture content on wet basis of the CPHs was determined to be 10.71 %.

The moisture content of a fuel directly affects its energy content and calorific value. Higher moisture content typically results in lower energy density and reduced heating value, as a portion of the energy is consumed in evaporating the moisture during combustion. With a moisture content of 10.71 %, the CPHs are expected to exhibit a relatively high energy content and calorific value, as the majority of the fuel is composed of dry, combustible material. The combustion behaviour and overall efficiency of a fuel is greatly being influenced by its moisture content. Lower moisture levels can lead to faster ignition, higher flame temperatures, and improved combustion rates, potentially enhancing the overall thermal efficiency of the combustion process. At a moisture content of 10.71 %, the CPHs are likely to exhibit favourable combustion characteristics, with rapid ignition and burnout rates, contributing to efficient energy conversion in gasifiers.

5.2. Mechanical Properties of the Cocoa Pod Husks

For this study, the compressibility was used to directly determine the hardness of the CPHs. The compressibility of a biomass refers to the ability of the biomass material to undergo a reduction in volume or an increase in density when subjected to compressive forces or pressure. There is generally an inverse relationship between the compressibility of a material and its hardness. Thus, harder materials tend to be less compressible, while softer materials are more compressible.

The compressibility of the CPH samples was determined to be 0.264, using equation [8]. This value indicates a moderate compressibility of the material, suggesting a relatively dense and rigid structure. A lower compressibility value, as observed for the CPHs, is associated with higher hardness.

Harder and less compressible biomass fuels tend to have better flow ability and handling characteristics, which can facilitate their transportation and feeding into combustion systems. Additionally, the higher density associated with lower compressibility can contribute to increased energy density per unit volume, potentially improving the overall energy yield from the fuel.

5.3. Chemical Composition of the Cocoa Pod Husks

The chemical compositions of the CPHs are shown in the Table 2, with their corresponding heating or calorific values calculated.

HHV or calorific value can be determined from the composition of the CPHs revealed by UA and PA, as follows:

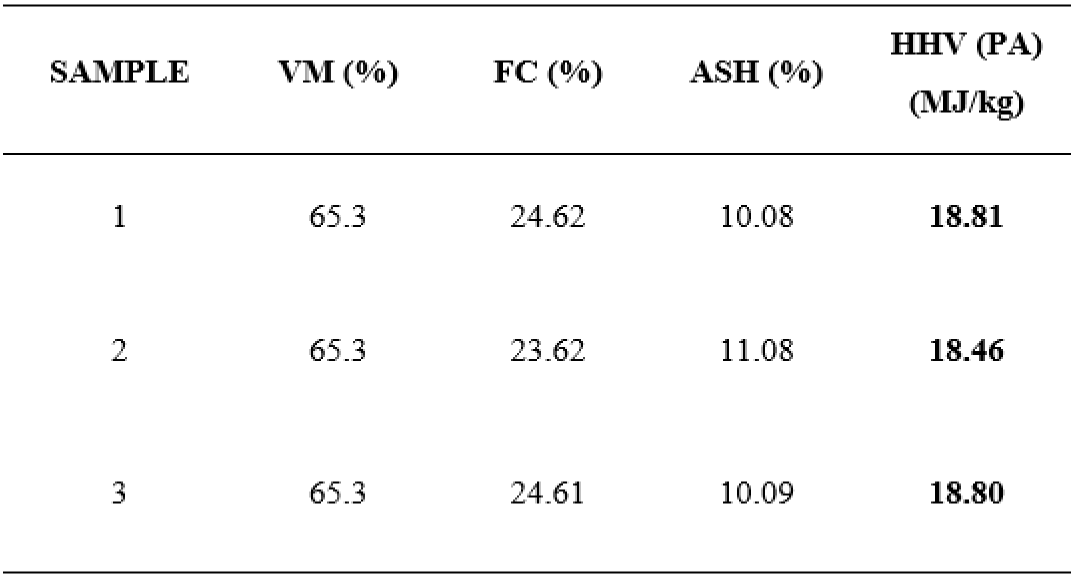
For PA

Calorific value = 0.3536 F.C + 0.1559 V.M - 0.0078 ASH ……………….............…. [9]

For UA

Calorific value = 0.3491 C + 1.1783 H + 0.105 S - 0.1034 O - 0.0151 N …….….…. [10]

Table 2: Heating value or caloric value from PA



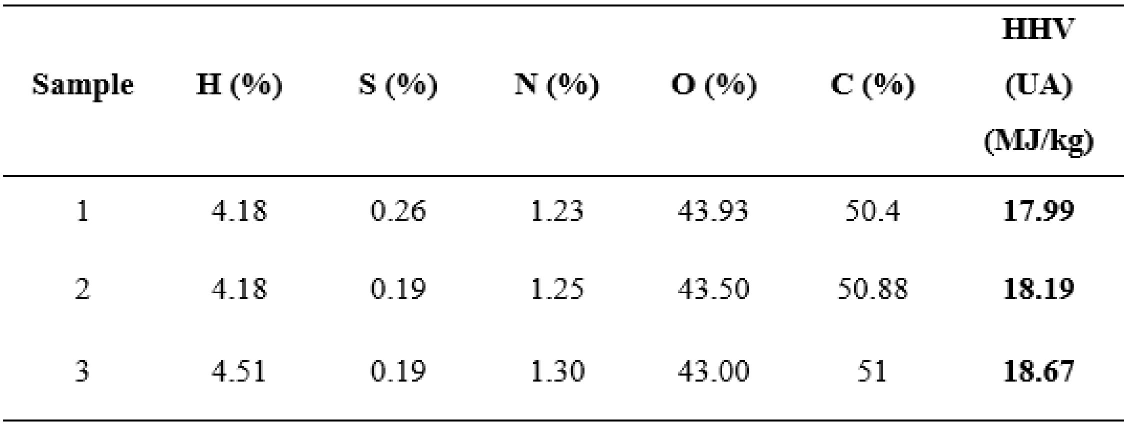
SAMPLE	VM (%)	FC (%)	ASH (%)	HHV (PA) (MJ/kg)
1	65.3	24.62	10.08	**18.81**
2	65.3	23.62	11.08	**18.46**
3	65.3	24.61	10.09	**18.80**

Source: data of the study

The samples' VM contents, which was constant at 65.3 %, showed a high concentration of volatile substances that aid in combustion. This number agrees with findings of Kemausor et al. (2015) and Ayamga et al. (2015) and also found that the higher the VM content, the faster the ignition potential. The solid C fraction was represented by the FC concentration, which ranged from 23.62 % to 24.62 %. This is significant values that mean a high heating value for the CPH. The numbers of this study are comparable to the values of Nelson et al. (2021) and Kumi (2017). It can also be observed from Table 4.2 that the higher the FC content, the higher the HHV. Between 10.09 % and 11.08 %, the ASH of the samples was comparatively constant. The values are again comparable to measurements recorded by Nelson et al. (2021) and Kumi (2017). The values recorded in this study can be said to be medium as they are not less than 10 % (Titiloye et al. 2013) and can be sought to be minimized in the future. Factors that influenced the ASH could have been the presence of plastics, soil, rocks, or any unforeseen contaminant. It elicits why the sample preparation is very crucial. Again, a high ASH could be indicative that the cocoa in the area have nutrient deficiency or are growing in a soil that has a significant level of toxicity (Nelson 2021). It elicits why the sample preparation is very crucial. High ASH are known to affect the reactor designs which leads to blocking problems and also lowers the high heating value. From Table 2, the consistency of this claim can be observed that the higher the ASH, the lower the HHV. The samples' HHV, which indicate the amount of energy in the CPHs, ranged from 18.46 to 18.81 megajoules per kilogram (MJ/kg). Averagely, the heating value obtained from the PA is 18.69 MJ/kg.

The findings of the PA show that CPHs have favorable properties that could make them useful as a solid fuel source. Given their moderate VM content, the CPHs may contribute to the overall release of energy by releasing combustible gases during the earliest stages of combustion. In an observed study where the VM may not be very high, the FC component offers a solid C portion that keeps the combustion process going. The samples' relatively low ash % is good since excessive ash levels can cause combustion systems to foul and slag, which lowers system performance and increases maintenance needs and costs. The observed levels of ASH are within a range that is suitable for biomass fuels, suggesting that CPHs are less likely to present many operating difficulties.

Table 3: Heating value or calorific value from the UA



Sample	H (%)	S (%)	N (%)	O (%)	C (%)	HHV (UA) (MJ/kg)
1	4.18	0.26	1.23	43.93	50.4	**17.99**
2	4.18	0.19	1.25	43.50	50.88	**18.19**
3	4.51	0.19	1.30	43.00	51	**18.67**

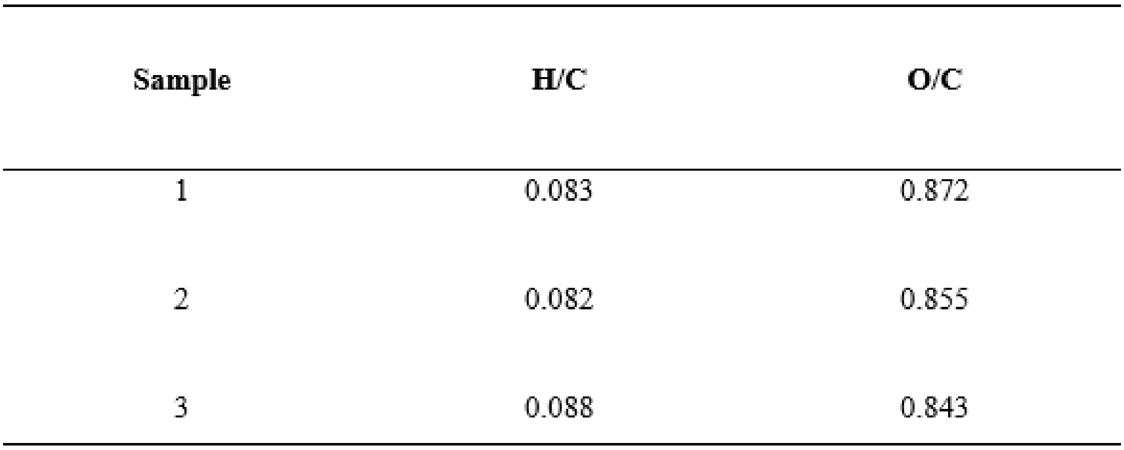
Source: data of the study

The energy content and improved combustion were both aided by the H content, which varied from 4.18 % to 4.51 %. With a range of 0.19 % to 0.26 %, the S concentration was comparatively low, which is ideal for lowering Sulphur oxide emissions. Nitrogen oxide generation during combustion may have been influenced by variations in the N level, which ranged from 1.23 % to 1.30 %. The O level varied between 43 % and 43.93 %, which facilitated burning. The principal element that carries energy, C, was found to be in the range of 50.40 % to 51 %. The final study yielded HHV ranging from 17.99 MJ/kg to 18.67 MJ/kg, which indicates the overall energy content of the CPHs. The average heating value from the UA is 18.28 MJ/kg.

The low S content with a range of 0.19 % to 0.26 % is beneficial since it lowers the possibility of Sulphur oxide emissions, which are known to exacerbate environmental problems like acid rain or mechanical problems with the chosen operating technology. This is in line with González-Arias et al. (2020) who reported that high values of C and H are desirable while S content should be minimal so that fouling problems during combustion in boilers can be avoided. Furthermore, if suitable combustion control mechanisms are put in place, the relatively low N content, ranging from 1.23 % to 1.30 % can assist in decreasing the generation of nitrogen oxides during combustion. The lower levels of S and N observed here affirms to the eco-friendly nature of the CPH as a feedstock.

The O content may be observed to facilitate combustion, but it leads to a lower HHV since it allows for more emission of C and water. The consistency of this claim can also be observed on Table 3 that the higher the O content, the lower the HHV.

Table 4: The ratio of H/C and O/C



Sample	H/C	O/C
1	0.083	0.872
2	0.082	0.855
3	0.088	0.843

Source: data of the study

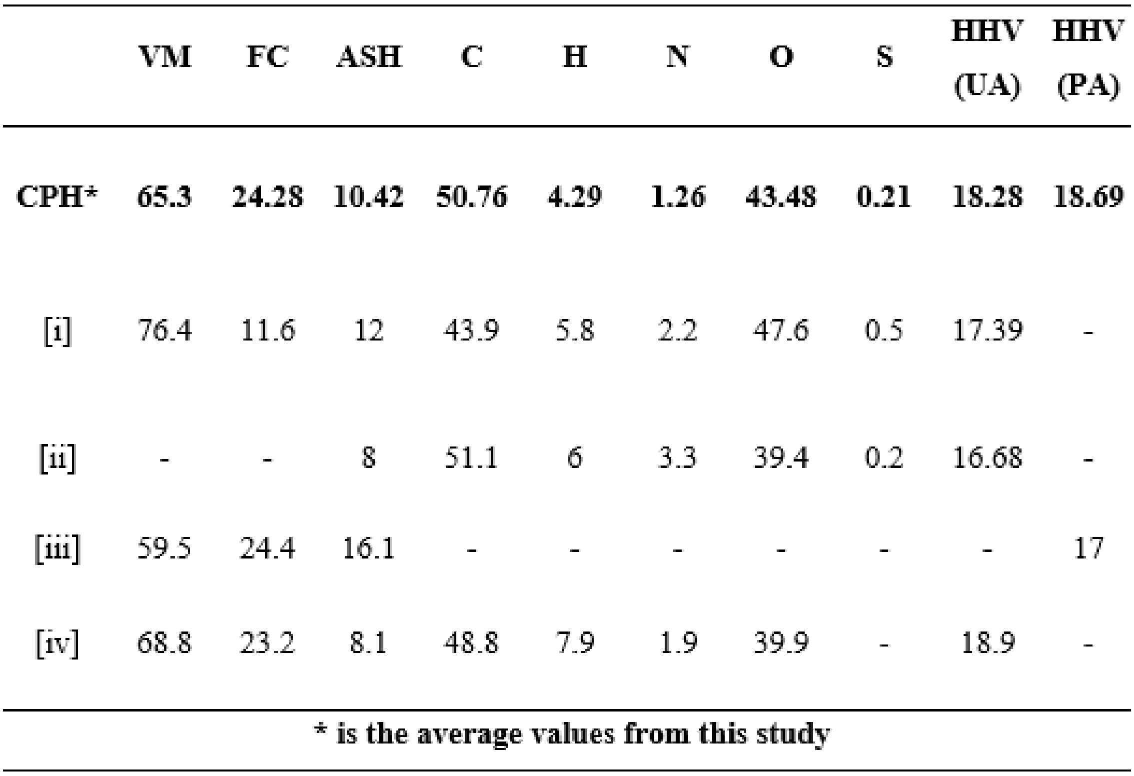
Reference to Table 4, the underpinning here is that the higher the H/C ratio, the higher the HHV since H has the highest HHV among other fuels. A high H/O ratio means there is a high presence of H. This can be observed that sample 3 with the highest H/C had the highest HHV. The same cannot be observed between samples 1 and 2. A possible way to explain this discrepancy was by considering the influence of their S and O contents. The O/C ratios are observed to be more than the H/C due to the high levels of O observed. This instigates a higher chance of more CO being produced than CH_4 and H in a thermochemical conversion to syngas.

CPHs have a moderate energy content that makes them appropriate for a variety of energy production applications, such as industrial boilers, furnaces, and home heating systems. The calorific values obtained from the final analysis are within an acceptable range for biomass fuels.

The final analysis' findings support the possibility of using CPHs as a sustainable biomass fuel source to generate energy. The energy potential of this biomass fuel is equivalent to that of other biomass fuels as confirmed by Titiloye et al. (2013); Martinez et al. (2015) who were determining the calorific value of certain agricultural leftovers such as rice husks, rice straw, corn straw, corn cob and cocoa pods.

The average chemical characteristics of the CPHs from the UA and PA are reported and compared to existing literature in the Table 5.

Table 5: Comparison of the UA and PA results



	VM	FC	ASH	C	H	N	O	S	HHV (UA)	HHV (PA)
CPH*	**65.3**	**24.28**	**10.42**	**50.76**	**4.29**	**1.26**	**43.48**	**0.21**	**18.28**	**18.69**
[i]	76.4	11.6	12	43.9	5.8	2.2	47.6	0.5	17.39	-
[ii]	-	-	8	51.1	6	3.3	39.4	0.2	16.68	-
[iii]	59.5	24.4	16.1	-	-	-	-	-	-	17
[iv]	68.8	23.2	8.1	48.8	7.9	1.9	39.9	-	18.9	-

*** is the average values from this study**

Notes: (i) Titiloye et al. 2013, (ii) Yadav et al. 2011, (iii) Syamsiro et al. 2012, (iv) Akinola et al. 2018

Source: data of the study

From the evaluation of the potential of CPHs as a feedstock for power generation, it was clearly demonstrated that CPHs are a potential feedstock since their calorific value was estimated to be 18.28 MJ/kg from UA and 18.69 MJ/kg from the PA at a moisture content of 11.53 % dry basis. This result is in accordance with that of (Yadav et al. 2011) who estimated a high heating value of 16.68 kJ/kg at 48 % moisture content; and a moisture content of 13 % with a heating value of 17.0 MJ/kg as reported by Syamsiro et al. (2012). Kilama et al. (2019), in their process of quantifying and characterizing CPHs for electricity generation in some rural areas in Uganda, estimated a heating or calorific value of 17.5 kJ/kg on a dry basis with a moisture content of 12.58 %. From the Table 2 and Table 3, it can be observed that the PA recorded higher HHVs than the HHVs of the UA. This can be attributed to the higher levels of O and VM content measured from our samples.

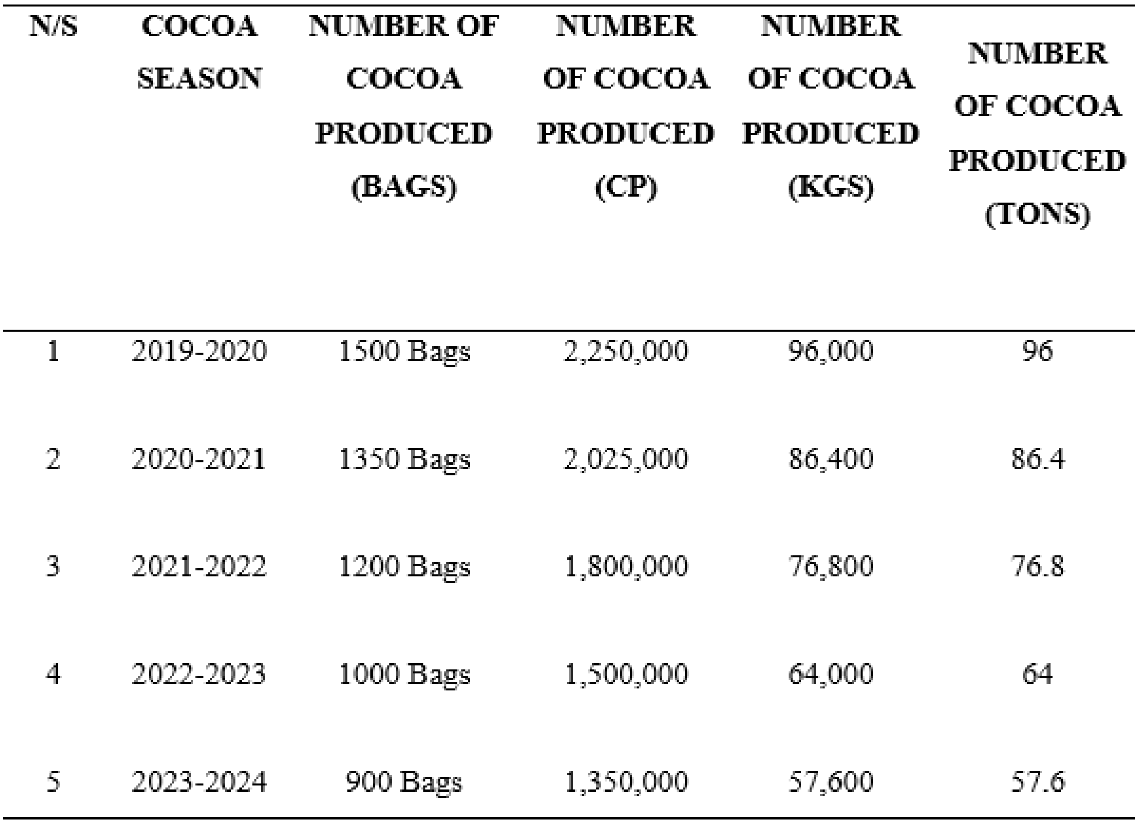
The results from this study as compared with results obtained from different researchers demonstrated that CPHs as a feedstock has a very good potential for small scale power generation over a long period of time.

In Edwenase community where cocoa is the main crop cultivated, the pod husks which are left to decay can be utilized for energy production, curbing the problem when it comes to electricity supply and also, preventing the CPHs to decay causing environmental pollution.

5.4. Annual Quantity of Cocoa Pod Husks Produced in the Edwenase Community

The total pod husks in tons produced by Edwenase each year was estimated by aggregating data of cocoa bags recorded by the LBCs from the community. The total cocoa produced can be seen in the Table 6 below.

Table 6: Total number of cocoa produced in Edwenase from 2019-2023



N/S	COCOA SEASON	NUMBER OF COCOA PRODUCED (BAGS)	NUMBER OF COCOA PRODUCED (CP)	NUMBER OF COCOA PRODUCED (KGS)	NUMBER OF COCOA PRODUCED (TONS)
1	2019-2020	1500 Bags	2,250,000	96,000	96
2	2020-2021	1350 Bags	2,025,000	86,400	86.4
3	2021-2022	1200 Bags	1,800,000	76,800	76.8
4	2022-2023	1000 Bags	1,500,000	64,000	64
5	2023-2024	900 Bags	1,350,000	57,600	57.6

Source: data of the study

The number of estimated cocoas produced in this area annually is 76 tons. To account for the CPHs that will be certain for RE generation, we made a feasibility observation that, 70 % of the produced cocoa are the recoverable available pods. The other 30 % covers the other uses of CPHs in the community like animal feed, soap ingredients and fertilizer. The recoverable CPHs are 53 tons. It can however be observed from Table 6 that the quantity of cocoa keeps decreasing each year. Farmers reported that this is due to poor weather conditions, lack of access to fertilizers, aging trees and losses to black pod disease. It is therefore essential to accentuate the positive potential of CPHs as a feedstock as it suggests that whereas the valorisation of CPH can promote economic development among farmers; it can also boost cocoa production as backed by (Proskuryakova 2023).

Recent studies conducted by Tsai et al. (2017) and Adjin-Tetteh et al. (2018) show that CPH has a relatively HHV of 17–18 MJ/kg which is in line with the findings of this study. The low quality of extension services in this area raises interest in the potential of this area in cocoa production and RE generation. According to Adjin-Tetteh et al. (2018), factors such as cultivation methods, environmental influences and differences in soil contaminations can impact greatly on HHV of CPH.

5.5. Edwenase´s Waste Management Practices of Agricultural Residues

From the discussions of the two assemblies organized, it was gathered that there were no waste management practices been used in Edwenase. The common observed agriculture residues in in the area are pineapple crowns, cassava peels, rice husks, maize straws, maize husks, and palm kernel shells. They residues are usually left on the farms when processed on-farms (Ouattara et al. 2021) or thrown in their backyards which serve as their disposing sites. Few farmers understood the reason for leaving the residues on the farms and were deliberate at this practice. The same was observed by ICCO (2019). Relevant to this study, the cocoa farmers explained the serious lack of access to fertilizers in the municipal and therefore nudging them to the application of their indigenous knowledge. The CPHs are thrown around the cocoa trees or around the crops being intercropped. This is to allow the rotten pods to release nutrients to the soil acting as fertilizer. Few farmers who had some access to extension services or some level of education practiced this same technology but observed that the CPHs were left five feet away from the tree. This is said to potentially increase the soil nutrients and soil water holding capacity (Ayeni et al. 2015).

Some farmers allowed their wives to utilize the CPHs for soap making as efforts to support their household income. The idea of using potash from CPHs to make soaps was also mentioned by Campos-Vega et al. (2018). There was a very high degree of male claimed dominance in the responses of the male farmers who asserted that they decided if the women had access to the pod husks for soap making. It emphasizes on the need for gender-assessment studies to understand how gender dynamics affect farming, valorizing of agricultural residues and household income in such areas. For the few mixed farmers, they emphasized on the high cost of animal feed. The agricultural residues like the placenta of the CPHs were a significant source of protein for their animals (Oduro-Mensah et al. 2020). These activities may have indirectly offsetted a small fraction of the agricultural residues which would have ended up as waste with no management means but there still remains largely a significant portion of agricultural residues like the cocoa pods which rot and become a menace by way of smell, eyesore sites and spread of bacteria or fungi. An attempt to gather information from the farmers during the assembly on what quantity of their cocoa are lost to infections from such fungi and bacteria failed as they do not account for such.

5.6. Proposed Technology for Cocoa Pod Husk Utilization in Edwenase

As part of the objectives of Ghana’s Renewable Energy Act, 2011 (Act 832), the use of RE which includes biomass is to be promoted (Nelson et al. 2021). Ghana has a significant amount of biomass available. Regardless of this abundance, very low levels of energy are generated from biomass. In rural communities, it is not economically plausible to be connected to the grid. This leaves a niche ready to be occupied by biopower sources such as CPHs. For example, maximally realizing the potential of the utilization of biodigesters can boost Ghana’s agriculture productivity by 25 % yet we have only 400 digesters established (BAGS 2019). This is outrageously wide of the 278,000 digesters identified by the Netherlands Development Organization as the possible establishing potential for Ghana’s biodigester utilization (Mohammed et al. 2017)

In the context of Ghana, CPHs are an abundant resource available for utilization. It contains significant amounts of sugar with structural polysaccharide-cellulose and hemicelluloses (Adams et al. 2018). Nelson et al. (2021) reported about 800,000 tonnes of CPHs to be generated annually in Ghana. This is a tremendous amount of a readily available resource that could be exploited for electricity production to provide economic gains and also environmental solutions for CPH waste disposal problems. In this research, Edwenase was identified to produce 76 tons of cocoa each year. This is a high enough number for electrifying the area.

The successful utilization for such an area hugely predicates on several factors, key to which is choosing the right technology. In choosing the right technology, the utilized biomass (CPHs in Edwenase) was observed with respect to the desired end use applications and requirements, the type and quality of the CPH, and the SEE factors gathered during the assembly. The choice of technology in other contexts have used these indicators- Maturity and commercialization, efficiency, scalability, and feedstock requirements (Maleka 2016).

Thermochemical conversion technologies such as combustion, gasification and pyrolysis could all be appropriate for this study due to the low levels of moisture content (10.71 %) observed. The observed VM content (65.3 %), low levels of N and S also suggest that the conversion technologies above could potentially have also been used. Whiles combustion of CPH would technically be the easiest option; the ASH producible could potentially be a hindrance. Even though generated ash can be used as fertilizer for enhanced cocoa growth, ash deposition is very critical during biomass combustion as it can reduce burner efficiency due to the agglomeration of the ash particles in the furnace, damage to the burner due to restriction of gas flow and cause maintenance issues such as impulsive shutdowns for cleaning ash deposits (Nunes et al. 2016).

In energy production, the pyrolysis of CPH is also a good option with higher power generating efficiencies at low scales of operation (Park et al. 2018). Bio-oils generated from CPH pyrolysis could be utilised for heating or electricity by direct burning.

Gasification is by far the most appropriate technology for converting CPH to electricity. Additional to its ability to utilise low-quality feedstock, it also converts the entire C content of the biomass material. Biomass gasification has a varied range of feedstock requirement and could be used to convert CPH into gas products for utilisation in small-to-medium scale decentralised electric power generation system (Lourinho et al. 2023). Since biomass gasification can provide a HHV product with better energy capture and lower emissions in comparison to combustion and pyrolysis, it is prudent to use gasification for the conversion of CPH to electricity. For a gasification system, C conversion, syngas composition, tars and soot formation and oxidation are important parameters. Nelson et al. (2021) found that, for energy production, it is the nature of the biomass (uniformity, heating value, ASH) together with the local availability of biomass and the end product required (heat, electricity, fuels, and chemicals) that makes large-scale implementation of energy production a hectic task.

Since CPH is locally available and has moderate amount of ash, gasification of CPH is the most feasible biomass conversion technology for electricity production in Edwenase.

To be specific, a gasifier generator can be used here to provide localized electricity using gaseous fuels derived from solid biomass feedstocks through the gasification process (Figure 7).

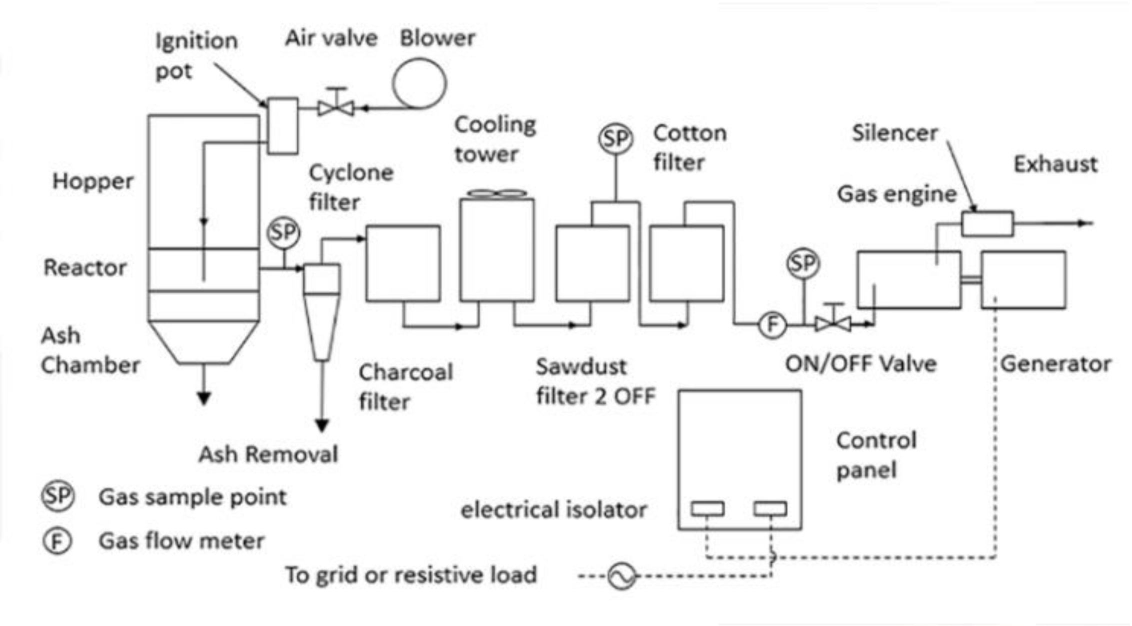


Figure 7: Schematic diagram of a gasifier generator.

Source: Worall et al. 2021

According to the description from Worall et al. (2021), the system consists of a reactor vessel and a hopper. A blower provides air to the reactor via an air valve and ignition pot. The hopper is filled with biomass and once gasification is initiated, the production gases are directed through a number of filters to remove particulates and tars that could damage the gas engine. A water cooler is provided to reduce the temperature of the producer gases. Following filtration, the producer gas enters a four (4) stroke, two (2) cylinder engine. The A.C. alternator produces 3 phase voltages at a frequency of 50 hertz (Hz). An electrical load is applied to the generator and the power output from the engine is measured.

A gas flow meter is sited between the final filter and the engine gas inlet, a gas sample point near to the gas inlet point is connected to a wall mounted gas monitor, measuring carbon monoxide (CO), CO_2, CH_4, and hydrogen gas (H_2). By measuring the level of CPH at the start of the experiment, the CPH mass can be determined, then checking the level at various times during the test. Temperatures at various points around the system would be measured by thermocouples and electrical parameters, voltage, current, frequency would be measured by a power meter sited on the control panel.

5.7. Total Energy Producible in Edwenase

This HHV suggests that when 1 kg of CPH is burned completely, it releases 5.08 kWh of energy in the form of heat. But no system is 100 % efficient (Xu 2023), which means that a part of the energy generated by the CPH will be lost. In this study, we recommended for the Edwenase community the use of the gasifier. According to Maleka (2016), the gasifier has an efficiency of 30 %. With 53 tons of cocoa producible every year at Edwenase, the total energy that can be generated in Edwenase in a year is 269,240 kWh. The electricity producible in the year as the electricity generation from biomass formula (Fellin et al. 2016) is 80,772 kWh. Asuamah et al. showed that the electricity consumed by a low class user community like Edwenase at the household level is 13.5 kWh per household in a month. Assuming the households in Edwenase are 150, it is found that they would consume 24,300 kWh in a year. Comparing to the electricity producible by the gasifier in a year, 80,772 kWh, the CPHs produced in Edwenase has 3 times the potential to supply the community at household level with electricity annually. Future studies must therefore focus on accounting for the variations in efficiency of the system and the availability of the feedstock. In reality, there may be additional losses and inefficiencies, as well as potential seasonal variations in the availability of CPHs.

Additionally, the calculation does not consider factors such as the cost of setting up and maintaining the gasifier system, the distribution of electricity within the community, and the potential need for energy storage or backup systems. Understanding the economics of bioenergy systems is crucial because whereas the energy balance may be positive, the costs of its entire chain for production and deployment can make it economically undesirable or unfeasible.

5.8. Assumptions and Potential Limitations of the Analysis

The limit of the analysis predicates on the use of CPH as feedstock for electricity generation in the Edwenase community. It was assumed that there was similar vegetation and cocoa growing conditions within each farm for the selected species and that the energy potential is reflective of all other farms. It was assumed that the gasifier runs at 30 % efficiency all year round with the rest of the energy lost through friction, inefficient conversions and heat.

5.9. SWOT Analysis for the Study

A swot analysis was conducted so as to identify what picture the findings of this study painted. IRENA (2022) observed that the increasing deployment of bioenergy and completely realizing its full socio-economic benefits is predicated on identifying the cross-cutting barriers and resolving them. In efforts to contextually understand what barriers Edwenase could face and what pillars deploying a biopower system in this community could have, the analysis was conducted.

Table 7: SWOT analysis of generating RE in Edwenase using CPHs.

INTERNAL FACTORS

STRENGTHS +	**WEAKNESSES –**
-Readily available feedstock. -Used Gasifier has a technology readiness level of 9. -Conversion technology and process are scalable. -High feedstock conversion rate and high HHV. -Little to no need for new land acquisition. -Feedstock is eco-friendly.	-Medium ASH levels. -The predominant specie (Hybrid) has the lowest CPH %. -Lack of techno-economic analysis on costs (Total Investment Costs, Levelized Cost of Electricity, Fixed Operation and Maintenance Costs, Variable Operation and Maintenance Costs) for such processes in localized contexts. -Low extension services in municipality.

EXTERNAL FACTORS

OPPORTUNITIES +	**THREATS –**
-Focusing on Amenolado species for future studies. -Bridging poverty gap between the urban and rural. -Explore gender-based studies pre-implementation and post-implementation of such projects in rural areas. -Set-up strong RE policies and extension services. -Design innovative interaction means between stakeholders for future competition management and capabilities improvement.	-Intensive shift and thereby increased use of CPHs for other valorized processes. Example, for soap making or for animal feed. -Competition from LBCs for CPH due to increasing request of the bio-resources industrial sector. -Change of land use or possible land grabs.

There is an interesting proposition that spells out of the analysis. The CPH being eco-friendly and having a high HHV makes it ideal for use in generating RE. However, it must be noted that valorising a material means a new sense of demand for it and demand drives price. In such a future, contest between stakeholders on who gets the CPHs and for what industrial need to satisfy it with will be key to determining how sustainable such projects can be and also maintain the holistic socio-ecosystem. A study of this kind will be magnanimously relevant. The barriers deducible from Table 7 summarises as policy uncertainty, financial and economic barriers, technology readiness, weak supply chain and a low level of awareness of bioenergy products (ibid p.55).

6. Conclusion and Recommendations

This feasibility study focused on the application of CPHs in Edwenase community in order to suggest a strategy for increasing RE and retrieving value-added by products. The amount of cocoa produced and cultivated in the community is abundant as it contributes to 2 % of the total 20 % of cocoa pods produced from Ashanti region, and with the CPH % volume obtained from this study being 67.69 % averagely shows a higher volume of the cocoa husks after the beans have been removed. The physical, mechanical and chemical properties of the CPHs as measured during the study reveals the CPHs as a potential fuel for energy production. The moisture content, particle and bulk density being the physical quantities measured were 10.71 % (on wet basis, 11.53 % on dry basis), 394.37 kg/m^3, and 290.4 kg/m^3 respectively. These relatively moderate physical properties placed the CPHs in a moderate position for its use as fuel for energy production. The compressibility test showed the CPHs to be moderately hard, of which is a requirement for all biomasses being used as a fuel for energy production. The notable medium content of ash measured in this study means CPHs can be a good feedstock, but it will be essential to find ways to minimize the ASH ad hoc to the operational challenges it poses to the gasifier. Here, it can be recommended that the PA and UA will be performed for separated species and not to be mixed as was done in this study. This will allow .us to measure which species in the Edwenase community have the highest ASH. Methods of addressing ash-related issues during CPH conversion can be used. Example, a number of additives can be added via the following means: using chemical adsorption and reactions to capture problematic ash; physical adsorbtion and elutriation of identified troublesome ash species from the gasier; augmenting the inert compounds in ash residue by increasing CPH ash melting temperature; and finally, by utilisig the dilution and powering effects from the additives to withhold the CPH ash sintering. The low levels of N and S measured promulgate CPHs as an eco-friendly feedstock. The high VM content suggests a faster ignition potential than the CPH and also to have a HHV due to its relatively high FC content.

Currently, there is no appropriate management of the waste from the cocoa pods in the community. What the farmers usually do is to leave the CPHs at a dumping site to decay, becoming an environmental menace by the way of the odor, unpleasant sites and the generation and spread of bacteria and fungi.

From the evaluation of the potential of CPHs as a feedstock for energy conversion processes, it was concluded that CPHs are a high-potential feedstock due to it calorific value of 18.28 MJ/kg comparable to widely used feedstock, such as wood, bagasse, rice husk and straw by other researchers. It was also demonstrated how the cocoa placenta can be prepared for the purposes of animal feed. The total CPHs produced in Edwenase annually is 76 tons. This number could be more. It was noted that there was poor accessibility to cocoa fertilizers by farmers within the municipality. This was the same that was reported in the Municipal Planning Coordinating Unit (2016) report from 2016. Giving farmers in this municipality access to cocoa fertilizers would cause most cocoa farmers to cease using CPHs as a source of fertilizer which would decrease the rate of fungi and bacteria infections, reduce the practice of decaying CPHs and most importantly make more pod husks readily recoverable for energy generation.

Other impacts and benefits of CPHs as use of feedstock of energy production are the lack of competition for the acquisition and need for extra land requirement for their production, as they were harvested from existing plantations at Edwenase community.

To utilize the CPHs, there are several potential applications. Some of these potential applications are as follows:

By burning or gasifying CPHs, you can use them as a biomass fuel source to produce heat or electricity. They are a good fuel for bioenergy applications due to their high fiber content.

For animal feed, to add dietary fiber and other nutrients, cocoa bean husks can be added to animal feed formulas. They can be added to livestock feed, including that of pigs, poultry, and cattle. As substrate for mushroom cultivation, CPHs' fibrous texture and nutrient content make them a viable substrate for the growth of edible mushrooms, including oyster mushrooms and other species.

CPHs can be applied to soil as a mulch or amendment in horticulture and agriculture. They can enhance the soil's nutrient availability, water retention capacity, and structure. CPHs can also be used for bio char production; by heating in the absence of O, a process called pyrolysis, CPHs can be turned into bio char. By adding the resulting bio char to the soil, the soil's fertility can be improved, and its water retention capacity can be increased.

Lastly, CPHs can be composted with other organic materials to create nutrient-rich compost that can be used in gardening or farming.

The choice in selecting a technology for the utilization of the CPHs depends on specific applications and local conditions. For this study, biomass energy production (Gasification) was selected to be the most appropriate technology for the utilization of the CPHs, as the community where this study was conducted faces a major challenge when it comes to electricity. As part of the target impacts, this study seeks to contribute to efforts made at creating a conducive environment for the socio-economic development of inhabitants of Edwenase community and all such communities. The trickling-down effect would be to help bridge the poverty gap between the rural and the urban. Also, using a gasifier as described above for energy production will limit the rate at which the CPHs stay on farm sites and are left to decay. It is therefore recommended that the gasifier, as described by Worall et al. (2021), be built and utilized to reduce the pollution caused by the CPHs and mainly, generate electrical power for the community. Gasification of biomass emerged more attractive than combustion, pyrolysis, ethanol production and anaerobic digestion because we observed that it converts the entire C content of the biomass material into fuel. As also noted by Sikarwar et al. 2016; the scale of operation (small, large, centralised, decentralised), feedstock flexibility (size and characteristics) and sensitivity to the amount of ash and tar yield, are essential considerations before choosing a gasifier due to the diverse range of acceptable reaction conditions for gasifiers. Supporting policies and regulations should be developed and implemented to attract investors. Also, there should be more focus on using RE resources to cut down on the over dependence of hydro-power in the country. This study found that the producible electricity from CPHs can supply low-class users such as Edwenase, 3 times their electricity demand at the household or residential level. In the general African context, it has been asserted that the rising electrification rate for most countries in synonymous to the increasing deforestation rate. This study is critical as the use of CPH requires no deforestation or new lands and will be key to bringing down the deforestation rates in the long run.

This study concluded with a firm recommendation on the importance of performing a techno-economic analysis of using CPHs to generate RE using the gasifier as the chosen technology in the Edwenase community. A preliminary study was launched to assess the costs of connecting such communities to the grid of a nearby town against the costs of producing their own energy using the CPHs with the gasifier as the chosen conversion technology. Using CC krom and Oseikrom as the two chosen areas, early results (which is results for about only 10 % of the entire study to be conducted) showed the need for 18 high tension poles and 32 low tension poles to connect Oseikrom to the grid in CC krom. This data will feed into providing information about the Levelized Cost of Electricity costs for such projects in local areas. The study will seek to also find the Total Investment Costs, Fixed Operation and Maintenance Costs and the Variable Operation and Maintenance Costs involved for the generation of RE for rural communities especially those that are deemed economically unsuitable for grid-extended electricity supply. Studies such as this are critical to allowing policymakers in Ghana to manage their energy-situation sustainably and also promote rural development. Also, gender-based studies must be performed in such areas to assess the potential productivity under equitable gender-based power dynamics.

7. References

- Adams P, Bridgwater T, Lea-Langton A, Ross A, Watson I. Biomass Conversion Technologies. In Greenhouse Gas Balances of Bioenergy Systems. Academic Press, Cambridge:107–139.
- Adanez J, Ollero P, Garcia-Labiano F, Gayan P. 2017. Biomass combustion in fluidized bed boiler: Potential problems and remedies. Fuel Processing Technology 167:530-534.
- Ademiluyi IO, Odusote JK, Adedokun MO, Dahunsi SO. 2019. Valorization of cocoa pod husk for bioethanol production using microwave-assisted acid pretreatment. Biomass Conversion and Biorefinery 9:617-628.
- Adjin-Tetteh M, Asiedu N, Dodoo-Arhin D, Karam A, Amaniampong PN. 2018. Thermochemical conversion and characterization of cocoa pod husks a potential agricultural waste from Ghana. Industrial Crops and Products 119:304-312.
- Akinola AO, Eiche JF, Owolabi PO, Elegbelee AP. 2018. Pyrolytic analysis of cocoa pod for biofuel production. Nigerian Journal of Technology:1-6.
- Akrofi MM. 2021. An analysis of energy diversification and transition trends in Africa. International Journal of Energy and Water Resources 5:1-12: DOI: 0.1007/s42108-020-00101-5
- Allcot H, Collard-Wexler A, O´Connell SD. 2016. How does electricity shortage affect industry? Evidence from India. American Economic Review 106:587-624.
- Amponsah-Doku B, Daymond A, Robinson S, Atuah L, Sizmur T. 2022. Improving soil health and closing the yield gap of cocoa production in Ghana – A review. Scientific African 15:1-11.
- AOAC. 1990. Official Methods of Analysis. 15th Edition. Washington, DC: Association of Official Analytical Chemist.
- Ashokkumar V, Venkatkarthick R, Jayashree S, Chuetor S, Dharmaraj S, Kumar G, Chen WH, Ngamcharussrivichai C. 2022. Recent advances in lignocellulose

biomass for biofuels and value-added bioproducts: A critical review Bioresource Technology 344:2.

- Asomaning J, Addo PK, Amponsah SK. 2018. Characterization and potential utilization of cocoa pod husk ash for soil stabilization. Journal of Materials and Environmental Science 9:684-693.
- ASTM. 2021. Standard Test Method for Volatile Matter Content of Activated Carbon Samples. ASTM International. Available from https://www.astm.org/d5832-98r21.html (accessed March 2024).
- Ayamga EA, Kemausuor F, Addo A. 2015. Technical analysis of crop residue biomass energy in an agricultural region of Ghana. Res.Conserv. Recycl 96:51–60.
- Ayeni LS, Saliyu M, Oyegbile S, Kawsar A, Ali K. 2015. Laboratory Experiment on Soil Nutrients Mineralization and Interaction As Affected By Cocoa Pod Husk, Kola Pod Husk and Urea Fertilizer in Alfisol. American Journal of Agricultural Science 2:144-149.
- Ayo-Omogie HN, Osanbikan AA. 2019. Comparative Influence of Dehulling on the Composition Antioxidative and Functional Properties of Sorrel (*Hibiscus sabdariffa L.)* Seed. Food and Nutrition Sciences 10:1-10.
- Azapagic A. Prodan S, Shallcross D. 2018. Decarbonizing cocoa production in Ghana: An integrated life cycle assessment and optimization approach. Journal of Cleaner Production 186:939-952.
- BAGS. 2019. Institutional Biogas Feasibility. Biogas Association of Ghana. Available from https://www.biogasghana.org/institutional-biogas-feasibility/ (accessed February 2024).
- Baldwin SA, Sovacool BK, Bumpus AG. 2020. The Emergence and Expansion of Global Renewable Energy Policy. Annual Review of Environment and Resources 45:1-27.
- Bandeira FJS, Ribiero Jr JAS, Mesquita ALA? Mesquita ALA, Torres EA. 2023. Potential Use of Palm Oil and Cocoa Waste Biomasses as Sources of Energy

Generation by Gasification System in the State of Pará, Brazil. Engenharia Agrícola:1-14.

- Bremner JM, Mulvaney CS. 1982. Nitrogen – Total. Methods of soil analysis Part 2. Agronomy 9:595-624.
- Campos-Vega R, Nieto-Figueroa HK, Oomah BD, 2018. Cocoa (*Theobroma cacao L.)* pod husk: renewable source of bioactive compounds Trends Food Sci. Technol. 81:172-184.
- Carley S, Lane B. 2019. The politics and policy of energy system transformation – explaining the German diffusion of renewable energy technology. Energy Research & Social Science 51:97-108.
- FAO. 2017. The future of food and agriculture – Trends and Challenges. Rome: FAO.
- FAOSTAT. 2021. Crops and livestock products. FAO, Rome. Available from http://www.fao.org/faostat/en/#data/QC (accessed March 2024).
- Fatma S, Hammed A, Noman M, Ahmed T, Shahid M, Tariq M, Sohail I, Tabassum R. 2018. Lignocellulosis biomass: A sustainable bioenergy source for the future. Protein &Peptide Letters 25:3.
- Fellin M, Negri M, Macri G, Bernardi B, Benalia S, Zimbalatti G, Andrea RP. 2016. Electricity from wood: a wood quality and energy efficiency approach to small scale pyro-gasification. Procedia – Social and Behavioural Sciences 223:1-8.
- Gnansounou E, Raman JK, Panichelli L. 2019. Techno-economic and Environmental Assessments on Second-Generation Bioethanol Production. Comprehensive Reviews in Food Science and Food Safety 18:597-611.
- González-Arias J, Sánchez ME, Martínez EJ, Covalski C, Alonso-Simón A, González R, Cara-Jiménez J. 2020. Hydrothermal Carbonization of Olive Tree Pruning as a Sustainable Way for Improving Biomass Energy Potential: Effect of Reaction Parameters on Fuel Properties. Processes 8:1-20.

- Haque MA, Barua S, Akisanya AR. 2019. Agriculture Residue Potential for Bioenergy Generation in the European Union: A Review. Energy Reports 5:1392-1409.
- Heanes DL. 1984. Determination of total organic carbon in soils by an improved chronic acid digestion and spectrophotometric procedure. Communications in Soil Science and Plant Analysis 15:1191-1213.
- Holechek JL, Gell HME, Sawalhah MS, Valdez R. 2022. A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050? Sustainability 14:1-22.
- Holt-Gimenez E, Herren H, Altieri MA. 2012. We Already Grow Enough Food for 10 Billion People … and Still Can´t End Hunger. Journal of Sustainable Agriculture:1-5.
- Hossain MS, Masud MH, Shahanaz S, Sharif A. 2020. Renewable energy in Bangladesh: Status, potential, and policies. Renewable Energy 152:347-357.
- Huang Y, Wang X, Huang S, Zhang Y. 2020. Biomass Power Generation and Its Impact on the Reduction of Agricultural Straw Burning in China: Evidence from a Provincial Panel Data Analysis. Renewable Energy 146:647-656.
- Hunter RC, Halverson TL, Anderson RD. 1984. Quality assurance for plant tissue analysis by ICP-AES. Commun. In Soil Sci. Plant Anal 15:1285-1322.
- Chen H, Qui R, Liu G, Zhao X. 2019. Comprehensive Utilization of Agricultural Crop Residues Based on Resource Economics. Resources, Conservation and Recycling 142:301-309.
- Cho EJ, Trinh LTP, Song Y, Lee YG, Bae H-J. 2020. Bioconversion of biomass waste into high value chemicals. Bioresource Technology 298:2.
- ICCO. 2019. Quarterly Bulletin of Cocoa Statistics. Abidjan: International Cocoa Organization.
- Ingram V, Van Rijn F, Waarts Y, Gilhuis H.2018. The Impacts of Cocoa Sustainability Initiatives in West Africa. Sustainability 10:1-20.
- IPCC. 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-

industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge: Cambridge University Press.

- IRENA. 2021. World Energy Transitions Outlook: 1.5 °C Pathway. Abu Dhabi: International Renewable Energy Agency.
- IRENA. 2022. Five Cross-cutting Barriers to Bioenergy Deployment and How to Address Them. Available from https://www.irena.org/News/expertinsights/2022/Sep/Five-cross-cutting-barriers-to-bioenergy-deployment-and-how-to-address-them (accessed April 2024)
- Jacobson MZ, Delucchi MA, Cameron MA, Mathiesen BV. 2017. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunglight (WWS) for all purposes. Renewable Energy 108:701-731.
- Jacobson MZ. 2019. Examining the feasibility of converting New York State´s allpurpose energy infrastructure to one using wind, water, and sublight. Eneergy Reports 5:981-991.
- Jiang F, He W, Ju W, Wang H, Wu M, Wang J, Feng S, Zhang L, Chen JM. 2022. The status of carbon neutrality of the world´s top 5 CO_2 emitters as seen by carbon satellites. Fundam. Res.2:357-366.
- Johansson B. 2013. Security aspects of future renewable energy systems- A short overview. Energy 61:598-605.
- Kemausuor F, Nygaard L, MacKenzie GA. 2015. Prospects for bioenergy use in Ghana using Long-range Energy Alternatives Planning model. Energy 93:672-682.
- Kilama G, Lating PO, Byaruhanga J, Biira S. 2019. Quantification and characterization of cocoa pod husks for electricity generation in Uganda. Energy, Sustainability and Society 9:1-11.

- Koirala R, Adhikari R, Dhakal S, Ghimire K. 2019. Review on the potential use of biomass energy sources in Nepal. Renewable and Sustainable Energy Reviews 101:65-78.

- Kumar A, Chadra M. 2019. Energy resources and use: The present scenario and possible paths for the future. Renewable and Sustainable Energy Reviews 102:54-64.

- Kumi EN. 2017. The Electricity Situation in Ghana: Challenges and Opportunities; CGD Policy Paper 109. Washington, DC: Centre for Global Development.

- Lee K, Miguel E, Wolfram C. 2020. Experimental evidence on the economics of rural electrification. Journal of Political Economy 128:1523-1565.

- Lourinho G, Alves O, Garcia B, Rijo B, Brito P, Nobre C. 2023. Costs of Gastification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation. Recycling 8:1-17.

- Maleka D. 2016. Assessment of the implementation of alternative process technologies for rural heat and power production from cocoa pod husks [MSc. Thesis]. KTH School of Industrial Engineering and Management, Stockholm.

- Mapcarta. 2024. Edwenase. Mapcarta. Available from https://mapcarta.com/N5327132445 (accessed April 2024).

- Martinez JD, Villamizan-Gallardo RA, Ortiz-Rodriguez O. 2015. Characterization and evaluation of cocoa (*Theobroma Cocoa L.*) pod husk as a renewable energy source. Agrpciencia 49:329-345.
- Mclean EO. 1965. Aluminium in Methods of Soil Analysis. Agronomy No. 9, Part 2. Madison: American Science Agronomy.
- Mensah SG, Kemausuor F, Brew-Hammond A. 2014. Energy access indicators and trends in Ghana. Renewable and Sustainable Energy Reviews 30:317-323.

- Mohammed, M.; Egyir, I.S.; Donkor, A.K.; Amoah, P.; Nyarko, S.; Boateng, K.K.; Ziwu, C. Feasibility study for biogas integration into waste treatment plants in Ghana. Egyptian Journal of Petroleum 26:695–703.

- Municipal Planning Coordinating Unit. 2016. Implementation of Municipal Medium-Term Development Plan (2014-2017). Annual Progress Report for 2016. Kumasi: Ejisu Juaben Municipal Assembly.
- Nelson DW, Sommers LW. 1982. Total carbon and organic matter. Methods of soil analysis Part 2. Madison: Soil Science of America.
- Nelson N, Darkwa J, Calautit J, Worall M, Mokaya R, Adjei E, Kemausuor F, Ahiekpor J. 2021. Potential of Bioenergy in Rural Ghana. Sustainability 13:1-16. DOI:10.3390/su13010381
- Nunes L, Matias J, Catalão J. 2016. Biomass combustion systems: A review on the physical and chemical properties of the ashes. Renewable Sustainable Energy Review 53:235-242.
- Nyasapoh MA, Elorm MD, Derkyi NSA. 2022. The role of renewable energies in sustainable developmwnt of Ghana. Scientific African 16:1-16.
- Oddoye EOK, Agyente-Badu CK, Gyedu-Akoto E. 2013. Cocoa and its by-products: Identification and utilization. Chocolate in Health and Nutrition 7:23-38. DOI: 10.1007/978-1-61779-803-0_3
- Oduro-Mensah D, Ocloo A, Nortey T, Antwi S, Okine LK, Adamafio NA. 2020. Nutritional value and satfety of animal feed supplemented with Talaromyces verruculosus-treated cocoa pod husks. Sci Rep 10:1-16.
- Ofori-Boateng C, Lee KT, Mensah M, Song J. 2015. Optimum condition of energy conversion of cocoa pod husk by stem gasification. Journal of Analytical and Applied Pyrolysis 113:185-189.
- Ofori-Boateng C, Lee KT, Mensah M, Song J. 2016. Cocoa pod husk gasification for hydrogen-rich gas production in fluidized bed reactor. Energy Conversion and Management 122:89-100.
- Olabijno OO, Olajide JO, Olalusi AP. 2017. Mathematical Modeling of Sun and Solar Drying Kinetics of Fermented Cocoa Beans. International Journal of Environment, Agriculture and Biotechnology 2:1-8.

- Oreamuno AMA, Croppenstedt A. 2023. Bottlenecks, stresses and risks in the cocoa supply chain in Ghana: recommendations to increase its resilience. Rome:FAO.
- Osman A, Fang B, Zhang Y, Liu Y, Yu J, Farghali M, Rashwan AK, Chen Z, Chen L, Ihara I, Rooney DW, Yap P-S. 2024. Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review. Environmental Chemistry Letters:1-40.
- Ouattara LY, Kouassi EKA, Soro D, Soro Y, Yao KB, Adouby K, Drogui AP, Tyagi DR, Aina PM. 2021. Cocoa pod husks as potential source of renewable high-value-added products: A review of current valorizations and future prospects. BioResources 16:1988-2020.
- Ouattara YL, Kouadio E, Kouassi EA, Doudjo S. 2021. Cocoa pod husk: A review. BioResources 16:1988-2020.
- Owusu PA, Asumadu-Sarkodie S, Obeng GY. 2019. The Ghanaian biomass industry: Technical and commercial challenges and prospects. Renewable Energy 139:235-247.
- Pandey VC, Singh SK, Yadav A, Singh JS. 2016. Crop-residue recycling for sustainable livelihoods and soil quality in the Indo-Gangetic plains of India. Environmental Development 19:20-31.
- Park S, Roy PS, Kim SH. 2018. Current Developments in Thermochemical Conversion of Biomass to Fuels and Chemicals. IntechOpen 2:19–41.
- Proskuryakova L. 2023. The Contribution of Low-Carbon Energy Technologies to Climate Resilience. Climate 11:1-22.
- Quansah DA, Adaramola MS, Anto E. 2017. Cost-competitiveness of distributed grid-connected solar photovoltaics in Ghana: case study of a 4 kWp polycrystalline system. Clean Techn Environ Policy 19:2431-2442.
- Ramos-Sánchez V, De Lathouder J, Faaij A. 2017. Assessment on the global potential for electricity generation from biomass in combination with carbon capture and storage. Biomass and Bioenergy 97:22-38.

- Selten M. 2015. Certification and wage labour in the cocoa sector in Ghana [MSc. Thesis]. Wageningen University, Wageningen.
- Sharma B, Ingalls M, Sarkar A. 2018. A Review on the Utilization of Biomass from Rice Industry for Sustainable Development. Bioresource Technology 249:1014-1022.
- Shinde R, Shaki DK, Mahapatra P, Singh CS, Naik SK, Thombare N, Singh AK. 2022. Management of crop residues with special reference to the on-farm utilization methods: A review. Industrial Crops and Products 181:1-10.
- Schutyser MA, Boot MD, Van Haveren J. 2018. A closer look at the lignin content of fresh and cupped willow. Biomass and Bioenergy 119:303-306.
- Sikarwar VS, Zhao M, Clough P, Yao J, Zhong X, Memon MZ, Shah N, Anthony FJ, Fennell PS. 2016. An overview of advances in biomass gasification. Energy Environ. Sci.9:2939–2977.
- Singh D, Chhonkar PK, Padley RN. 19999. Soil, Plant & Water Analysis – A Method Manual. New Delhi: IARI.
- Sovacool BK, 2016. How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Research & Social Science 13:202-2015.
- Sovacool BK, Ryan SE, Stern PC, Janda K, Rochlin G. 2017. Waxing critical: A review of California low carbon fuel standard critiques. Energy Policy 101:263-276.
- Stern DI. 2016. The role of energy in economic growth. Annals of the New York Academy of Science 1381:233-257.
- Syamsiro M, Saptoadi H, Tambunan BH, Pambudi NA. 2012. A preliminary study on use of cocoa pod husks as a renewable source of energy in Indonesia. Energy for Sustainable Development:74 – 77.
- Titiloye JO, Abu Bakar MS, Odetoye TE. 2013. Thermochemical Characterisation of Agricultural Wastes from West Africa. Industrial Crops and Products 47:199-203. DOI: 10-1016 / j-indcrop.2013.03.011

- Tofu DA, Wolka K, Woldeamanuel T. 2022. The impact of alternative energy technology investment on environment and food security in northern Ethiopia. Scientific Reports 12:1-11.
- Tsai CH, Tsai WT, Liu SC, Lin LQ. 2017. Thermochemical characterization of biochar from cocoa pod husk prepared at low pyrolysis temperature. Biomass-Convers. Biorefinery 8:237–243.
- Wiafe ED, Asamoah G. 2018. Land-cover change assessment in Ejisu – Juabeng district in Ghana. Eurasian Journal of Forest Science 6:1-8.
- Worall M, Darkwa J, Adjei E, Calautit J, Kemausuor F, Ahiekpor J, Nelson N, Mokaya R. 2021. A small-scale gasifier-generator fuelled by cocoa pod husk for rural communities in Ghana. International Conference on Applied Energy 2020:1-4.
- World Energy Council. 2019. World Energy Issue Monitor. London: World Energy Council.
- World Population Review. 2024. Cocoa Producing Countries 2024. World Population Review. Available from https://worldpopulationreview.com/country-rankings/cocoa-producing-countries (accessed March 2024).
- Xu J. 2023. A review of the second law of thermodynamics and its application. Theoretical and Natural Science 13:102-108.
- Yadav JP, Singh BR. 2011. Study on future prospects of power generation by bagasse, rice husk and municipal waste in Uttar Pradesh. SAMRIDDHI: A Journal of Physical Sciences, Engineering and Technology:63-75.
- Yahaya AM, Karli B, Gul M. 2015. Economic analysis of cocoa production in Ghana: the case of eastern region. Custos e Agronegocio 11:336-352.
- Yalew AW. 2022. The Ethiopian energy sector and its implications for the SDGs and modeling. Renewable and Sustainable Energy Transition 2:1-11.
- Yapo BM, Besson V, Koubala BB, Koffi KL. 2013. Adding Value to Cocoa Pod Husks as a Potential Antioxidant-Dietary Fibre Source. American Journal of Food and Nutrition 1:29-45.

- Yuan X, Su C-W, Umar M, Shao X, Lobont O-R. 2022. The race to zero emissions: Can renewable energy be the path to carbon neutrality? Journal of Environmental Management 308:1-5.
- Zhang L, Ling J, Lin M. 2023. Carbon neutrality: A comprehensive bibliometric analysis. Environ. Sci. Pollut. Res.30:45498-45514.
- Zhang R, Lin KLiMSuR, Chen Y. 2018. Biochar Improves Soil Aggregate Stability and Water Availability in a Mollison After Three Years of Field Application. Science of The Total Environment:613-614,1300-1310.

Appendices

List of the Appendices:

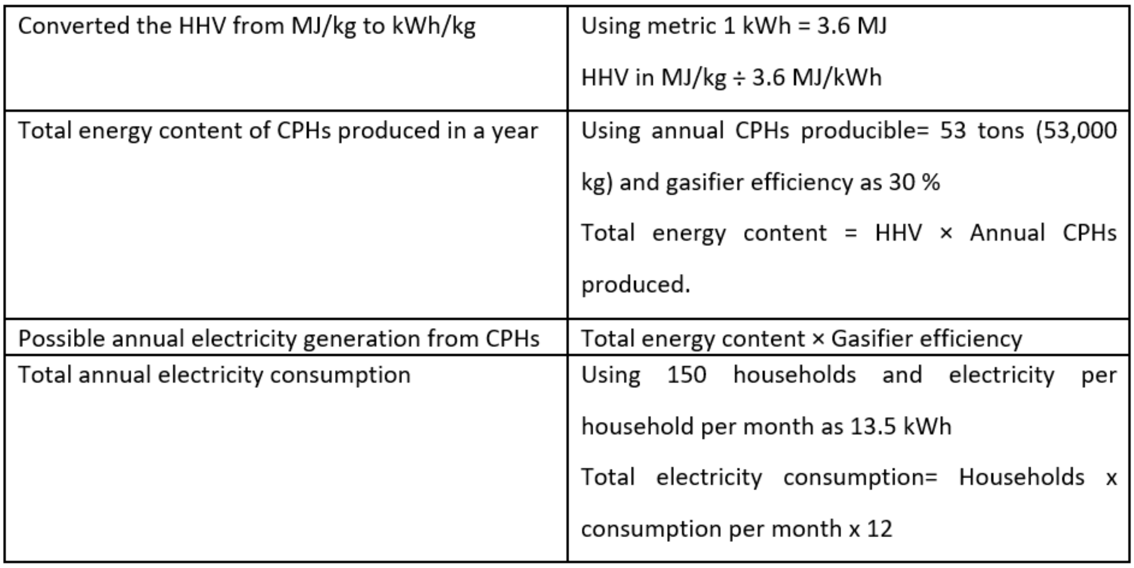
Appendix 1: Photo documentation from field observations

Appendix 2: Table supporting formulas for Producible Electricity

Appendix 1: Photo documentation from field observations

Appendix 2: Table supporting formulas for Producible Electricity

Table 1: Formulas for Producible Electricity and Electricity Consumable in Edwenase.



Converted the HHV from MJ/kg to kWh/kg	Using metric 1 kWh = 3.6 MJ HHV in MJ/kg ÷ 3.6 MJ/kWh
Total energy content of CPHs produced in a year	Using annual CPHs producible= 53 tons (53,000 kg) and gasifier efficiency as 30 % Total energy content = HHV × Annual CPHs produced.
Possible annual electricity generation from CPHs	Total energy content × Gasifier efficiency
Total annual electricity consumption	Using 150 households and electricity per household per month as 13.5 kWh Total electricity consumption= Households x consumption per month x 12