
DRP-CCDRM

INTERNATIONAL MASTER PROGRAMME IN ENERGY AND GREEN HYDROGEN

SPECIALITY: Bioenergy, Biofuels, and Green Hydrogen Technology

MASTER THESIS

Subject/Topic:

ASSESSMENT OF THE BIOENERGY POTENTIAL OF CASSAVA PEELS IN TOGO: BIOGAS AND HYDROGEN PRODUCTION AND LIFE CYCLE ASSESSMENT

2023-2025

Presented on September 30, 2025

by:

Abiré PAGOUSOOU

Exam Committee members:

Chair: Milohum Mikesokpo DZAGLI, Professor, Université de Lomé – Togo

Examiner/judge: Koffigan AGBATI, Associate Professor, Université de Lomé - Togo

Main Supervisor: Tchamye Tcha-Esso BOROZE, Associate Professor, Université de Lomé - Togo

Co-Supervisor: Satyanarayana NARRA, Professor, University of Rostock - Germany

DECLARATION

I hereby certify that I am the sole author of this master's thesis entitled *"Assessment of the bioenergy potential of cassava peels in Togo: Biogas and Hydrogen production and Life Cycle Assessment."* This work was carried out independently, using only the reference sources and materials permitted. All sources consulted have been appropriately acknowledged and cited. Furthermore, I affirm that this thesis has not been submitted, in whole or in part, for any other academic qualification or examination elsewhere.

Rostock, 25th August 2025

Abiré PAGOUSOOU

DEDICATION

I dedicate this work to my late father, Celestin Allaguem PAGOUSOOU, and my mother, Francine Kalla KADERA, for their wisdom and unconditional belief in my potential. A special tribute to my uncles and older brothers, whose presence and advice have consistently reminded me that I am never alone on this path. To my whole family and friends who believed in me, this achievement is as much yours as it is mine. May this work stand as a testament to resilience, purpose, and the power of shared hope.

ACKNOWLEDGMENTS

First and foremost, I thank God Almighty, whose grace, guidance, and strength have carried me through this journey. None of this would have been possible without His presence.

I want to express my deepest gratitude to all those who have supported me throughout this academic path.

I sincerely thank the funders, the Federal Ministry of Education and Research (BMBF), and the WASCAL program, for awarding me the scholarship that enabled this master's program. Their financial support and dedication to climate education have played a crucial role in shaping my journey.

I would like to acknowledge Prof. Adamou Rabbani, WASCAL Director at the University of Abdou Moumouni, where I spent my first and second semesters, for his leadership and support.

I would like to thank Dr. Komi Agboka, WASCAL Director at the University of Lomé, and Dr. Prosper Begedou, WASCAL Deputy Director at the University of Lomé, for their mentorship and guidance, which have played a crucial role in shaping my academic path.

Special thanks to the Coordinator of the H_2 Programme at the University of Lomé.

I also extend my sincere thanks to the President of the University of Lomé, Prof. KPODAR, for providing a conducive academic environment during my third semester.

My heartfelt thanks go to the Vice Chancellor of the University of Rostock, where I had the privilege of completing my internship. The research in Germany was helpful for both my research and personal and professional development. I am deeply grateful for such a valuable opportunity.

To my major Supervisor, Dr. Tchamye Tcha-Esso BOROZE, my Co-supervisor, Prof. Satyanarayana NARRA, and my daily supervisor, MSc Djangbadjoa GBIETE, I am immensely grateful for their insightful feedback and support. Their guidance and contributions have been a cornerstone of this thesis.

I am also thankful to the esteemed members of the jury for their time, feedback, and expertise during my defence, which greatly contributed to the enhancement of my work.

I extend special thanks to the Director and the research team of the Department of Waste and Agriculture at the University of Rostock for providing a nurturing and collaborative learning environment, as well as to the team members from Niger who participated during the first and second semesters. The journey there was unforgettable.

I want to express my heartfelt appreciation to my friends and colleagues from the same master's program. I am grateful for the moments of laughter, teamwork, experiences, and resilience we shared.

Finally, I want to give a special thanks to my family and loved ones. Thank you for believing in me and standing by my side. Your encouragement and faith in me have been my most significant source of strength.

ABSTRACT

Energy insecurity and environmental degradation remain significant challenges for development in West Africa. Togo illustrates these issues through rapid population growth, urbanization, and a heavy reliance on imported fossil fuels. Cassava farming, vital for rural livelihoods and food security, produces substantial peel waste during processing. This underused biomass is often discarded or burned, worsening land and water pollution. Turning this waste into renewable energy could reduce environmental damage, cut fossil fuel use, and help Togo meet its climate goals.

This study investigates how cassava peels can serve as a renewable energy source through anaerobic digestion to generate biogas, followed by hydrogen production via steam methane reforming (SMR). The research encompasses physicochemical analysis of cassava peels, biochemical methane potential (BMP) testing with various substrate-to-inoculum ratios (1:3, 1:2, 1:1, and 2:1), simulation of the SMR process using Aspen Plus for hydrogen production, and a life cycle assessment (LCA) to evaluate environmental impacts.

Cassava peels showed a high volatile solids content (91.03%) and a carbon-to-nitrogen ratio of 88.9, indicating that co-digestion could enhance efficiency. BMP tests achieved a maximum methane yield of 469.5 mL CH_4/g VS at a 1:2 ratio. Aspen Plus simulations demonstrated effective methane conversion to hydrogen, with a mole flow rate of approximately 1.19 kmol/h, corresponding to a mass flow of 2.41 kg/h of high-purity hydrogen (~99.99%) after purification. The hydrogen yield from the Aspen Plus simulation was 0.10 kg/Nm^3, which is lower than the values reported by S. Phan et al. [1] and D. Singh et al. [2] who found yields ranging from 0.15 to 0.20 kg/Nm^3 under similar conditions in an experimental simulation, but closely matches the experimental production range of 0.13-0.16 kg/Nm^3 from Ayodele et al. [3].

The life cycle assessment was performed from gate to gate, using 1 m^3 of biogas produced and 1 kg of hydrogen as the functional unit. It evaluated five impact categories, including climate change, acidification, particulate matter, photochemical ozone formation, and eutrophication, using the OpenLCA software. Results indicate that producing biogas and hydrogen from cassava peels significantly reduces greenhouse gas emissions, fossil energy use, and overall environmental impact compared to conventional fossil-based methods.

Keywords: Cassava peels; biogas potential; hydrogen simulation; life cycle assessment; energy security.

RESUME

L'insécurité énergétique et la dégradation de l'environnement demeurent des défis majeurs pour le développement en Afrique de l'Ouest. Le Togo illustre ces problèmes par une croissance démographique rapide, une urbanisation et une forte dépendance aux combustibles fossiles importés. La culture du manioc, essentielle aux moyens de subsistance ruraux et à la sécurité alimentaire, produit d'importants déchets d'épluchures lors de la transformation. Cette biomasse sous-utilisée est souvent jetée ou brûlée, aggravant la pollution des sols et des eaux. Transformer ces déchets en énergie renouvelable pourrait réduire les dommages environnementaux, diminuer la consommation de combustibles fossiles et aider le Togo à atteindre ses objectifs climatiques.

Cette étude examine comment les peaux de manioc peuvent servir de source d'énergie renouvelable grâce à la digestion anaérobie pour produire du biogaz, suivie de la production d'hydrogène par reformage du méthane à la vapeur (SMR). La recherche comprend une analyse physicochimique des peaux de manioc, des tests du potentiel biochimique du méthane (BMP) avec différents ratios substrat/inoculum (1:3, 1:2, 1:1 et 2:1), une simulation du procédé SMR avec Aspen Plus pour la production d'hydrogène et une analyse du cycle de vie (ACV) pour évaluer les impacts environnementaux.

Les peaux de manioc présentaient une teneur élevée en matières solides volatiles (91,03 %) et un rapport carbone/azote de 88,9, ce qui indique que la codigestion pourrait améliorer l'efficacité. Les tests BMP ont permis d'obtenir un rendement maximal en méthane de 469,5 mL de CH_4/g VS dans un rapport de 1:2. Les simulations Aspen Plus ont démontré une conversion efficace du méthane en hydrogène, avec un débit molaire d'environ 1,19 kmol/h, correspondant à un débit massique de 2,41 kg/h d'hydrogène de haute pureté (~99,99 %) après purification. Le rendement en hydrogène issu de la simulation Aspen Plus était de 0,10 kg/Nm^3, ce qui est inférieur aux valeurs rapportées par S. Phan et al. [1] et D. Singh et al. [2], qui ont trouvé des rendements compris entre 0,15 et 0,20 kg/Nm^3 dans des conditions similaires lors d'une simulation expérimentale, mais qui correspond étroitement à la production expérimentale comprise entre 0,13 et 0,16 kg/Nm^3 de Ayodele et al. [3]. L'analyse du cycle de vie a été réalisée de porte-à-porte, en utilisant 1 m^3 de biogaz produit et 1 kg d'hydrogène comme unité fonctionnelle. Cinq catégories d'impact ont été évaluées, dont le changement climatique, l'acidification, les particules fines, l'ozone photochimique et l'eutrophisation, à l'aide du logiciel OpenLCA. Les résultats indiquent que la production de biogaz et d'hydrogène à partir de peaux de manioc réduit considérablement les émissions de gaz à effet de serre, la consommation d'énergie fossile et l'impact environnemental global par rapport aux méthodes conventionnelles à base de combustibles fossiles.

Mots-clés : Peaux de manioc ; potentiel de biogaz ; simulation de l'hydrogène ; analyse du cycle de vie ; sécurité énergétique.

ACRONYMS AND ABBREVIATIONS

AC : Ash Content
AD : Anaerobic Digestion
ADF : Acid Detergent Fibre
ADL : Acid Detergent Lignin
AP: Acidification Potential
BMBF: Federal Ministry of Education and Research
BMP : Biochemical Methane Potential
CC: Climate Change
CH_4 : Methane
CO : Carbon mono-oxide
CO_2 : Carbon Dioxide
CP : Cassava Peels
Cr : Chromium
CRT : Cell Retention Time
CSTR : Continuous Stirred-Tank Reactor
Cu : Copper
DM : Dry Matter
DSID : Direction des Statistiques agricoles , de l'Informatique et de la Documentation
EP: Eutrophication Potential
FAOSTAT : Food and Agriculture Organization of the United Nations Statistics Division
FC : Fixed Carbon
FM : Fresh Matter
GCV : Gross Calorific Value
GHG : Greenhouse Gases
GWP : Global Warming Potential
H/H_2 : Hydrogen
H_2S : Hydrogen Sulphide
HRT : Hydraulic Retention Time
HTWGS : High Temperature Water Gas Shift
IEA: International Energy Agency
INSEED : Institut National de la Statistique et des Études Économiques et Démographiques
kPa: Kilo Pascal
L : Liter
LCA : Life Cycle Assessment
LCI : Life Cycle Inventory
LCIA : Life Cycle Impact Assessment
LTWGS : Low Temperature Water Gas Shift
MC : Moisture Content
Mn : Manganese
MSW : Municipal Solid Waste
N/N_2 : Nitrogen

NDF : Neutral Detergent Fibre
NGO : Non-Governmental Organization
NH_3 : Ammonia
Ni : Nickel
NO_x : Nitrogen Oxides
O/O_2 : Oxygen
OFMSW : Organic Fraction of Municipal Solid Waste
OLR : Organic Loading Rate
P : Phosphorus
Pb : Lead
pH: Potential of hydrogen
POF: Photochemical Ozone Formation
PMF: Particulate Matter Formation
PSA : Pressure Swing Adsorption
SDGs : Sustainable Development Goals
SC : Substrate Concentration
S/C : Steam-to Carbon
S/I : Substrate-to-inoculum
SPE: Système Permanent d'Enquetes
SMR : Steam Methane Reforming
SO_2 : Sulphur Dioxide
SPE : Permanent Survey System
QGIS : Quantum Geographic Information System
TGA : Thermogravimetric Analysis
TS : Total Solid
VFA : Volatile Fatty Acid
VS : Volatile Solid
WASCAL : West African Science Service Center on Climate Change and Adapted Land Use
WGS : Water Gas Shift
WGSR : Water Gas Shift Reaction

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS

INTRODUCTION

1. Background

Climate change has become a critical issue, primarily due to human activities, and its impact is becoming increasingly pressing as the world's population continues to grow. Fossil fuels account for the largest share of the world's energy; however, their use generates significant amounts of greenhouse gases. The discovery of fossil fuels (oil, natural gas, coal) and their socio-economic role in the industrial revolution have promoted their development to the point where they currently account for 80 % of the global energy balance, however, the exploitation of these fossil fuels has proven to be harmful to the environment as it is the primary source of carbon dioxide(CO_2) emissions, and therefore, the the leading cause of climate change faced by humanity [4]. This issue has become more serious due to urbanization. On the other hand, municipal solid waste, especially organic waste, which is one of the most generated types, is unfortunately poorly managed in the environment. Rapid suburbanization in many emerging nations has generated substantial amounts of solid waste. Urban solid waste management is a major environmental issue, affecting public health, ecology, and climate. Global municipal waste production causes multiple ecological impacts, including greenhouse gas emissions, ocean plastic accumulation, and nitrogen pollution [4]. Globally, 7–9 billion tons of waste are produced annually, and municipal solid waste (MSW) is a category of waste stemming from households, which can also include commercial and industrial wastes, depending on the reporting standard [5]. The combination of inadequate waste management and climate change is compounded by energy insecurity, creating a vicious circle. In a world where energy supplies are becoming increasingly scarce, especially those derived from non-renewable sources, limited access to sustainable energy sources is becoming a pressing issue in many parts of the world. The problem of energy security is even more pressing in West African countries, particularly in developing countries like Togo. According to Gafa et al., the findings indicate significant energy poverty levels, with rates ranging from 53.5% to 98.8% in Togo, a West African country with a population of approximately 8 million [6]. Sub-Saharan Africa is one of the areas in the world where energy demand is increasing dramatically due to the pressure of demographic factors and urbanization [7].

To create a balanced future that respects natural resources, we must advance technology that not only supports sustainable growth but also aligns with environmental protection as we confront these issues. According to Yang et al. [8], given these challenges, it becomes essential to foster technologies and strategies that not only promote sustainable growth but also align with environmental conservation. It is high time to consider innovative solutions that support the Sustainable Development Goals (SDGs), particularly SDG 7, which aims to ensure access to affordable and clean energy, and SDG 13, which focuses on combating climate change, to secure a sustainable and resilient future for our planet. Consequently, biogas and green hydrogen (green H_2) emerge as promising avenues for partially mitigating the dual challenges of inadequate waste management and energy insecurity, especially within the Togolese context. By employing feedstock techniques and technologies, energy must be generated from sustainable and economically viable renewable resources. Because they produce digestate, the viability of biogas generated from organic waste as a renewable energy source is questioned, and the digestate can be utilized as a farming compost [9]. The anaerobic digestion (AD) process generates methane-rich biogas (called biogas) that can be converted into electrical energy, making it a recognized, environmentally acceptable waste management technique. The biogas can be produced from municipal solid waste, agricultural waste, industrial waste, and household waste, offering significant energy worldwide, as well as from food waste. Biogas has various applications, including heating, energy generation, cooking, and vehicle fuel. Additionally, the sludge from the AD of waste materials can act as a biofertilizer to enhance soil fertility. Biogas, then, represents a sustainable solution that addresses waste management challenges while providing a pathway to renewable energy generation; its production is likely to be preferred not only for its cleanliness and sustainability but also because it is derived from organic waste. Therefore, it does not result in the loss of food or biodiversity, and aligns with the SDGs [10]. Biogas from biomass is one of the best sources of renewable energy, as it can be used for heating, as a fuel or a natural gas equivalent, and can be converted to electricity, as noted by Yussouff et al. [11]. It is an economical form of renewable energy with the potential to meet the energy demands of the global rural populace [12]. The AD can also serve as a basis for hydrogen production, either through process enhancement to increase hydrogen production or through the steam methane reforming reaction of the methane gas obtained at the end. Zappi et al. stated that anaerobic systems have been shown to produce biogas that is easily used to generate energy; however, specific processes can be performed to enhance the concentration of hydrogen further [13]. Direct H_2 production during AD is a more straightforward process compared to the second way. H_2 production from biogas follows a syngas route, a mixture of carbon monoxide (CO), hydrogen (H_2), and CO_2, through various processes to obtain purified H_2 steam [14].

H_2 can be produced without greenhouse gas emissions through water electrolysis using renewable electricity or via biological processes such as anaerobic digestion, dark fermentation, photo-fermentation, bio-photolysis, or thermochemical processes, including steam methane reforming, gasification, and pyrolysis [15]. H_2 is then viewed as a clean and promising energy carrier. AD, a crucial process that facilitates the production of both biogas and H_2, supporting the transition to sustainable and renewable energy sources, is a suitable choice. Due to its potential to produce effective H_2 energy from biomass and organic waste, anaerobic bacteria-based fermentation is regarded as a more favourable biological pathway for hydrogen synthesis. Furthermore, H_2 production from biomass waste can achieve the dual benefits of clean energy generation and waste management, as agricultural and municipal wastes can be handled simultaneously [16]. It has been attested that H_2 may be a promising pillar in the transition toward a decarbonized society, as it offers several advantages over traditional fossil energy sources, including low emissions, high conversion efficiency, and high energy density [17]. The authors continued by stating that by 2050, hydrogen-based energy consumption is expected to account for 22% of the world's final energy consumption and will reduce CO_2 emissions by up to 80 gigatons, representing 20% of cumulative emission reductions.

Cassava peels (CP) can be used as a substrate to produce biogas through mono-digestion or co-digestion [18] , and subsequently, H_2. Cassava (*Manihot esculenta,* CRANTZ), a perennial shrub in the Euphorbiaceae family, is a major food crop, especially in Africa, according to [19]. It is Africa's most crucial tuberous crop and its highest per capita consumption, around 800g per person/day, occurs in Sub-Saharan Africa, where it is the primary energy source for almost 40% of the population and Togo with a production of 1,117,880 tonnes in 2019, equivalent to 0.5819% and 0.3682% respectively of the total production of Africa and the world, occupies 19th place in the ranking of 39 African cassava-producing countries [20]. According to the production report for the 2023-2024 agricultural campaign in Togo, among root and tuber crops, cassava is the most cultivated species, followed by yams [21]. Figure 0.1 highlights Togo's position in the sub-region, along with the percentage it occupies. While cassava root production in Togo is expected to rise from 1,224,641 tons in 2022 to 1,245,539 tons in 2023, as reported by the Système Permanent d'Enquetes (SPE) [22], the same applies to the solid waste generated as peels during processing. In Africa, about 25–37% of the 2017 production is released as waste in the form of peels and pulp, and 60,000 L of effluent was generated per tonne of cassava tuber processed [23]. In Togo, when cassava roots are limed, we obtain gari and/or attieke, and the starch produced is used to make tapioca; cooked, it can be eaten in pieces and is used to make foufou. These generated wastes are usually disposed of in water bodies, unfinished buildings, undeveloped plots of land, and any available open spaces along roads. Oghenejoboh et al [24] stated that the CP contribution to environmental degradation is far higher than all other cassava solid wastes. The management of cassava waste varies across several processing centers and countries.

In Africa, many cassava processors do not benefit from the waste they produce, as demonstrated by Olukanni et al. [25], and this is also applicable to Togo. However, cassava waste can be utilised as a biogas substrate, either alone or in combination with livestock manure, according to their experiment [26]. It is possible to obtain not only biogas but also H_2 via the methane reforming process [27]. There are two main categories of cassava waste used in bioenergy processes: thermochemical methods, which include gasification, pyrolysis, and combustion, and biochemical methods, which include anaerobic digestion and the fermentation of bioethanol [28]. Figure 0.2 illustrates the various products and methods for cassava waste conversion into energy. Issues related to climate change, environmental sustainability, and energy security are driving the shift to clean energy sources in Togo.

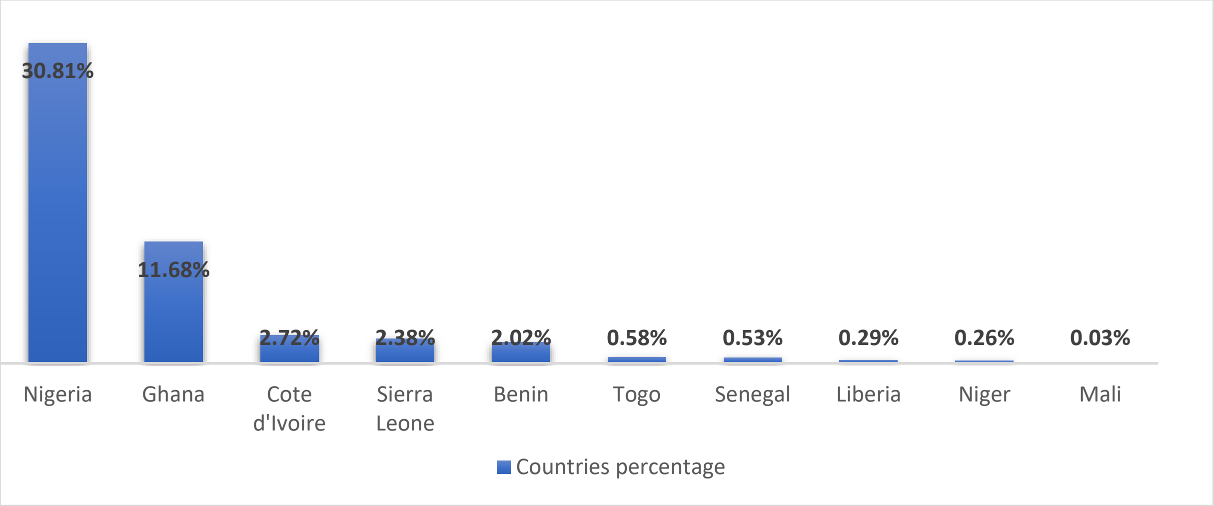


Figure 0.1. Cassava-producing countries in West Africa, from the biggest to the smallest producer, and their percentage of African and world production for 2019 (adapted from [20]).

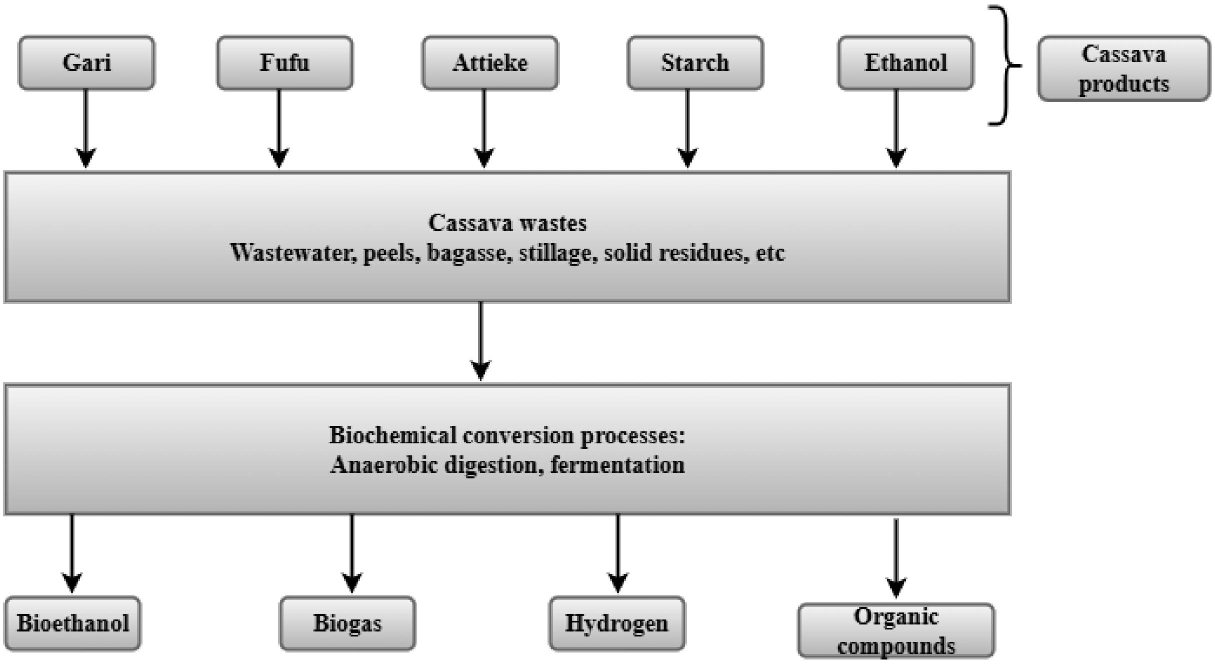


Figure 0.2. Biochemical conversion of cassava-based wastes into valuable products (adapted from [29])

A study conducted by Okudoh et al. [30] focused on biogas production from cassava and its by-products, it was revealed that from cassava peels, a methane content of approximately 51% and a biogas yield exceeding 87 m^3/kg VS (volatile solids) is obtained, highlighting the promising potential of cassava-based substrates in renewable energy generation.

2. Problem statement

In Togo, beyond direct consumption, Non-Governmental Organizations (NGOs) and cooperatives in areas such as Vogan and Kpalimé process cassava roots into gari and attieke, generating significant waste. Figure 0.3 illustrates the cassava tubers along with their peels. About 25-30% of the roots (see Appendix A: Flow Chart of Attiéké and/or Garri Production with peel generation percentage), as indicated by Ekop IE et al. [29], are considered waste as peels; this finding corroborates the study conducted by Kemausuor et al. [19], which reported that 30% of the cassava roots processed are discarded as peels. The CP waste in Togo presents both environmental and economic challenges due to poor management and a lack of valorization strategies. These residues, generated in large quantities during cassava processing, are primarily discarded, resulting in pollution and disposal costs for the government, as well as ecological concerns. Currently, CP is either spread on the soil as fertilizer without energy recovery, fed to livestock such as sheep and goats, or released into the environment based on traditional practices and insights from agricultural authorities. Gmakouba et al. highlighted that cassava processing in Togo generates substantial amounts of peel waste; however, the absence of a structured system for its valorization hinders its potential utilization [31]. This underutilization is especially concerning given that they are suitable for biogas production through AD, which could provide renewable energy while yielding digestate that serves as biofertilizer, offering dual environmental and agronomic benefits. Meanwhile, Togo faces significant energy insecurity, with disparities in electricity access between urban and rural areas; only 26% of rural households have access to electricity, compared to 88% in urban areas, according to INSEED (Institut National de la Statistique et des Études Économiques et Démographiques) [32]. In regions such as the savanna and Kara, where biomass remains the dominant energy source (98% and 95%, respectively), according to Yenlide et al., reliance on traditional fuels perpetuates environmental degradation [33]. The absence of efficient waste-to-energy strategies represents a significant opportunity lost in addressing both waste management and energy poverty. Issues related to climate change, ecological sustainability, and energy security are driving the shift to clean energy sources in Togo. By valorizing CP waste into biogas and H_2, Togo can advance sustainable energy solutions, reduce dependence on fossil fuels, and promote environmental conservation. Several studies have investigated the valorization of cassava peels for biogas and H_2 production, confirming their potential as a renewable energy source.

Research by Aisien et al. demonstrated that CP can generate biogas, especially when combined with cow dung as an inoculum [12]. However, it did not explore H_2 production or assess the environmental impact through a life cycle assessment (LCA). Other studies have focused on optimizing AD conditions using chemical pretreatments to enhance methane yield [34]. However, they did not examine the scalability or applicability of these methods for large-scale energy solutions. Additionally, investigations into CP-based H_2 production have revealed that, while feasible, H_2 yields are lower compared to those of other organic substrates. Research also lacked comparative analysis with alternative sources, as well as the integration of biogas-to-hydrogen conversion methods [15]. While some studies have acknowledged the environmental benefits of utilizing CP, including waste reduction and energy generation [35], no comprehensive LCA has been conducted to quantify its carbon footprint or economic viability. Despite extensive research on CP valorization in other regions, such as Nigeria and Ghana, as reported in Ukaegbu-Obi's study [36], a significant gap remains in the structured management and industrial implementation of these technologies. Without an effective system to harness CP for sustainable energy solutions, opportunities for bioenergy development, environmental conservation, and improved energy security remain largely untapped. This study aims to bridge these gaps by providing a comprehensive evaluation of cassava peels as a feedstock for both biogas and hydrogen production in Togo. Additionally, an LCA will be conducted to evaluate the environmental footprint and sustainability of CP valorization. To optimize biogas yield, this study will also vary the substrate-to-inoculum ratio to determine the most efficient conditions for maximizing biogas production. By addressing these research gaps, this study will contribute to the development of a structured waste-to-energy strategy, reducing dependence on fossil fuels and enhancing rural energy security.

Cassava tubers

Cassava waste

Figure 0.3. Cassava tubers and cassava peels (Source: Original photograph taken on-site in Lomé, Togo, on 15th March 2025)

3. Research questions

This study was motivated by these questions:

- What is the national production of cassava in Togo, and the potential quantity of cassava peels generated after processing? Furthermore, what are the physical and chemical characteristics of these peels relevant to their use in renewable energy production?
- What is the biogas yield potential of cassava peels under varying substrate-to-inoculum ratios?
- What is the H_2 potential that can be produced from this potential?
- What is the LCA of biogas production and H_2 production through the steam methane reforming (SMR) process from CP?

4. Research hypothesis

The following formulated hypothesis guided the present study:

- The country has a vast potential for CP, whose physicochemical compositions favor a high biogas yield from AD.
- CP has an important potential for biohydrogen production.
- The life cycle analysis of the biogas and hydrogen production processes shows that the recycling of CP complies with environmental standards.

5. Objectives

Given the gap in valuing CP for biogas production through anaerobic digestion and hydrogen production via Steam Methane Reforming, this study's main goal is to assess and promote cassava peels for biogas and hydrogen generation in Togo. The specific objectives:

- To evaluate the potential of cassava peels at the national level and investigate the characteristics of cassava peels for biogas production.
- To evaluate the biogas potential of cassava peels through biochemical methane potential tests (BMP tests).
- To simulate hydrogen potential through SMR from biogas using Aspen Plus Software.
- To conduct an LCA of biogas and H_2 production from CP.

6. Structure of research

The study is structured in five (5) parts. The introduction, which not only develops the background and problem statement but also formulates the hypotheses through research questions, and finally outlines the specific objectives, is the first part. The state of knowledge, which is considered as the second part and first chapter, the literature and better explanation of the concept of anaerobic digestion will be reviewed; exploration of the literature on obtaining biogas and hydrogen from cassava peels and the operating conditions or parameters, the concept of simulation using Aspen Plus software will be reviewed, as well as the LCA concept. Chapter two, materials and methods, which is the third part, is dedicated to the methodology and materials used for the study, including the evaluation of the national potential of cassava feedstock (CP) collection zone, the feedstock characterization, biogas production test methods, simulation of hydrogen production, and environmental analysis by LCA.

The fourth part, Chapter Three, Results and Discussion, presents the results and discusses their interpretation.

The final part presents a summary of key findings, conclusions, and recommendations, concluding the work.

CHAPTER I: LITERATURE REVIEW

1.1. Biogas production by anaerobic digestion

1.1.1. The concept and the metabolism of anaerobic digestion

The AD is a biological process in which microorganisms decompose organic matter in the absence of oxygen (an anaerobic environment). This process is most often used to produce biogas. The AD is a process by which organic material is converted microbiologically under anaerobic conditions into biogas [37]. AD is an efficient technology for the sustainable conversion of various organic wastes, such as animal manure, municipal solid waste, livestock effluents, crop residues, and agro-industrial co-product wastes, into biogas. The biodegradable material, waste, or organic matter is commonly referred to as substrate. AD methods decompose organic substrates under oxygen-free conditions, utilizing anaerobic microorganisms. The end-products of AD are biogas and organic nitrogen compounds [38]. In general, any biodegradable organic matter is suitable for anaerobic digestion to produce biogas, and Table 1.1 presents the common substrates used in this process. The nature of organic waste is, therefore, the first factor to consider when choosing the substrate for anaerobic digestion. Beyond the fact that all biodegradable organic waste is a suitable candidate for the anaerobic digestion process, several criteria must be met to achieve satisfactory results. The AD of organic waste relies heavily on the substrate's physical and chemical properties, which directly influence biogas yield and process stability. Three (3) main physiological groups of microorganisms are involved: fermenting bacteria, organic acid-oxidizing bacteria, and methanogenic archaea [37].

Table 1.1. Common substrates of anaerobic digestion

Category	Source
Agricultural waste	Livestock manure Energy crops Harvest remains Farm mortality
Industrial waste	Food/beverage processing Pharmaceutical industry Slaughterhouse waste Dairy product waste Agro-processing residues

Municipal waste	Organic fraction of MSW (OFMSW) Sewage sludge Yard trimmings Food waste from restaurants/cafeterias Supermarket waste

Source : [39]

The substrate used can affect the production and composition of biogas [40]. Thus, the combination of substrate availability, biogas efficiency, and environmental and economic considerations is the primary factor to consider when selecting an appropriate material [41]. To be more specific, the primary nutritional composition of interest in substrates includes carbohydrates, proteins, and fats [43]. A high lignin content necessitates chemical pretreatments to improve accessibility for microbial action, whereas a low lignin content benefits more from biological approaches. Biogas produced consists mainly of methane (CH_4) and carbon dioxide (CO_2),but also contains small quantities of some components, namely ammonia (NH_3), hydrogen sulphide (H_2S), hydrogen (H_2), oxygen (O_2), nitrogen(N_2), and carbon monoxide (CO) [40]. The percentage composition of CH_4 produced from AD is usually in the range 50–75%, while that of CO_2 is about 25–50%; the composition of H_2S in the biogas ranges from 0–3% and depends on the concentration of sulfur in the substrate, while that of nitrogen gas is in the range of 0–10% [44]. This gas (biogas) is used to generate electricity, heat, and cooking fuel, and could be upgraded to biomethane for injection into gas grids or as vehicle fuel. Besides biogas, another product is the digestate. The digestate is a bio-fertilizer in the agricultural sector [41]. During this process, the substrate undergoes four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [34], [45], [46]. All these biochemical phases are directly linked in such a manner that the byproduct of one phase serves as the substrate for the next phase and is associated with it [47].

➢ First stage: Hydrolysis

During the first stage, which is hydrolysis, the substrate’s complex molecules, such as proteins, lipids, and carbohydrates, are broken down into small organic compounds like fatty acids, sugars, and amino acids. Hydrolytic bacteria are mainly involved in the digestion of complex polymers (carbohydrates, proteins, and fats) into simpler soluble monomers (sugars, amino acids, and long-chain fatty acids) by the action of their various hydrolytic enzymes, according to Castellano-Hinojosa et al. [48]. Laiq Ur Rehman et al. [49] stated that the degradation mechanism starts with the formation of “cellulosome,” a multi-enzyme complex formed by hydrolytic bacteria for the degradation of organic substrates, in which different hydrolytic enzymes are released, and hydrolytic bacteria cannot produce enzymes without a cellulosome.

The type and complexity of the polymers determine their degradability; for instance, hydrolysis of carbohydrates occurs in a matter of hours, whereas hydrolysis of proteins and lipids may take several days. The relative abundance of hydrolytic bacteria mostly depends on the type of inoculum, operating temperature, cell retention time (CRT), and substrate [50]. Some compounds in this stage are ready to be converted into biogas, but most compounds require further breakdown through the three subsequent steps.

The general reaction is shown in Equation (1) and the step follows a chemical reaction, as illustrated in Equation (2).

$$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2 \quad (1)$$

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \quad (2)$$

- **Second stage: Acidogenesis**

The second stage is acidogenesis. During this stage, which is also known as the acidification phase, a fermentative (acid-generating) bacterium called acidogens breaks down the intermediate products produced during the first stage (hydrolysis) to produce hydrogen and carbon dioxide, as well as lower fatty acids like acetic, propionic, and butyric acid. Organic acids formed during this stage include butyric acid, propionic acid, acetate, and acetic acid, with the release of other compounds such as alcohols, H_2, and CO_2. Generally, two (2) types of acidogenic bacterial communities are present in the process, named facultative anaerobic acidogens and obligatory anaerobic acidogens. Facultative anaerobic acidogens carry out the first stage of the process, while obligatory anaerobic acidogens are active in the later stages of anaerobic digestion [49]. In the fermentation stage, the acidogenic bacteria convert glucose, amino acids, and lipids into organic acids, volatile fatty acids (VFAs), CO_2, and H_2 gas [37]. Substrate composition and concentration are the most influential parameters. In addition to H_2, CO_2, and fatty acids, small quantities of lactic acid and alcohols are also formed.

These reactions are illustrated in Equations (3)-(5).

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \quad (3)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \quad (4)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (5)$$

CH_3COOH serves as a substrate for methanogenic microorganisms and is the most significant organic acid produced at this phase [51].

- **Third stage: Acetogenesis**

In the third stage, the organic substrates produced in the second step are further digested into acetate, H_2, CO_2, and other coumpounds, which methanogens can use for methane production [52]. As mentioned, during acetogenesis (lactic acid formation), acetogenic bacteria convert the products of the previous step into biogas precursors (acetic acid, hydrogen, and carbon dioxide).

Two distinct groups of acetogenic bacteria use different mechanisms to produce acetate [50]. The first class of bacteria, known as homoacetogenic bacteria, continuously convert CO_2 and H_2 into acetate as described in [53]. However, their activity can be inhibited by high hydrogen levels, which are more favourable for hydrogenotrophic methanogens. These methanogens use hydrogen to produce methane, helping to maintain low hydrogen pressure in AD. The second type of bacteria, hydrogenotrophic methanogens, play a critical role in converting hydrogen into methane and stabilizing the AD process. Additionally, the conversion of VFAs into acetate depends on the hydrogen partial pressure, which must be extremely low for this process to be effective. Any change in this interaction would cause the system to accumulate VFAs, which would impair AD performance [49] . The decrease in the acetate concentration, in turn, supports the activity of acetoclastic methanogens, which contribute more than 70% of methane production because of an increase in the pH of the digester [54].

Equations (6)-(8) illustrate the chemical reactions in the acetogenesis stage [34].

$$\mathrm{CH_3CH_2COO^-} + 3\mathrm{H_2}O \leftrightarrow \mathrm{CH_3COO^-} + \mathrm{H^+HCO_3^-} + 3\mathrm{H_2} \tag{6}$$

$$\mathrm{C_6H_{12}O_6} + 2\mathrm{H_2O} \leftrightarrow 2\mathrm{CH_3COOH} + 2\mathrm{CO_2} + 4\mathrm{H_2} \tag{7}$$

$$\mathrm{CH_3CH_2OH} + 2\mathrm{H_2O} \leftrightarrow \mathrm{CH_3COO^-} + 3\mathrm{H_2} + \mathrm{H^-} \tag{8}$$

- **Fourth stage: Methanogenesis**

The final stage is where methane (CH_4) is produced, known as the methanogenic stage, a process that occurs under anaerobic conditions. This stage is strictly anaerobic as the methanogenic bacteria cannot survive in the presence of oxygen [55]. Methanogens are slow-growing, anaerobic microorganisms that are extremely sensitive to oxygen and can only break down a few types of organic compounds to produce carbon and energy. Methanogenic bacteria use H_2 and CO_2, along with formate, methanol, and acetate as substrates in the absence of O_2 and produce CH_4 as the final product [55]. CH_3COOH (acetate) and H_2 are converted into CO_2 and CH_4 by two (2) distinct groups of bacteria, namely acetophilic and hydrogenophilic bacteria. Acetophilic bacteria convert acetate into CH_4 and CO_2, while hydrogenophilic bacteria convert H_2 and CO_2 into CH_4. Methanogenic bacteria use H_2 and CO_2, along with formate, methanol, and acetate, as substrates in the absence of O2 and produce methane as the final product. The reactions in this stage are illustrated in Equations (9)-(11).

$$\mathrm{CH_3COOH} \rightarrow \mathrm{CH_4} + \mathrm{CO_2} \tag{9}$$

$$\mathrm{CO_2} + 4\mathrm{H_2} \rightarrow \mathrm{CH_4} + 2\mathrm{H_2O} \tag{10}$$

$$2\mathrm{CH_3CH_2OH} + \mathrm{CO_2} \rightarrow \mathrm{CH_4} + 2\mathrm{CH_3COOH} \tag{11}$$

Table 1.2 outlines all chemical reactions that occur during the process, and the overall mechanism is presented in Figures 1.1 and 1.2.

Table 1.2. Chemical equations involved in the anaerobic digestion process

Stage	Equations	References
Hydrolysis	$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2$ $C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2$	[34]
Acidogenisis	$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ $C_6H_{12}O_6 \rightarrow 3CH_3COOH$	[44]
Acetogenisis	$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+HCO_3^- + 3H_2$ $C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$ $C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$	[56]
Methanogenisis	$CH_3COOH \rightarrow CH_4 + CO_2$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ $2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$	[57]

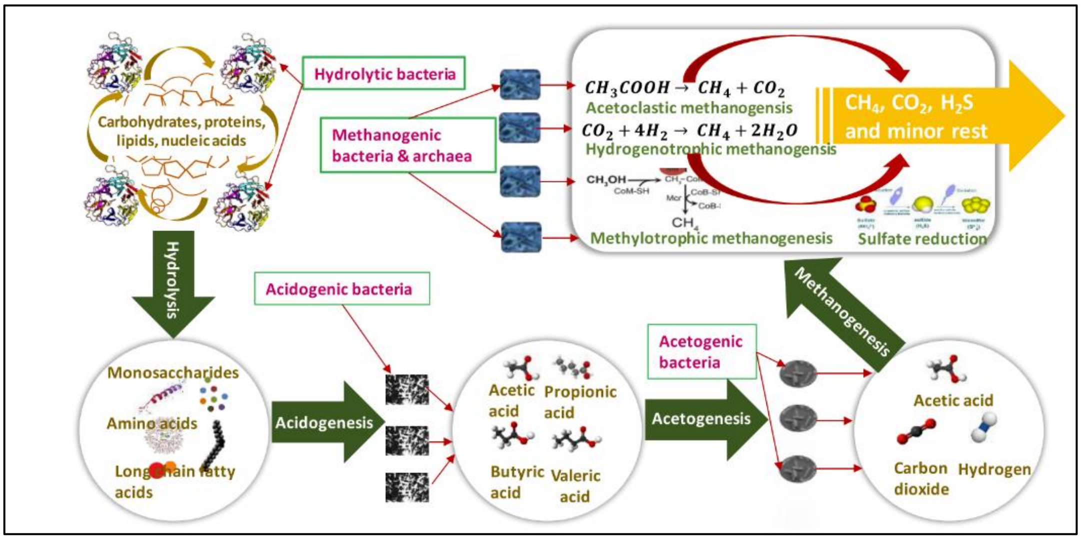


Figure 1.1. Mechanism of anaerobic digestion [51]

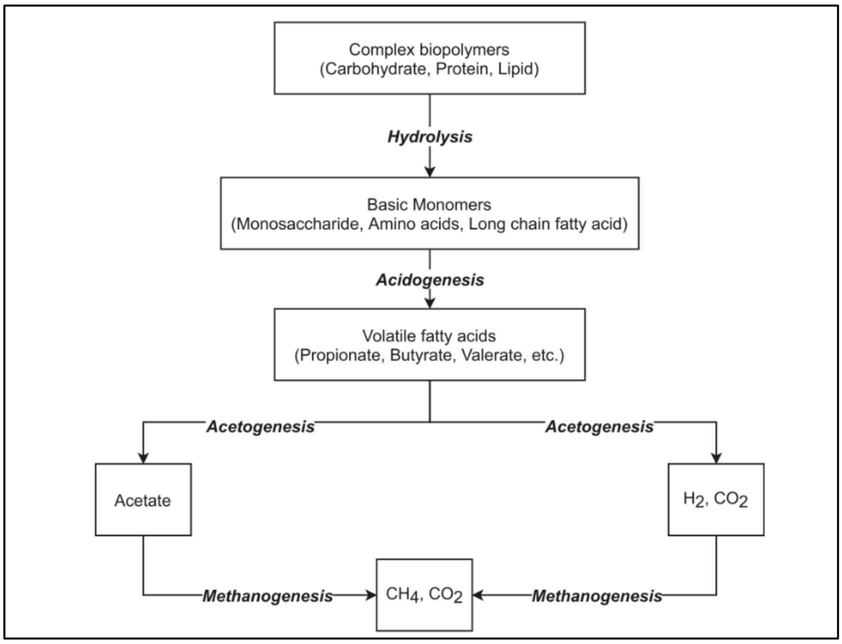


Figure 1.2. Simple representation of anaerobic digestion stages[39]

The various substrates must be pre-treated before use. The aim is to optimise the production and yield of methane, i.e., biogas. Substrate pretreatment processes are designed to enhance the availability and facilitate the utilization of organic matter by anaerobic microorganisms [42].

1.1.2. Factors influencing anaerobic digestion in a batch mode

Batch mode is a processing method where a set amount of substrate is placed in a reactor, such as a digester, for a specified period. Unlike a Continuous Stirred-Tank Reactor (CSTR), where substrates are continuously fed and effluent is constantly removed, batch processing involves no such continuous input or output during the digestion period. In a CSTR, substrates are regularly supplied, and digested material is continuously extracted.

Batch mode is generally preferred for laboratory-scale applications because of its flexibility, simplicity, precise control over the digestion environment, and cost-effectiveness. The characteristics of various process parameters (factors) significantly affect the quantity and quality of biogas production. These parameters include feedstock (substrate) type, as mentioned previously, and pretreatment, potential of hydrogern (pH), temperature, retention time, organic loading, pressure, and inhibitory components [51].

1.1.2.1. Substrate characteristics

The substrates' composition is crucial. The types and amounts of proteins, lipids, and carbohydrates in the substrate will have a significant impact on the composition and production of biogas. Higher and faster biogas production is typically the result of more easily biodegradable components, such as carbs. In general, smaller particle sizes provide more surface area for microbial activity, which can accelerate hydrolysis and increase the overall amount of biogas produced. Microbial growth and activity also depend on the availability of nutrients, such as micro- and macronutrients (including nitrogen, phosphorus, potassium, and trace elements) found in the substrate. An unbalanced nutritional composition may restrict the production of biogas. The carbon-to-nitrogen ratio is essential to the metabolism of microorganisms. A balance between the energy source (carbon) and the building blocks of cells (nitrogen) is ensured by an ideal range, frequently cited as 20-30 by Yankyera Kusi et al. [58].

1.1.2.2. Inoculum characteristics

The origin and quantity of the microbial community (the inoculum) have a significant impact on the process's efficiency. An inoculum that is both active and well-adapted is necessary. All phases of anaerobic digestion are ensured to proceed effectively by a varied microbial community. The breakdown of polymeric materials and their ultimate conversion into methane gas are primarily carried out by bacterial and archaeal populations, which are mainly observed in the anaerobic digestion process [59]. To guarantee the constant conversion of organic substrates to CH_4 and CO_2, a well-organised, closely interacting bacteria–archaea community with a certain "elasticity," or the capacity to quickly adjust to changing conditions or return to a previous state after a disturbance, is necessary [60]. The inoculum must be active at the time of sampling and is digesting complex organic substrates. For methane yield, the methanogens' specific activity is especially crucial [61].

1.1.2.3. Operational parameters

- **Effects of the pH on the process**

The value of pH directly affects the metabolic activities of anaerobic microorganisms, and different microbial groups responsible for various stages of anaerobic digestion have specific pH preferences. Anaerobic bacteria need different pH ranges for their growth [52]. The pH directly influences the growth and composition of the microbial community as noted by Elefsiniotis et al. [62] and regulates the activity, stability, and solubility of essential enzymes. For best results, the ideal pH range is between 6.5 and 8, as methanogenic bacteria generally operate within a pH range of 7 to 8. This is confirmed by Atelge et al., who stated that there is an increased risk of inhibition in reactors when the pH is below six or above 8.5 [43]. It is essential to regulate or monitor pH levels before and throughout the process, as primary biogas production occurs during the methanogenic phase. The pH value during anaerobic fermentation is derived from the reaction of alkaline or acidic metabolic products and substrate components.

Maintaining neutral alkalinity is crucial for optimal microbial activity and digestion efficiency. By preventing acidification and maintaining a stable pH, the system can achieve better performance and enhanced biogas production. Atelge et al. confirmed this statement by saying that external alkalinity addition may be required for both BMP assays and continuously fed AD systems to maintain neutral alkalinity if substrates lack alkalinity and/or contain significant quantities of organics, with a risk of VFAs accumulation [43].

- **Temperature**

Process temperature is a critical parameter, as it determines the metabolic rates of anaerobic microorganisms, and each group of bacteria during the digestion (acidogenic, acetogenic, and methanogenic) has an optimum temperature range for growth and activity for optimum yield of biogas. For example, hydrolysis has an optimum temperature between 30–50 °C (Anaerobic digestion of cellulose and hemicellulose in the presence of humic acids). Temperature is one of the most significant parameters influencing AD, because it not only influences the activity of enzymes and co-enzymes, but also influences the methane yield and digestate (effluent) quality [63]; [64]; [45]. At a higher digester temperature of 53°C (thermophilic conditions), most pathogens are killed significantly faster; 90% of them are destroyed within less than one hour. In contrast, at a lower temperature of 35 °C (mesophilic conditions), it takes several days to achieve the same 90% reduction in pathogens [65]. The anaerobic degradation rate of organic matter increases with temperature when comparing psychrophilic, mesophilic, and thermophilic processes [64]. Mesophilic digestion operates optimally between 30°C and 40°C and is commonly used due to its stability and lower energy requirements. In contrast, thermophilic digestion operates between 50°C and 60°C. Figure 1.3 illustrates the influence of temperature on the methanogenic growth. Indeed, mesophilic digesters remain attractive because of their lower heater energy costs compared to thermophilic and psychrophilic digesters [66]. Psychrophilic fermentation (10-20°C) yields low gas volumes and leads to process instability due to slow microbial activity. In contrast, mesophilic conditions (30-40°C) provide a stable and efficient balance for methane production. Thermophilic fermentation enables rapid degradation but is more sensitive to acid accumulation and temperature stress [67].

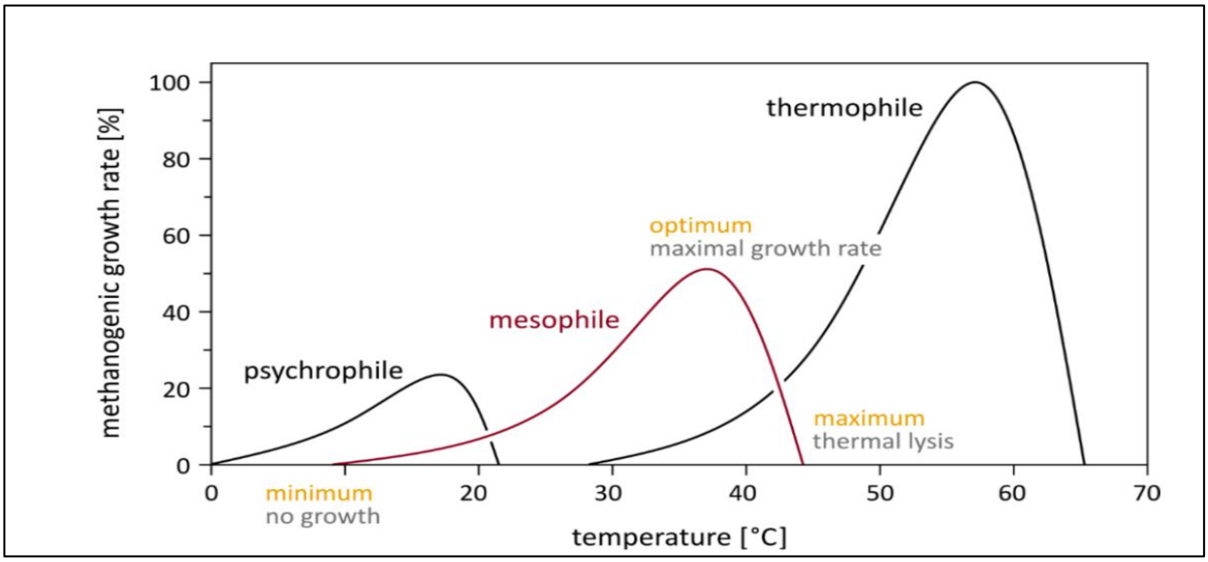


Figure 1.3. Influence of temperature on methanogenic growth rate [67]

- **Hydraulic Retention Time**

Hydraulic Retention Time (HRT) is the average amount of time that the liquid or wastewater remains in the digester during the process. Further, HRT is the average duration that liquid remains in a digester, calculated by dividing the digester volume (V) by the influent flow rate (Q), as expressed in the following Equation (12).

$$\mathrm{HRT} = \frac{\mathrm{V}}{\mathrm{Q}} \tag{12}$$

It is a critical parameter because it determines the time required for microorganisms to break down organic matter and is related to the loading rate. A shorter HRT corresponds to a higher loading rate [65]. Shorter HRTs may reduce stability and methane content; lowered HRT may lead to microbial washout and eventually result in digester failure. Generally, mesophilic digestion can be completed within 15 to 30 days. Optimizing hydraulic retention time (HRT) is crucial, as a duration that is too short can wash out microbes and reduce degradation, while one that is too long can underutilize reactor volume and lower system throughput based on [68].

- **Organic Loading Rate (OLR)**

It is a crucial factor in assessing the precision and repeatability of the test. It is used to describe the initial ratio of substrate to inoculum that was introduced into the test system. Usually stated as g VS/L, this is the quantity of organic substrate (measured as volatile solids, VS) added per unit volume of inoculum (in L). It is typically expressed in Equation (13).

$$\mathrm{OLR} = \frac{\mathrm{C}}{\mathrm{HRT}} \tag{13}$$

Where C is the feed concentration in g·VS/L, and HRT is the hydraulic retention time.

Maintaining a consistent or gradually adjusting the OLR through frequent or continuous substrate addition is vital, as excessive OLR can cause process imbalance and system instability due to the overproduction of volatile acids reaching inhibitory levels, while an insufficient OLR results in underutilization of the digester's capacity and limits energy recovery according to L. Naik et al. [68]. It is desirable to maintain a consistent OLR in an anaerobic digester process because it increases the volume and duration of organic substrate fed into the system, thereby enhancing the rates of biogas and methane generation. Increased OLR leads to increased biogas generation; however, for microorganisms to fully convert and digest organic matter, a more extended retention period is required. Additionally, adding too much volatile solids to the digester may increase the production and buildup of volatile acid, which affects the digester's pH and alkalinity. Microbial activity, biomass degradability, and reactor design all affect the actual loading rate [69].

- **Substrate to Inoculum (S/I) ratio**

In AD, the substrate-to-inoculum (S/I) ratio is a crucial operational parameter that significantly impacts the process's overall performance, stability, and efficiency. The inoculum, when supplied to the substrate, provides. Slimane et al. [70] stated that when studying the influence of the inoculum-substrate ratio on mesophilic anaerobic digestion, the S/I ratio plays a vital role in driving the biochemical pathways and kinetics of the anaerobic digestion process, as well as the stability of the digestion. This statement means that the inoculum supplied to the substrate provides process stability. The substrate fed to the anaerobic reactors can significantly alter the digestion process due to the differences in the quantities of the three principal organic components: carbohydrates, lipids, and proteins [71]. Additionally, while batch reactors are typically not continuously mixed, the initial mixing to ensure homogeneity is crucial for achieving good contact between the substrate and inoculum.

1.2. Biogas production from cassava peels

1.2.1. Cassava peels as substrate

Based on its morphology, i.e., foliage, stem, and tuber characteristics, cassava can be classified as a single species in the Euphorbiaceae family [72]. Cassava is a vital crop with diverse uses, playing a critical role in food security and agricultural economies in many tropical regions. Cassava peels, commonly found in the environment, offer a promising substrate for energy generation, particularly through anaerobic digestion when optimal conditions are met. Studies suggest that these peels are a viable candidate for valorization through anaerobic digestion, owing to their significant quantity and the environmental challenges linked to their disposal. The study of Ukaegbu-Obi [36] demonstrated that agro-wastes like cassava peels, though typically problematic due to their hydrogen cyanide content, can be effectively converted into biogas through anaerobic digestion and produce 52.35% of methane and 37.13% of carbon dioxide. While cassava peels alone yield low biogas, pretreatment and the use of rumen fluid as inoculum significantly improve gas production, making the process feasible even for domestic-scale energy recovery. This utilization of cassava peels not only mitigates waste management concerns but also facilitates renewable energy production, thus advancing sustainable agricultural practices. N. Ismail et al. [73] have clearly illustrated the compatibility of cassava wastes (cassava peels and stems) for biogas production as an alternative energy source using an anaerobic process. It was studied and proven by Yussouff et al. that the production of biogas and bioethanol from CP is visible [11].

1.3. Biohydrogen production

1.3.1. Concept of biohydrogen production using steam methane reforming

Steam methane reforming is the most widely used industrial method for producing H_2, in which CH_4 reacts with high-temperature steam (700–1,000 °C) over a nickel-based catalyst to produce synthesis gas, a mixture of H_2 and CO. This is followed by a water-gas shift reaction, which converts carbon monoxide and steam into additional hydrogen and carbon dioxide. The process efficiency is influenced by variables such as temperature, pressure, catalyst type, and carbon dioxide management. The entire SMR (steam methane reforming) process can be summarized in three Equations (14)- (16), where the last equation represents the overall reaction [74].

$$\mathrm{CH_4 + H_2O = 3H_2 + CO} \quad (\Delta\mathrm{H298K{=}206kJ/mol}) \tag{14}$$

$$\mathrm{CO + H_2O = CO_2 + H_2} \quad (\Delta\mathrm{H298K{=}\ {-41}kJ/mol}) \tag{15}$$

$$\mathrm{CH_4 + 2H_2O = CO_2 + 4H_2} \quad (\Delta\mathrm{H298K{=}\ {+165}kJ/mol}) \tag{16}$$

Natural gas is first desulfurized using a catalyst, then mixed with treated steam and heated before entering a nickel-based catalytic reformer, where it partially converts into hydrogen, carbon monoxide, and carbon dioxide. The gas mixture is then cooled via steam generation and passed through a shift converter, where remaining CO reacts with steam to form additional hydrogen and CO_2. After cooling, the gas enters a pressure swing adsorption (PSA) unit to separate pure hydrogen. At the same time, the off-gas is recycled as reformer fuel, supplemented by natural gas [74]. The quantity of CO_2 produced mainly depends on the presence of the carbon element and the technique used for production, and to counter its effects, a method termed carbon sequestration is proposed. Carbon sequestration aims to reduce atmospheric CO_2 by storing it underground or underwater; however, risks include long-term leakage, soil and crop disruption, and threats to marine ecosystems [75]. In essence, fossil fuel reforming involves purifying the feedstock, converting it to hydrogen and carbon oxides via steam reforming or oxidation, and then sequentially removing carbon monoxide through primary and secondary purification steps. In H_2 production, the syngas from steam methane reforming undergoes a two-stage Water Gas Shift (WGS) reaction, where carbon monoxide reacts with steam over a catalyst, first at around 350 °C in the High Temperature Shift (HTS) stage, then at 190–210 °C in the Low Temperature Shift (LTS) stage, to convert CO into additional hydrogen and carbon dioxide, enhancing overall H_2 yield [76]. A study of U. Izquierdo et al. has proved that H_2 can also be produced from biogas through steam reforming at 600–1100 °C (an endothermic reaction) with the aid of a catalyst [77]. The main steps of the process are summarized in Figure 1.5, which compare the conversion of chemicals and energy from fossil resources via the steam reforming process in Figure 1.4; the efficiency of conversion depends on temperature. The resulting hydrogen serves as a renewable energy source suitable for use in transportation, fuel cells, or injection into the natural gas grid. Singh et al. have successfully estimated the electricity generation and environmental potentials of H_2 produced from biogas using food waste in south-western Nigeria [3].

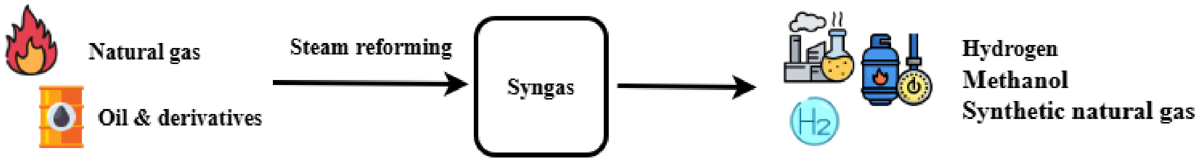


Figure 1.4. Chemicals and energy from fossil resources via steam reforming (adapted from [14])

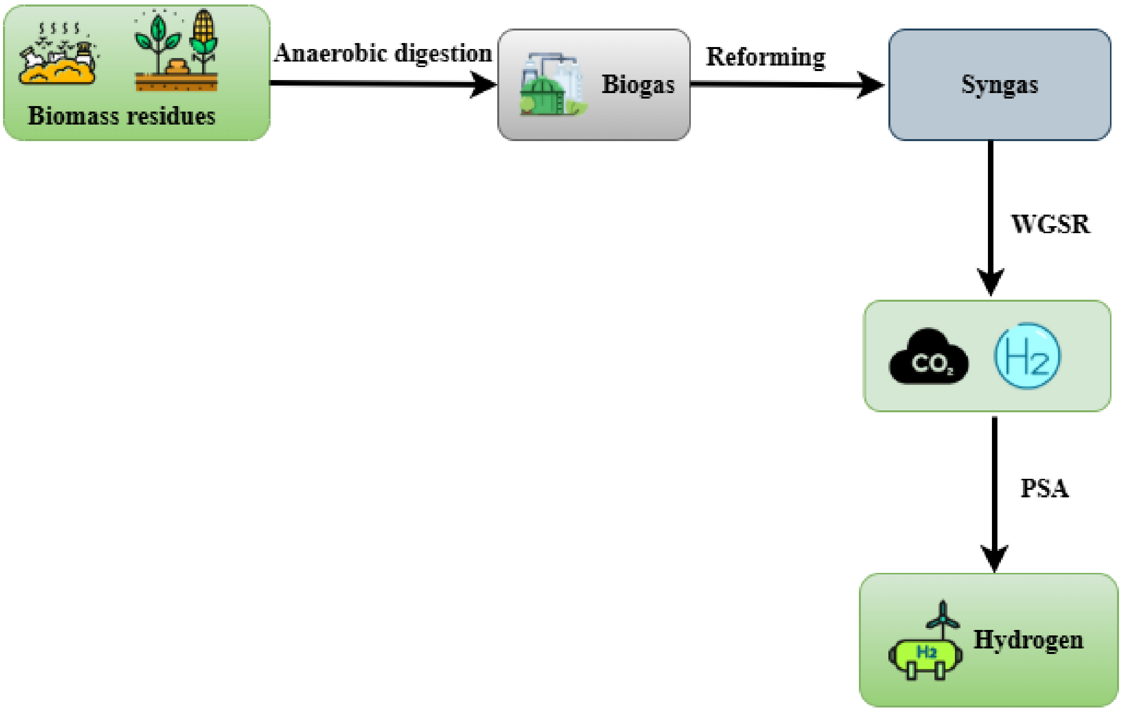


Figure 1.5. Main steps for the production of hydrogen from biogas via the syngas route (adapted from [14]).

1.3.2. Simulation through AspenPlus software

The simulation of hydrogen production enables a comprehensive evaluation of process efficiency, energy consumption, and environmental impact before any physical implementation. Leveraging computational models optimizes key parameters, making it a crucial tool for identifying sustainable and cost-effective alternatives in energy production. Various software tools, such as Aspen Plus, Simcenter Amesim, and Ansys, can be used to simulate hydrogen production. Two methods are employed to model SMR flow: the surface-based technique and the volume-based approach. Modeling the SMR using a surface-based approach requires a significant amount of processing time. However, the volume-based approach is computationally less time-consuming [94]. In our study, the hydrogen production simulation was conducted using a volume-based approach and Aspen Plus (AP) software. This advanced process modeling software enables a detailed evaluation of thermodynamic and kinetic behaviors in steam methane reforming (SMR). We chose this approach for its simplicity and reduced computational time. In the SMR-based hydrogen production simulation, both reaction kinetics and thermodynamic equilibrium play crucial roles in determining process efficiency. The use of kinetic-based simulation in Aspen Plus software models the processes of methane steam reforming and the water gas shift reaction, both of which are essential for producing hydrogen [78]. It has been stated that the reaction kinetics based on first-order rate equations describe the conversion rates of methane reforming and water gas shift reactions, which directly impact hydrogen yield and reactor performance (See Appendix B: Kinetics involved in the hydrogen production simulation). Serhan et al. [79] confirmed this statement. Additionally, Gibbs free energy minimization ensures that chemical equilibrium is reached under defined temperature and pressure conditions, allowing for the accurate prediction of product compositions [80]. The simulation incorporates sensitivity analysis to optimize operating parameters such as temperature, pressure, and steam-to-carbon ratio (S/C), enhancing H_2 production efficiency as recommended by Amran et al. [78]. Furthermore, integrating biogas as a feedstock enables a sustainability assessment that evaluates its impact on the carbon footprint and overall operational feasibility. Aspen Plus integrates kinetic models with thermodynamic calculations, offering a credible and scientifically grounded approach to simulating H_2 production from methane derived from biogas (See Appendix B: Kinetics involved in the hydrogen production simulation). This integration facilitates process optimization and enhances energy efficiency [1]. An example of a typical flowsheet in the software is described in Figure 1.6.

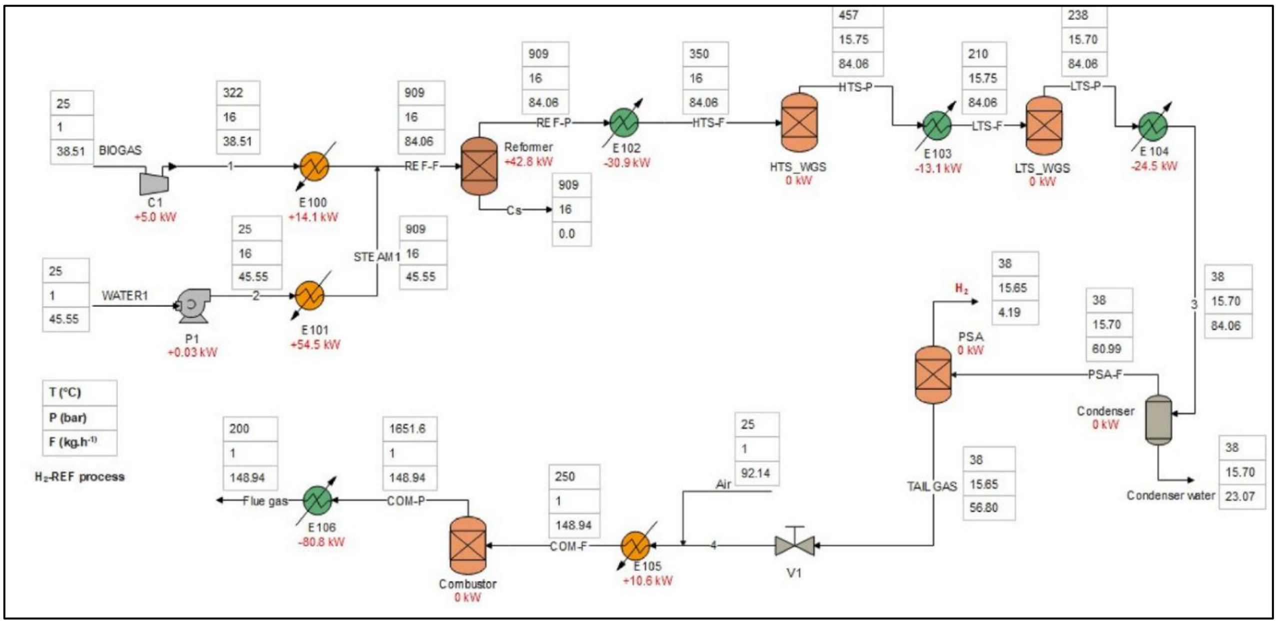


Figure 1.6. Flowsheet of hydrogen production using biogas simulation in Aspen Plus software [1]

1.4. Life Cycle Assessment

Life Cycle Assessment (LCA) is a widely used environmental evaluation method that assesses the total impact of a product or process from raw material extraction to its end of life. In bioenergy research, LCA plays a crucial role in comparing greenhouse gas emissions, energy consumption, and resource depletion across various production pathways. The analysis consists of four (4) key phases (See Figure 1.7), beginning with the definition of the goal and scope, which establishes the study's purpose, intended application, and target audience. This phase also involves defining the functional unit, system boundaries, allocation procedures, studied impact categories, life cycle impact assessment (LCIA) models, and data quality requirements. An extensive overview of ReCiPe 2016, a harmonized impact assessment methodology used in Life Cycle Impact Assessment (LCIA) to quantify environmental effects at both midpoint and endpoint levels [81]. The second phase, Life Cycle Inventory (LCI), systematically compiles input and output data on materials, energy consumption, and emissions throughout the process. F. Cherubini demonstrated the importance of LCI in estimating net greenhouse gas emissions for bioenergy applications, highlighting its relevance in ensuring an accurate environmental footprint [82]. The Life Cycle Impact Assessment (LCIA) phase then applies established models, such as ReCiPe 2016 and CML 2001, to quantify environmental effects based on the LCI data. These methodologies enable a detailed evaluation of climate change performance and sustainability factors in biomass utilization. Finally, the Interpretation identifies hotspots, evaluates uncertainties, and suggests optimization strategies to enhance sustainability performance, as noted by Cristobal-Garcia et al. [83]. These steps enable LCA to serve as a vital tool for assessing the environmental feasibility of bioenergy systems, ensuring informed decision-making on sustainable resource management.

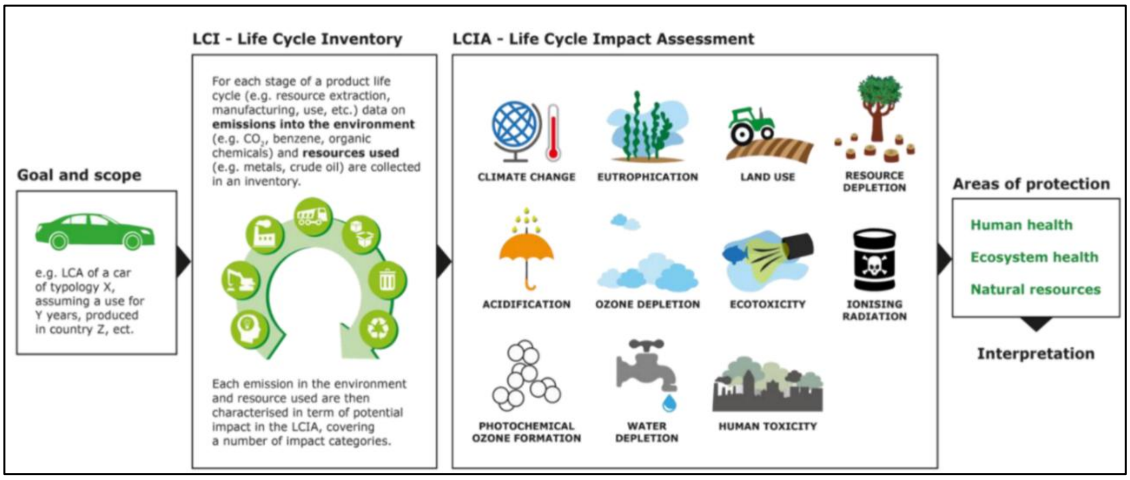


Figure 1.7. Life cycle assessment steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation [83].

CHAPTER II: MATERIALS AND METHODS

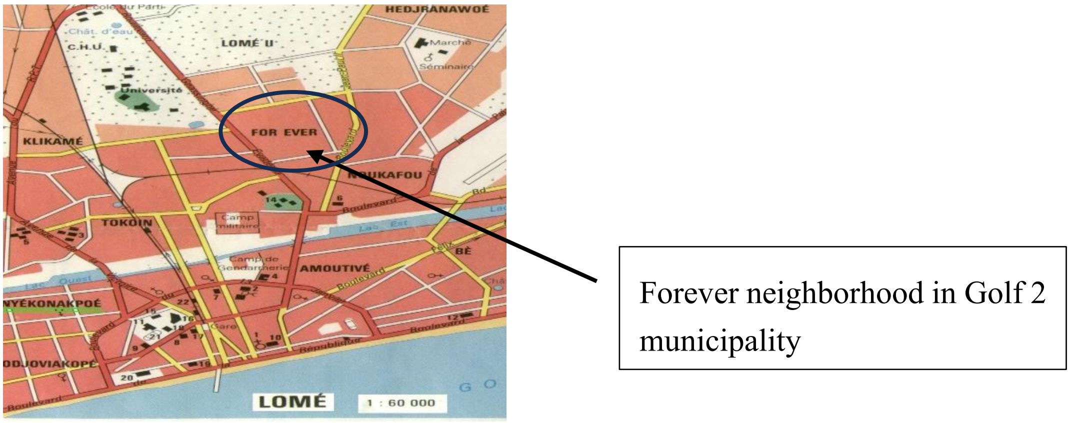
This chapter outlines the methodological framework employed to investigate the research questions. It details the materials, instruments, procedures, and analytical techniques used, ensuring transparency and reproducibility. The chosen methods are aligned with the laboratory standards and best practices identified in the literature.

2.1. Methodology for data collection and materials

2.1.1. Study area and sample collection

In Togo, the Plateaux and Maritime regions are the primary contributors to tuber production, with a particular emphasis on cassava. Among the various cultivars, the CRI-Sika Bankye variety is noteworthy for its 'sweet' characteristics, which include glycosides predominantly located in the peel. This cultivar is extensively utilized in Lomé (Golfe 2 municipality), the capital city, for the preparation of attieke, a traditional dish highly regarded by the local population. Figure 2.1 presents the area map realized with QGIS software.

During the processing phase, women manually peeled the cassava tubers, and the peels were carefully collected in Lomé to prevent contamination with other parts of the tubers. Subsequently, the collected peels were transported to the laboratory in a plastic bag for further pre-treatment and analytical investigations.



Forever neighborhood in Golf 2 municipality

Figure 2.1. Cassava peels collection area, Lome Golfe, Togo adapted from Centerblog.net

2.1.2. Sample pre-treatment

The collected CP were first dried naturally in the sunlight using a plastic carpet for seven days. After sun drying, the CP was then dried in an oven using two aluminium dishes for 24 h at a temperature of 105 °C. The dried samples were ultimately ground using a dry food kitchen blender, which could produce samples of 1 mm in size, to achieve better homogeneity and practical mixing in the case of AD. Following pretreatment, one (1) kg of representative CP samples was carefully collected and prepared for both subsequent physicochemical characterization and as the substrate for the biogas production tests. The ground samples were then stored in air-tight plastic bottles, covered with aluminium foil to minimize degradation, until further experimentation in Germany (See Figure 2.2).

Figure 2.1: Peels pretreatment

2.2. Research approach and design

The research approach of this study is divided into four parts: the first part deals with the national estimation of CP and the in-depth characterizations, the second part describes the methods for testing biogas production of the samples, the third part covers the processes and procedures for simulating hydrogen potential using AspenPlus and the last part concerns the LCA of the different gases using OpenLCA software.

2.3. Evaluation of national potential

2.3.1. Data collection

Estimating national cassava production in Togo required the collection of reliable data, which was achieved through a thorough review of existing literature and consultation with statistical databases. This estimation relied on secondary data obtained from various authoritative sources, including the Food and Agriculture Organization of the United Nations' Statistics Division (FAOSTAT). National statistics were also consulted, drawing upon agricultural campaign data and comparative analyses provided by the National Institute of Statistics and Economic and Demographic Studies (INSEED), as well as relevant publications from the Ministry of Agriculture, Village Hydraulics and Rural Development, the Permanent Survey System (SPE), and the Directorate of Agricultural Statistics, Information and Information (DSID). The most recent data collected from these sources pertain to the years 2018-2024.

2.3.2. Estimation of cassava peels generated

The first stage in analysing energy potential from cassava waste is assessing the quantities of waste generated. The estimation of CP generated nationally was determined by applying a representative percentage of peel weight to the total annual cassava production. Compared to mechanical peeling of cassava roots, which typically yields a greater proportion of peel removed, manual peeling, although less accurate, removes a smaller portion of the tuber. In Togo, manual peeling is the most commonly used method, generating a considerable portion of peels [84].

According to Odediran et al. [85], the peel ratio in Nigeria is 23%, consistent with the broader range of 15%–35% noted by Adebayo et al. [86]. Studies conducted in Ghana, however, showed a higher average peel ratio. A study that examined four (4) different types of cassava in Ghana revealed that the average peel ratio was 30.3%, with moisture content being the reason for the difference [87]. Our own experiment was conducted by measuring the weight of our CP after processing, following manual peeling, and the results were expressed as 16% of the peels.

Additionally, Kemausuor et al. confirmed that 30% of processed cassava roots are discarded as peels, a figure consistent with observations from cassava processing flowcharts, where waste proportions typically fall between 25% and 30% [19]. Given these findings, a percentage of 20% for CP was chosen to represent a balanced average that encompasses the range of values reported in the literature. This choice also considers our own measurement, positioning the selected percentage as a reasonable estimate that reflects both the literature and experimental findings.

This percentage was then multiplied by the determined annual cassava production figure for 2018-2024 to get the estimated amount of cassava peels. The calculation is made with the Equation (17).

$$\mathrm{TCP\ (in\ tons)} = \mathrm{ACP} \times \mathrm{CP/R} \tag{17}$$

With TCP=Total Cassava Peels, ACP=Annual cassava production, CP/R=cassava to peels ratio

2.4. Physicochemical characterization

The characterization of CP samples is crucial in this study, as it is a key objective in determining the national potential for biogas and H_2 production. Understanding the suitability of CP as a biogas feedstock will be helpful. Characterization can reveal the presence of compounds, such as toxins (like cyanogenic glycosides from cassava) or high lignin content (which is less biodegradable), that may hinder the AD process.

This understanding, therefore, enables the selection of suitable pretreatment techniques to mitigate these impacts and informed choices during AD tests. Knowing the physical (like total solids) and chemical properties, such as carbon to nitrogen ratio (C/N ratio) and pH, helps determine optimal operating conditions and calculate the necessary ratios for the process.

2.4.1. Proximate analysis

The principle of proximate analysis is to identify the main constituents of a biomass sample by examining their physical and chemical characteristics after undergoing particular treatments. The parameters determined included moisture content (MC), volatile solids (VS), total solids (TS), and ash content (AC).

- **Determination of moisture content (MC), volatile solids (VS), total solids (TS), and ash content (AC)**

The determination of water content, volatile substance content, and ash content is based on the thermogravimetric analysis (TGA) method, which monitors the mass loss of the sample as a function of temperature and time. The LECO TGA 701 system (presented in Figure 2.3) is used to perform the analysis under controlled conditions. To initiate the procedure, an empty crucible is heated to a temperature of 105°C for a minimum duration of 30 minutes. It is then cooled in a desiccator and weighed to obtain the initial mass (m_a). A predetermined quantity of the sample, ranging from 1 to 2 grams, is introduced into the crucible, and the combined mass is measured (mb). The crucible containing the sample is then positioned within a thermogravimetric analysis (TGA) system, where the analysis is conducted in three distinct phases.

The first phase of the analysis focuses on determining the moisture content. During this phase, the sample is heated to 105°C until a consistent weight is attained, signifying the loss of moisture. In the subsequent phase, the temperature is elevated to 550°C, facilitating the measurement of volatile substances as organic compounds evaporate, contributing to a further decrease in mass. Finally, the sample is subjected to an additional heating phase, reaching temperatures of up to 850°C, at which point the residual mass indicates the ash content, composed of non-combustible residues.

Upon the conclusion of the analysis, the furnace lid automatically opens, allowing for the retrieval of the cooled crucibles. The masses of the samples are systematically recorded and exported for assessment using a structured Excel template to ensure accuracy in calculations. The moisture content (MC), volatile substances (VS), total solids (TS), and ash content (AC) are subsequently derived from the mass differences observed throughout the thermal treatment process. TS, MC, VS, and AC were calculated using Equations (18)-(21).

$$\mathrm{TS} = \frac{(m_c - m_a)}{(m_b - m_a)} * 100 \qquad (18)$$

$$\mathrm{MC} = 100 - \mathrm{TS} \tag{19}$$

$$\mathrm{VS} = \frac{(\mathrm{m_b}-\mathrm{m_c})}{(\mathrm{m_b}-\mathrm{m_a})} * 100 \tag{20}$$

$$\mathrm{AC} = \frac{(\mathrm{m_d}-\mathrm{m_a})}{(\mathrm{m_c}-\mathrm{m_a})} * 100 \tag{21}$$

Where m_a is the mass of the empty crucible (g), m_b the mass of the crucible containing the CP sample (g), mc the mass of the crucible containing the dry mass of the sample(g), and m_d the mass of the crucible containing the remaining ash after complete combustion (g). The equipment for the analysis is presented in **Error! Reference source not found.**.

To ensure an accurate comparison, the values have been converted to dry matter (DM) using Equation (22) and to a total solids' basis (%TS) using Equation (23), allowing for a better understanding of the actual proportion of components without the influence of humidity.

$$\%\mathrm{DM} = \frac{\text{Value on }\%\mathrm{FM}}{\%\mathrm{DM}/100} \tag{22}$$

$$\%\mathrm{TS} = \frac{\text{Value on }\%\mathrm{DM}}{\%\mathrm{TS}/100} \tag{23}$$

- **Determination of fixed carbon (FC)**

Fixed carbon content was determined through the following Equation (24).

$$\mathrm{FC} = 100 - \mathrm{VS} - \mathrm{AC} \tag{24}$$

2.4.2. Fiber content

The cellulose, hemicellulose, and lignin fractions were examined using the Weende Method (crude fibre). The determination of Acid Detergent Fibre (ADF), Acid Detergent Lignin (ADL), and Neutral Detergent Fibre (NDF) followed an in-house methodology. This process allowed for the identification of acid-insoluble components, crude lignin, and neutral detergent fibre fractions within a sample through chemical extraction and gravimetric analysis.

- **Sample preparation**

Samples are dried at 105°C for 24 hours to remove moisture. Empty crucibles are subjected to calcination at 500°C for 2 hours to remove contaminants. The dried samples are then ground to a particle size of ≤1 mm, ensuring uniformity for analysis. Fibrebags used for filtration were dried at 105°C for 1 hour before use.

- **ADF and NDF solutions**

For ADF determination, a solution is prepared by mixing distilled water, 98% sulfuric acid, and N-cetyl-N, N, N-trimethylammonium bromide in a 5 L volumetric flask. The solution is stored at 18-20°C in the dark to maintain stability. Similarly, the NDF solution consists of EDTA disodium salt, disodium tetraborate decahydrate, sodium dodecyl sulfate, and triethylene glycol, adjusted to a pH of 6.9-7.1.

- **ADF analysis**

Fibrebags are weighed empty (m_1), and 1g of dried sample is measured (m_2). A glass spacer is inserted, and the Fibrebags are placed in the sample carousel. Excess fat is removed by rinsing the samples with hexane. The Fibretherm FT 12 system executes the washing sequence with ADF solution, followed by drying at 105°C overnight. The dried mass is recorded (m_4). If ADL (crude lignin) analysis is required, the Fibrebags are subjected to 72% sulphuric acid treatment at room temperature for 3 hours, rinsed with hot water, dried at 105°C for 24 hours, and weighed (m_7). As a final step, samples are ashed at 500°C for 2 hours to determine residual lignin content, recording the mass (m_5). The results are calculated through the following Equation (25):

$$\mathrm{ADF} = \frac{(m_4 - m_1) - (m_5 - (m_6 - m_3))}{((m_2 - m_1) \times \mathrm{TS}) \times 100 \times 100} \tag{25}$$

Where:

ADF=share of acid detergent fiber (%TS)

m_1 = mass of empty dried Fibrebag (g)

m_2 = mass of Fibrebag with sample before drying (g)

m_3 = mass of empty crucible for blank reading (g)

m_4= mass of the crucible & Fibrebag after drying (g)

m_5= mass of the crucible & Fibrebag after calcination (g)

m_6= mass of the crucible & Fibrebag after calcination of the blank reading (g)

TS= Total solids of dried and milled sample (%)

- **NDF analysis**

Samples undergo boiling in NDF solution, which removes hemicellulose, leaving the cellulose and lignin components intact. Fibrebags are initially weighed empty (m_1), followed by recording the mass with the sample (m_2). After washing, drying at 105°C for 24 hours, and weighing (m_4), the Fibrebags are ashed at 500°C, and the final weight (m_5) is recorded. The results are calculated through the following Equation (26):

$$\mathrm{NDF} = \frac{(m_4 - m_1) - (m_5 - (m_6 - m_3))}{((m_2 - m_1) \times \mathrm{TS}) \times 100} \times 100 \tag{26}$$

Where:

NDF= share of neutral detergent fibre (%TS)

m_1 = mass of empty dried Fibrebag (g)

m_2 = mass of Fibrebag with sample before drying (g)

m_3 = mass of empty crucible for blank reading (g)

m_4= mass of the crucible & Fibrebag after drying (g)

m_5= mass of the crucible & Fibrebag after calcination (g)

m_6= mass of the crucible & Fibrebag after calcination of the blank reading (g)

TS= Total solids of dried and milled sample (%)

- **ADL analysis**

The share of ADL is determined through equation (27):

$$\mathrm{ADL} = \frac{(\mathrm{m_7}-\mathrm{m_1})-(\mathrm{m_5}-(\mathrm{m_6}-\mathrm{m_3}))}{((\mathrm{m_2}-\mathrm{m_1})\times \mathrm{TS}\,)\times 100} \times 100 \tag{27}$$

Where:

ADL=share of acid detergent lignin (%TS)

m_7= mass of the ADL-crucible & Fibrebag after drying (g)

- **Determination of the hemicellulose, cellulose, and lignin fractions**

The following relations of (28), (29) and (30) allowed to do it:

$$\%\mathrm{Hemicellulose} = \mathrm{NDF} - \mathrm{ADF} \tag{28}$$

$$\%\mathrm{Lignin} = \mathrm{ADL} \tag{29}$$

$$\%\mathrm{Cellulose} = \mathrm{NDF} - (\mathrm{Hemicellulose} + \mathrm{LigninA}) \tag{30}$$

The equipment for the analysis is presented in the Figure 2.4.

Figure 2.2: LECO TGA 701 system

Figure 2.3: Fibretherm FT 12

2.4.3. Ultimate analysis

Ultimate analysis is a technique used to determine the elemental composition of a substance, typically applied in chemical and material science. The methodology employed for the ultimate analysis of CP followed standardized procedures to ensure accuracy in elemental composition, calorific value determination, and quantification of heavy metals. Sample collection adhered to the guidelines set by DIN EN ISO 21646 (2022-09), wherein the biomass was homogenized and crushed to <1 mm for uniform particle size distribution, a crucial step. The ultimate analysis of carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and phosphorus (P) was conducted using DIN EN ISO 21663 (2021-03). Heavy metals were quantified according to DIN 22022-2 (2001-02) following aqua regia flux digestion, a protocol widely recognized in studies on biomass toxicity and environmental impact. The calorific value assessment utilized DIN EN ISO 21654 (2021-12), applying bomb calorimetry to determine gross and net calorific values. The methodological framework applied ensured reproducibility and aligned with the laboratory's standards at the University of Rostock.

2.5. Biogas production test

2.5.1. The inoculum collection

The inoculum utilized in the batch AD testing was collected on May 13, 2025, from the Hofladen Hof Postma biogas plant in Lambrechtshagen, Germany. This mesophilic biogas plant, which features continuous stirring, primarily uses cow manure and straw as its feedstock. A plastic bucket was used for collection, and the inoculum was left untreated; however, it was starved for one week before the experimental setup. After collection, the inoculum was stored at ambient temperature, allowing it to settle for one week in the laboratory. This preparation ensured optimal conditions for subsequent analysis. See **Error! Reference source not found.** f or details.

2.5.2. Batch anaerobic digestion tests

2.5.2.1. Experimental setup

- **Bioreactors and incubation conditions**

Biogas production tests were conducted in batch reactors with a gross volume of 500 mL and a net volume of 400 mL, with each experimental condition run in two (2) replicates. They included control reactors containing only the inoculum to account for endogenous biogas production. The batch AD tests were carried out following the VDI 4630 regulation [88]. The ANKOM Gas Production System is designed to measure the kinetics of biogas formation for this study. It features digestion vessels with a volume of 500 ml and measuring modules (bioreactors) positioned at the top. Each measuring module includes a pressure sensor, a purge valve, and a pressure release valve. The pressure sensor tracks the increase in pressure within the digestion vessel, maintaining a constant temperature and volume, which allows for an accurate assessment of biogas production over time. The purge connector allows the headspace to be inerted with nitrogen before the experiment. Additionally, to the digestion modules (reactors), one so-called zero module measures the current ambient pressure. The experimental setup is presented in Figure 2.6.

The tests were conducted under controlled mesophilic temperature conditions (37°C), maintained using a water bath, for 30 days. For the standard procedure, a maximum overpressure of 5 kPa (50 mbar) is predefined. After a 10-minute delay to achieve uniform starting conditions, data recording is initiated. The accompanying software calculates the cumulative pressure increase for each digestion vessel, taking into account changes in ambient pressure, and saves the data at predefined intervals. The standard setting for the recording interval is 30 minutes, ensuring consistent and accurate monitoring of biogas production throughout the experiment.

- **Substrate and inoculum preparation**

The substrate preparation involved the use of pre-treated CP, which were subsequently mixed with inoculum at S/I of 1:3, 1:2, 1:1, and 2:1. Two tests were conducted for each ratio, including two (2) positive controls containing only 3g of cellulose and blanks (inoculum only) for a total of twelve (12) bottles. The variation of ratios was conducted to optimize biogas production yield, and the different ratios (based on volatile solids, VS) were employed. This range is consistent with previous research on the effect of the labile organic fraction in food waste and the substrate/inoculum ratio on the AD for a reliable methane yield, done by Kawai et al. [89]. It also facilitates the comparison of inoculum-rich (1:3 and 1:2) conditions, which are supposed to carry out a stable process with 50-55% CH_4 content [89], and substrate-rich (1:1 and 2:1) conditions to prevent acidification during the process, following Elbeshbishy et al. [90]. Overall, ratios of 1:3 and 1:2 were tested to ensure adequate microbial activity for the breakdown of cassava peels' lignocellulosic components, while ratios of 1:1 and 2:1 were used to explore higher substrate loading. Further details are referred to Appendix C2: Calculations for the BMP test setup. The ANKOM system is shown in Figure 2.5.

The ANKOM bioreactor system

Figure 2.4: ANKOM system

The objective of the study was to establish the optimal conditions for biogas production. The substrate concentration fluctuates according to these ratios since the amount of inoculum was fixed at 300 g, which adheres to the minimum required by regulations. Consequently, the concentration for each ratio is adjusted based on the following Equation (31):

$$\mathrm{SC} = \frac{\mathrm{GV_{reactor}} \times \mathrm{Q_{subsrate}}}{\mathrm{NV_{reactor}}} \qquad (31)$$

With SC, the substrate concentration, GVreactor, reactor gross volume in liters, Qsubstrate, the organic fraction of the substrate in gVS, and $\mathrm{NV_{reactor}}$, the reactor net volume in liters.

For that, we also set the organic fraction of the substrate, respectively, through the following Equation (32).

$$\mathrm{Q_{substrate}} = \mathrm{Q_{Inoculum}} \times \mathrm{S/I} \qquad (32)$$

With $\mathrm{Q_{substrate}}$, the substrate quantity in gVS; $\mathrm{Q_{inoculum}}$, the quantity of inoculum in gVS and S/I the substrate-to-inoculum ratio.

The quantity of inoculum was found through the following Equation (33).

$$\mathrm{Q_{inoculum}} = 300 \times \mathrm{VS_{inoculum}}(\%) \qquad (33)$$

The calculations for the setup, detailing the different substrate ratios and their corresponding volatile solids concentrations used in the BMP tests, as well as the proximate characteristics of the inoculum (the digestate sludge) and the cellulose, are detailed in Appendix C1: Characteristics of inoculum & cellulose and Appendix C2: Calculations for the BMP test setup.

The substrate/inoculum ratio (based on volatile solids) should not exceed 0.4 g VS (substrate) per g VS (inoculum). For the experiment, each vessel is filled with 300 to 400 g of inoculum, depending on its volatile solids content and other properties, to ensure adherence to this ratio and maximize biogas production.

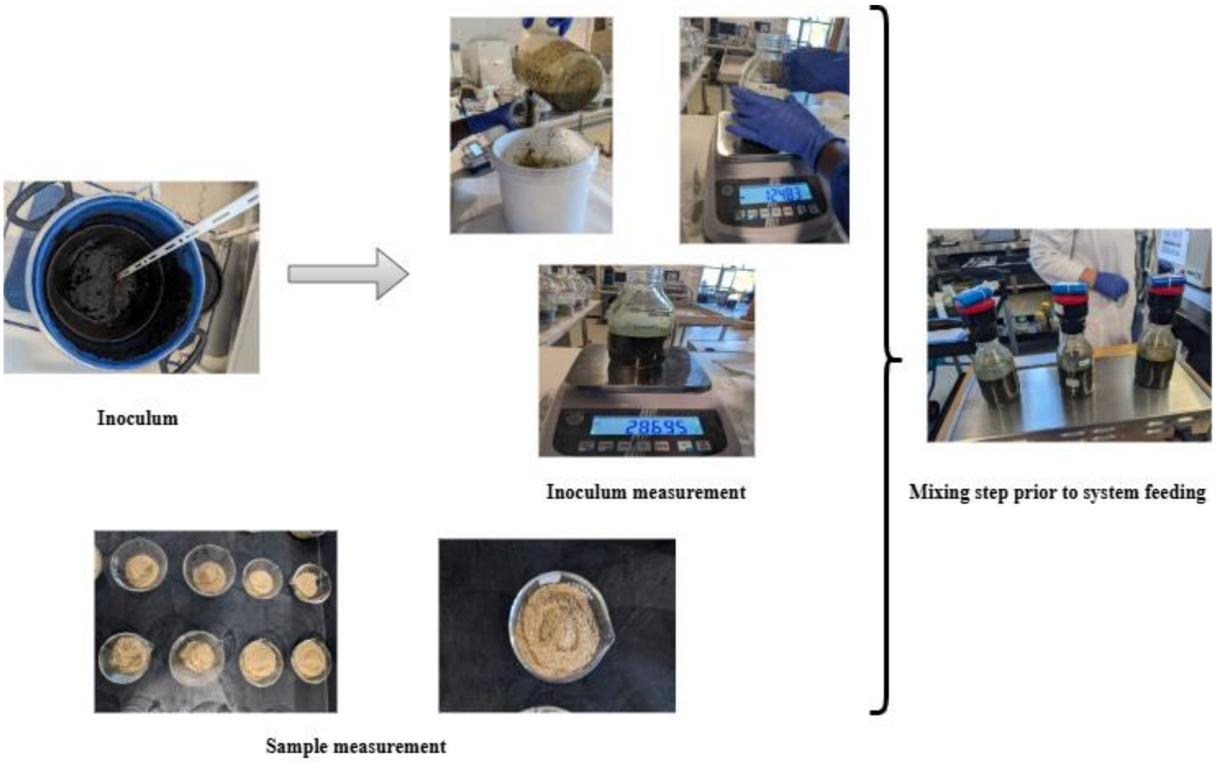


Figure 2.5: BMP test setup

2.5.2.2. Biogas yield and methane yield calculations

The amount of substance is directly proportional to the pressure increase in the digestive vessels, as described by Equation (34).

$$dn = dp.\frac{V_0}{R.T} \tag{34}$$

Where V_0 is the headspace of the digestion vessels, R is the universal gas constant equal to 8.314 J/mol.K, T is the temperature, dp is the differential pressure, and dn is the differential mole number.

At pressures below 150 kPa (abs), the gas can be approximated as an ideal gas with a molar volume of v_0=22.4 l (N) mol^{-1}. To calculate the volume of the biogas produced, Equation (35) is used, which requires knowing the headspace volume.

$$dV = dp.\frac{V_0 \times v_0}{R.T} \tag{35}$$

Where dV is the differential volume and v_0 is the standard molar volume of an ideal gas at standard temperature and pressure (STP) equal to 22.4 L/mol.

All reactors (vessels) are numbered, and the volume of each digester is measured using the gravimetric method (filling with water at 20 °C). This allows for the calculation of the headspace volume when the digestion vessels are balanced during filling (empty, with inoculum, and with substrate). In several tests, the density of the inoculum has been found to range from 998 to 1.002 kg/m³, allowing us to assume an average density of 1.000 kg/m³ for the inoculum. It was also important to consider the density of the substrate, particularly if its volume significantly contributes to the total volume of the material.

The specific biogas yield (V_{spez}) of the substrate can be calculated by subtracting the total biogas volume produced from the inoculum, determined from blank tests, and relating this to the input mass of the substrate. The calculation for each data set, all 30 minutes, follows Equation (36):

$$V_{spez}(t) = \frac{V_{Br}(t) - V_{Spez(i)}(t) \times m_i}{oTM(S)} \quad (36)$$

Where:

$V_{spez}(t)$ is she specific biogas volume at the time t in l(N)/kgVS

$V_{Br\,(t)}$ is the total biogas yield of the vessel at time t in l(N)

$V_{spez(i)}$ the specific biogas yield of the inoculum at time t in L (N)/kgFM

$m_{i,}$ the mass of inoculum in the vessel in kgFM

oTM the substrate mass in the vessel in kg

2.6. Simulation methods and Life Cycle Analysis

2.6.1. Hydrogen production processes, simulation, and process flow diagram

For the simulation, Aspen Plus version 14 (V14) was used as the software. Either the equilibrium constant or the minimisation of Gibbs free energy is typically used to determine the thermodynamic equilibrium in a particular reactor [91].

Due to the absence of chromatographic capabilities within the laboratory and the limited timeframe available for analysis, it was not possible to perform gas composition testing. Consequently, the composition values used in this study were sourced from Ukaegbu-Obi [36] due to the similar conditions and the substrates used for CP. The sum of the measured percentages of biogas components may not always add up to exactly 100% due to measurement uncertainties or the presence of unquantifiable trace gases. To ensure the consistency and validity of calculations in process simulation software, the sum of the molar or volumetric fractions of all components must be precisely 100%. Therefore, the biogas composition was normalized to 100% for each component using Equation (37).

Then, the simulation of the SMR process began with the preparation of the biogas feed, which had a composition of 52.35% methane, 37.13% carbon dioxide, 1.80% nitrogen, 0.29% hydrogen sulfide gas, a hydrogen gas content of 2.76%, 0.03% oxygen gas content, and 0.06% water vapour percentage content. This biogas is further mixed with steam to maintain a steam-to-carbon (S/C) ratio of 3:1, which minimizes coke formation and enhances methane conversion [1]. Based on the study of Franchi et al., a value of 3:1 is used for the S/C to maximize H_2

output and minimize carbon creation, heat losses, and system inefficiencies [92]. The simulation employed the PRMHV2 thermodynamic model, which is well-suited for high-temperature, high-pressure systems containing both polar and non-polar components [14]. The SMR reactor is modeled using the RGibbs module, which employs Gibbs free energy minimization, and operates at 909°C and 16 bar conditions, known to optimize reaction equilibrium and syngas yield [93]. Following SMR, H_2 production was further enhanced by the Water-Gas Shift (WGS) reaction, conducted in two reactors: HTWGS at 350°C and 15.75 bar, and LTWGS at 210°C and 15.70 bars [93]. The gas stream was then sent to a Pressure Swing Adsorption (PSA) unit, operating at 38°C and 15.65 bar, to achieve a 99.9% hydrogen purity by selectively removing unreacted gases and impurities [93]. Figure 2.7 presents the units involved, and Table 2.1 presents the process conditions. A plant that processes 1 tonne (1000 kg) of volatile solids (VS) from CP per day (1000 kg VS/day) was simulated and represented in Figure 2.8. To determine the biogas mass flow and the steam mass flow rate, Equations (38) and (39) were used. (See Appendix D: Formulas for biogas mass flow & steam mass flow calculations)

$$\%_{\text{normalized}} = \frac{\%_{\text{measured}}}{\text{Total }\%_{\text{measured}}} \times 100 \qquad (37)$$

$$\text{Biogas mass flow } \left(\frac{\text{kg}}{\text{day}}\right) = \sum \text{masses components} \qquad (38)$$

$$\text{Steam mass flow rate}(\dot{m}_{\text{H2O}})\left(\frac{\text{kg}}{\text{day}}\right) = \dot{n}_{\text{H2O}} \times \text{Mass molar } H_2O \qquad (39)$$

Table 2.1. Process conditions in Aspen Plus for hydrogen production via SMR using biogas

Property method	**PRMVH2**						
	CH_4	**CO_2**	**N_2**	**O_2**	**H_2**	**H_2S**	**H_2O**
Biogas composition (%)	55.45	39.31	1.91	0.03	2.92	0.29	0.06
Biogas mass flow	23.48kg/hr						

Reformer		
Reformer temperature	909 °C	
Reformer pressure	16 bars	
S/C ratio	3/1	
Steam mass flow rate	44.65kg/hr	
Combustion		
	N_2	O_2
Air combustion (vol%)	79	21
Inlet temperature	250 °C	
Pressure	1 bar	

Source: [1]

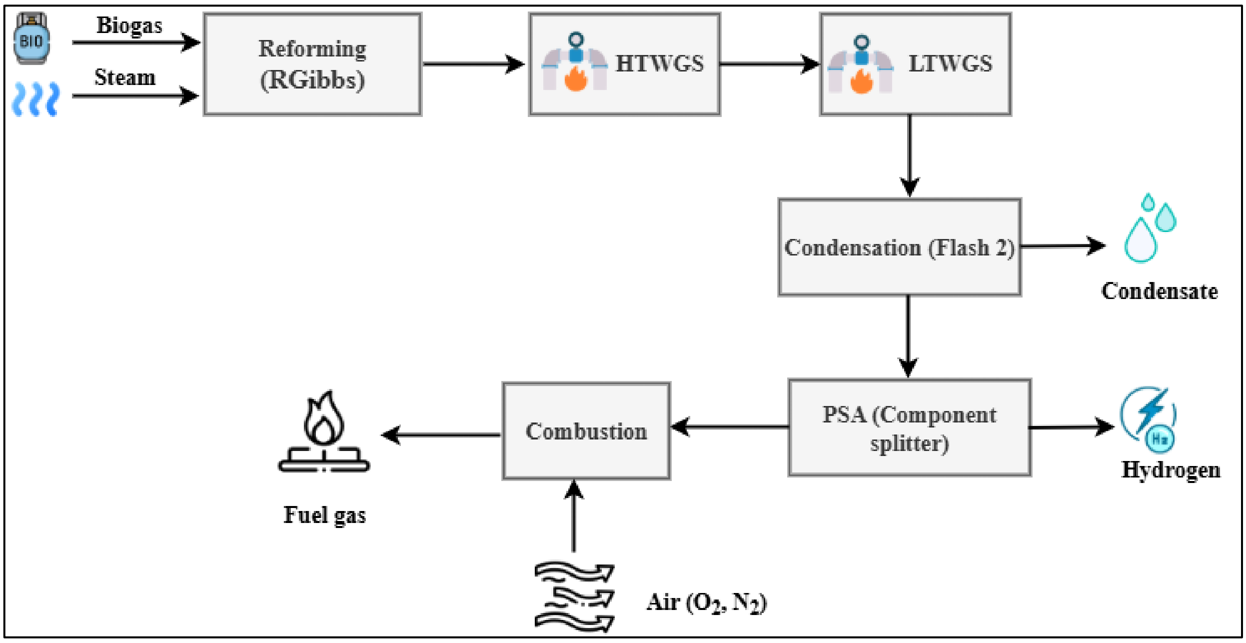


Figure 2.6: Block flow diagram and different units of hydrogen production from biogas (adapted from [1])

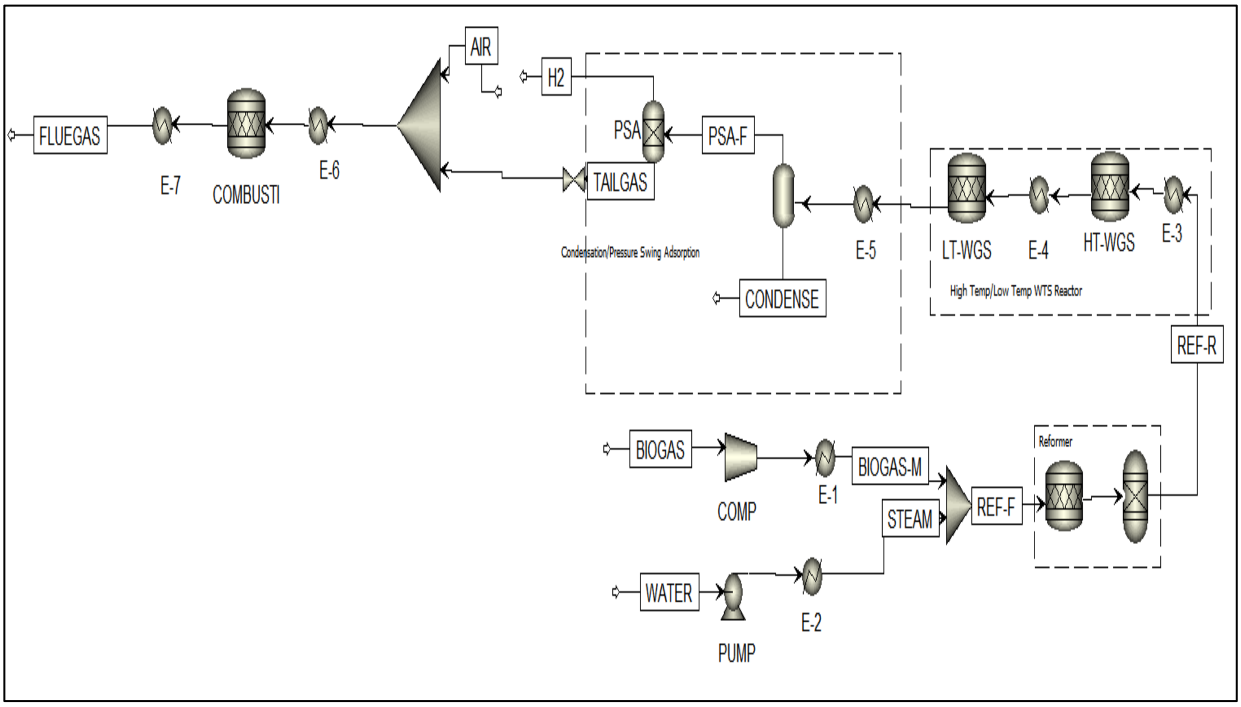


Figure 2.7: Flowsheet of hydrogen production simulation by SMR (Aspen Plus software)

- **Validation of the simulation results**

To ensure the reliability of the Aspen Plus simulation, a comparative validation was conducted using two independent data sources:

- **Industrial simulation benchmark:** A separate Aspen Plus model developed using operational data obtained from an active industrial site [1]. This model served as a benchmark to assess the realism of the simulation conditions and outputs, as mentioned.
- **Experimental data comparison**: Laboratory-scale experiments were performed under controlled conditions to generate empirical data [3].

2.6.2. Life Cycle Assessment approach

The Life Cycle Assessment (LCA) simulation is conducted using OpenLCA version 2.5.0, following a cradle-to-gate approach to analyse the environmental impacts of biogas production and biohydrogen production from cassava peel-derived biogas. For this study, two assessments were done. The overall LCA was conducted according to ISO 14040-44 (ISO 14040: 2006; ISO 14044: 2006) in four (4) phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase [95] . This study presents a gate-to-gate life cycle assessment, focusing exclusively on the AD process and the subsequent SMR of the produced biogas.

Five (5) impact categories, including climate change (CC), acidification potential (AP), particulate matter formation (PMF), photochemical ozone formation (POF), and eutrophication potential (EP), were chosen for discussion. This selection was based on their high relevance to both AD and SMR processes. These categories are widely recognized in the literature as essential for assessing the environmental footprint of energy conversion technologies. [82] highlighted their importance in evaluating bioenergy pathways, particularly in terms of air emissions, global warming, and nutrient enrichment. Similarly, Teresa Costa-Campi et al. [96] showed that these indicators effectively capture key environmental trade-offs in systems involving biogas generation and H_2 production. By focusing on these five core categories, the analysis emphasizes the most critical environmental dimensions without sacrificing methodological rigor. For this study, life cycle inventory data were sourced from Ecoinvent version 3.11, ensuring high-quality and transparent datasets consistent with internationally recognized LCA methodology standards. The system boundary of the two processes is shown in Figure 2.9.

2.6.2.1. LCA for biogas production

The LCA methodology for biogas production evaluated the environmental impact of obtaining biogas from CP waste. The system boundary followed a gate-to-gate approach, covering the AD process. This system boundary was selected to capture the full range of environmental impacts associated with a part of the upstream production phases while excluding downstream stages such as biogas utilization or end-of-life treatment. The functional unit was set to 1 m^3 of biogas produced. This approach aligns with well-established LCA practices in bioenergy systems, as exemplified by Morero et al. where cradle-to-gate boundaries facilitate a focused evaluation of production-related impacts [97]. The inventory analysis encompassed input materials, including CP, as well as electricity for processing, and processes such as waste pretreatment and anaerobic digestion. Table 2.2 shows the inventories. Primary and secondary data were used for this analysis. The primary data consisted of laboratory experiments that quantified key process parameters, including biogas yield, CH_4 and CO_2 composition, TS and VS of the substrate, and quantities of digestate. Secondary data were sourced from scientific publications, including Aziz et al. [98], Wang et al. [99], and Ibrahim et al.'s work [100]. These studies established life cycle databases, including Ecoinvent 3.11, which provided information on background processes such as electricity generation, diesel fuel combustion, and emission factors. The outputs consisted of biogas, digestate waste, and emissions related to methane leakage and CO_2 release. The impact assessment applied ReCiPe 2016 methodologies, aligning with Huijbregts et al. [81] to quantify the climate change from methane leakage and CO_2 emissions, as well as the eutrophication and acidification effects from wastewater discharge, as studied by Rehl et al. [101]. The choice of the ReCiPe 2016 method to conduct the impact assessment is motivated by its comprehensive and harmonized characterization of environmental impact categories. The interpretation focused on key variables, including the five cited categories, to refine sustainability performance and optimize the system.

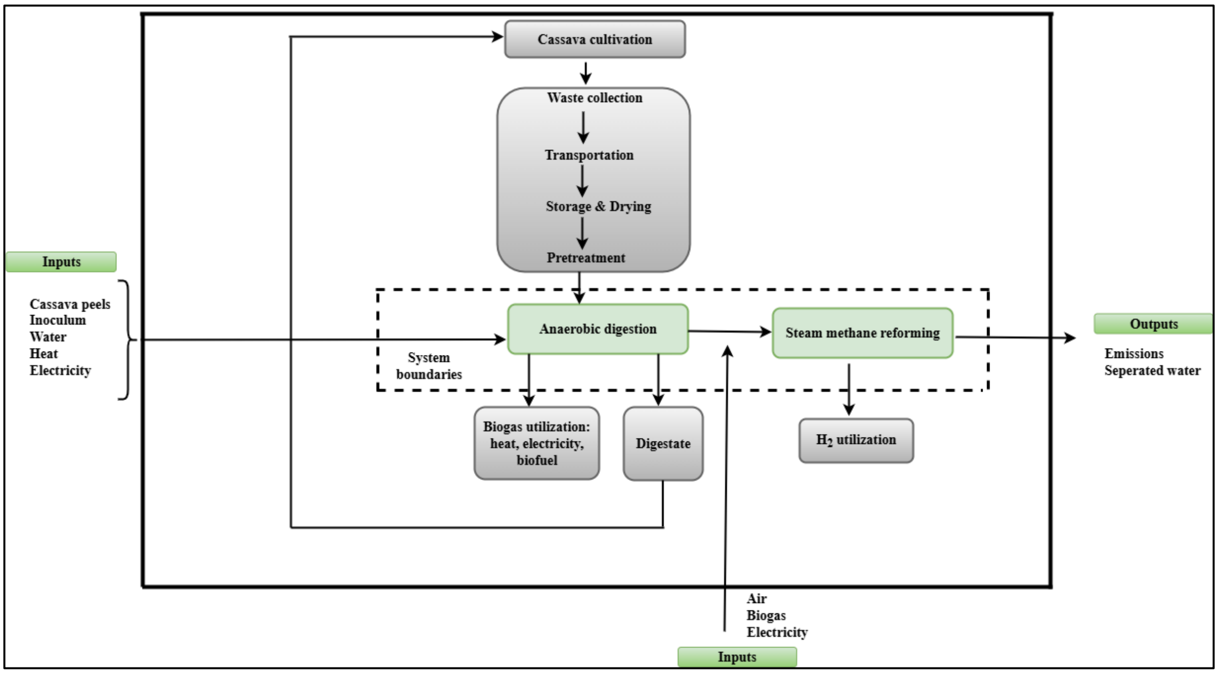


Figure 2.8: System boundaries of LCA

Table 2.2. LCI of biogas production through anaerobic digestion

Input	Quantity	Output	Quantity	Reference
Sized cassava peels	2.4kg	Biogas	1 m^3	[19]
Inoculum (digestate, TS 4.6%, VS 2.8%)	0.48kg	Digestate	3.5 kg	[102]
Energy for heat	1.08MJ	Heat	1.08MJ	[103]
Electricity	0.36MJ	Electricity	0.36MJ	[103]
Water	0.72kg	Water vapor	0.72kg	[104]
		Carbon dioxide	0.77kg	This study
		Methane	0.39kg	This study
		Hydrogen sulfide	0.0044kg	This study
		Nitrogen	0.024kg	This study
		Water vapor	0.72kg	This study & [104]

2.6.2.2. LCA for hydrogen production

For H_2 production, the LCA assessed the environmental impact of SMR using biogas as the source of methane. The system boundary covered biogas feed (biogas and water) preparation, SMR reactor operation, Water-Gas Shift (WGS) processes, and Pressure Swing Adsorption (PSA) purification, following a cradle-to-gate perspective. The analysis adopted a system boundary that begins with the input of biogas/biomethane (as output from the preceding process

LCA) and continues through all key stages of H_2 generation, purification, and associated energy and material flows, up to the output of purified hydrogen at the plant gate. This system structure conforms to recent LCA conventions on renewable hydrogen from biogas, such as the approach described by Hajjaji et al. [105] in the International Journal of Hydrogen Energy. It also aligns with the best practices for cradle-to-gate analysis of the hydrogen production life cycle assessment. The functional unit was defined as one (1) kilogram of H_2 produced according to Hajjaji et al.'s research, enabling direct comparison to the benchmarks and GHG estimates reported in contemporary studies [105].

The inventory analysis (presented in Table 2.3) compiled biogas input derived from cassava waste, steam for reforming, and overall energy consumption, as studied by Abawalo et al. [106]. The core processes involved methane reforming, WGS reactions that convert carbon monoxide to carbon dioxide and hydrogen, and PSA, which ensures a purified hydrogen output with minimal losses of unreacted methane. The biogas production data are adapted from laboratory analysis, whereas the reforming inventory data are obtained from process simulation using Aspen Plus software. An environmental impact assessment was applied using ReCiPe 2016, which quantified carbon footprint contributions from SMR and PSA emissions and evaluated the system's energy consumption in megajoules per kilogram (MJ/kg) of H_2 [106]. Interpretation focused on the environmental impacts observed across different impact categories, rather than on process optimization or sensitivity analysis. The aim is to assess the relative contributions of each category.

Table 2.3. LCI for H_2 production

Description	Amount	References
Inputs		
Biogas feedstock (dry basis)	1 m^3	Primary data
Methane in biogas	0.39 kg	Primary data
Steam (H_2O vapor)	1.2 kg	S/C ratio
Electricity (compression, heating, PSA)	1 kWh	H_2 simulation
Nitrogen	10 kg	-
Oxygen	2.5 kg	[107]
Outputs		
Purified Hydrogen (99.99% purity)	1 kg	-
Carbon dioxide (biogenic emissions)	1.5 kg	[108]
Methane slip / fugitive methane	0.06 kg	[109]
Waste heat (recoverable internal use)	1 kWh	This study
Wastewater	1.2 kg	[110]

Oxygen	2.5 kg	[107]
Nitrogen	10 kg	This study

The methodological approach described in this chapter provides a basis for data collection and analysis. By adhering to established protocols and ensuring methodological rigor, the study is positioned to yield reliable and valid results. The next chapter presents the findings derived from this framework.

Chapter III: RESULTS AND DISCUSSION

This chapter presents the empirical findings of the study and interprets them in relation to the research questions and existing literature. The results are organized by hypothesis, followed by a critical discussion that explores their implications and relevance to the field.

3.1. Results

3.1.1. Evaluation of the national cassava peel potential

3.1.1.1. National cassava production

Before assessing the national potential of cassava peels, the country's tuber production, particularly cassava, was evaluated, highlighting cassava production in tonnes. The total tuber production amounts to 240,614 tonnes for the 2023-2024 crop production campaign, representing an increase of 168,000 tonnes, or 7.51%, compared to the previous season (See Appendix E1: Comparison of root and tuber crop production in tonnes for 2023-2024 and 2022-2023). Figure 3.1 highlights the comparison of root and tuber crop production in tonnes from 2018 to 2024. According to speculation, the increases are 8.34% for cassava, 6.68% for yams, 0.81% for taro, and 0.13% for sweet potatoes. Cassava remains the most produced tuber, reaching 1.32 million tonnes in the 2023-2024 campaign, with a notable 8.34% growth. These figures indicate a rising trend in tuber production, particularly cassava, highlighting its growing importance in agricultural output (See Appendix E2: Comparison of root and tuber crop production in tonnes of each region from 2018 to 2024).

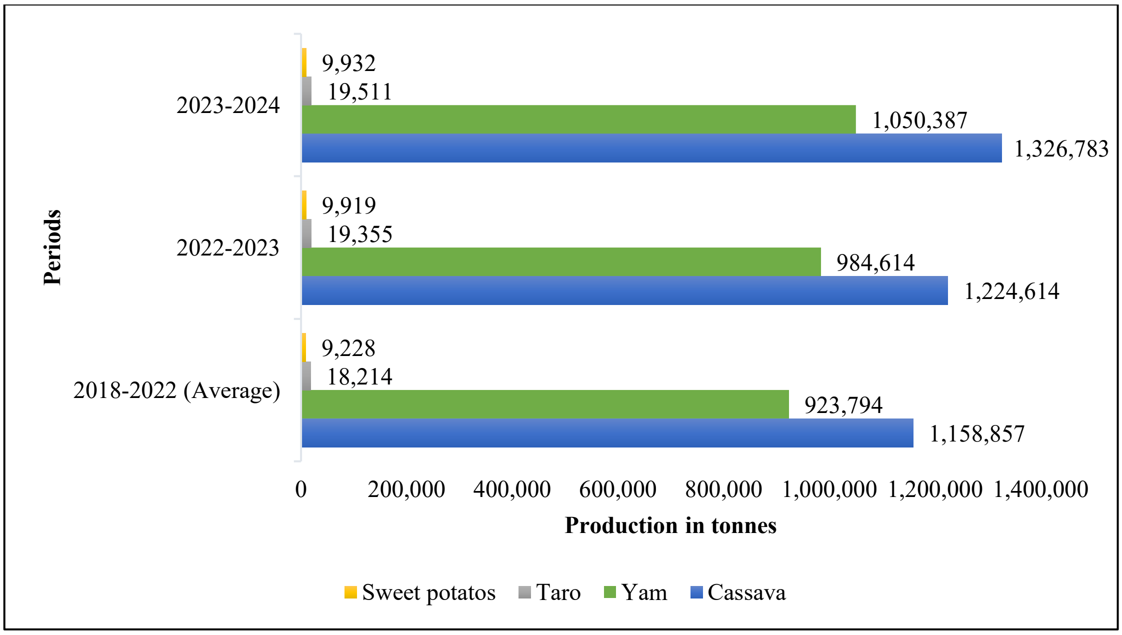


Figure 3.1. Comparison of root and tuber crop production in tonnes from 2018 to 2024 (adapted from [21])

Cassava production has significantly increased across all regions from 2018 to 2024, reflecting both agricultural expansion and improved yields. The 2023–2024 campaign reflects a nationwide positive trend, with every region showing growth both compared to last year and relative to historical averages.

Between 2022–2023 and 2023–2024, cassava production increased across all regions of Togo, with the Plateaux region showing the strongest growth both year-on-year (9.5%) and compared to its average for 2018–2022 (17.4%). Maritime remains the top producer, recording a steady rise of 8% from the previous year and 12.5% above its five-year average. Centrale and Kara also showed notable improvements, while Savanes, though producing lower volumes overall, maintained a consistent upward trend (See Appendix E2: Comparison of root and tuber crop production in tonnes of each region from 2018 to 2024). The data reflect a clear national shift toward higher cassava productivity. Figure 3.2 illustrates the general production of the regions, showing the production areas and their share in total production.

In the 2023-2024 campaign, Maritime leads with 34%, followed closely by Plateaux at 33%. Centrale accounts for 19%, while Kara represents 13%. The Savanes region has the smallest share at 1%.

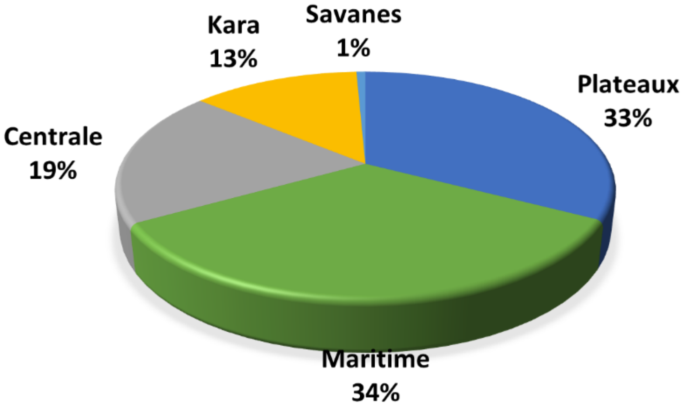


Figure 3.2. Roots and tubers production share in different regions in 2023-2024
(adapted from [21])

3.1.1.2. National cassava peel potential

The trend in cassava production and peel generation across the three periods shows a consistent increase in both parameters. Between 2018 and 2022, the average cassava production was 1,158,857 tons, yielding 231,771.4 tons of peels. In contrast, between 2022 and 2023, production increased to 1,224,614 tons, with peel waste reaching 244,992.8 tons. The highest values were recorded in 2023–2024, when cassava output reached 1,326,783 tons, resulting in 265,365.6 tons of peels, as shown in Figure 3.3.

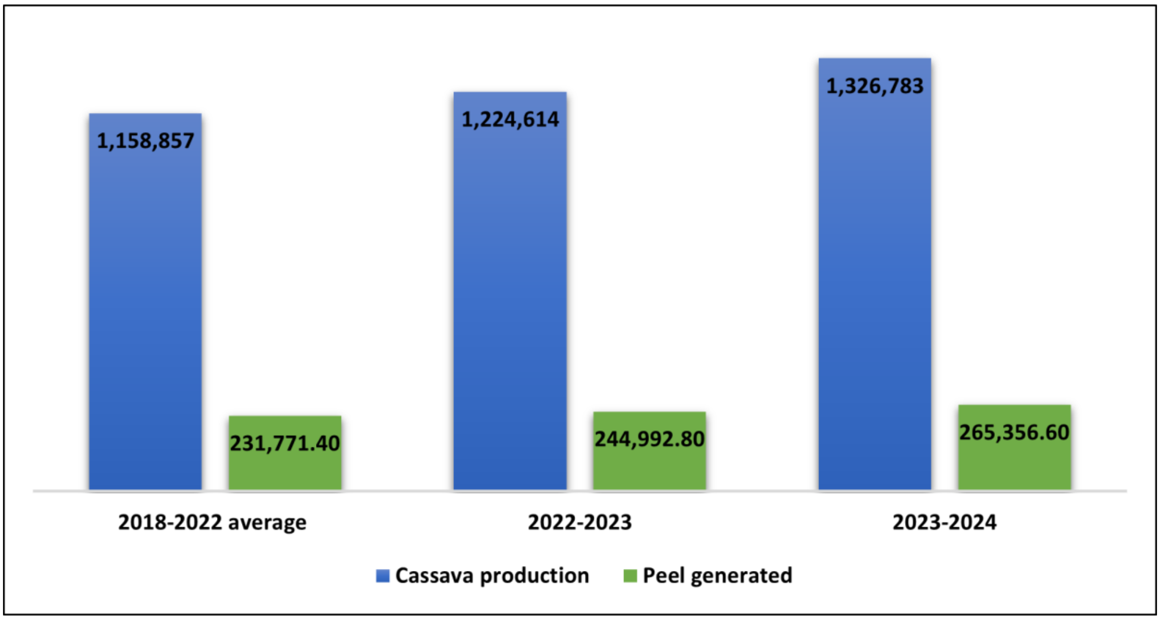


Figure 3.3. National cassava peel potential in tonnes

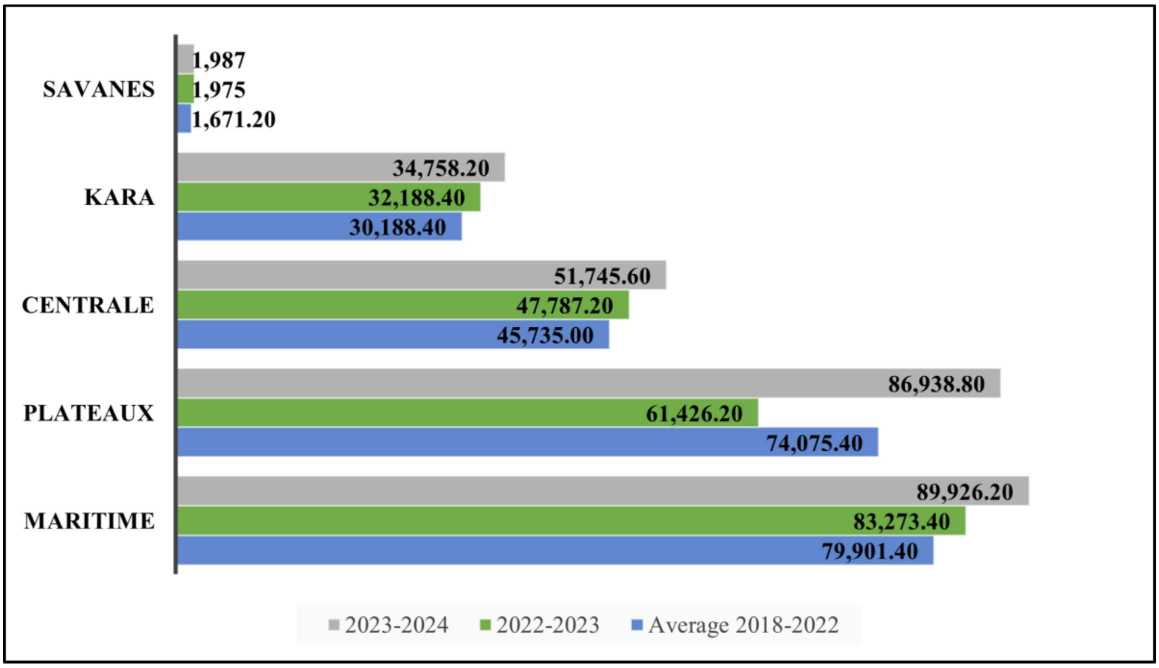


Figure 3. 4. Cassava peel's potential in tonnes for each region

In each region of Togo, the generation of cassava peels varies according to the level of production in that region. The Maritime region recorded the highest volume, followed by Plateaux, which showed a notable increase compared to previous years. Centrale and Kara also contributed significantly, with both areas displaying steady growth in peel production. The Savanes region, while generating a smaller quantity, maintained a consistent pattern over the years. These variations, as shown in Figure 3.4 above across regions, highlight differences in the scale of cassava cultivation and processing, reflecting distinct production dynamics nationwide.

3.1.2. Characterization

3.1.2.1. Proximate analyses

The proximate analysis of cassava peel based on fresh matter (FM) reveals a high total solids (TS) content of 97.61%, indicating a minimal moisture content (MC) of 2.39%. With volatile solids (VS) at 91.03%, the peels consist predominantly of organic matter, while the fixed carbon (FC) at 2.39% highlights a small portion of residual carbon. (See Appendix E3: CP characterization results).

3.1.2.2. Ultimate analysis

The carbon content of cassava peels was found to be 42.4% (dry basis), with hydrogen at 6.13%, nitrogen at 0.477%, phosphorus at 0.12%, and oxygen at 43.2%. The C/N and C/P ratios were calculated at 88.9 and 353.3, respectively. The results present the composition of heavy metals as followed: lead (Pb) was detected at 0.55 mg/kg, and nickel (Ni) at 8.04 mg/kg, manganese (Mn) at 42.9 mg/kg, copper (Cu) at 3.55 mg/kg, and chromium (Cr) at 21.1 mg/kg, consistent with the threshold levels reported in international biomass monitoring efforts. The gross calorific value was measured at 16,419 KJ/kg (as received) and 17,034 KJ/kg (dry basis), while the net calorific value was determined to be 15,043 KJ/kg (as received) and 15,698 KJ/kg (dry basis). (See Appendix E3: CP characterization results).

3.1.2.3. Fiber content

The fiber composition of the cassava peel sample indicates that the Neutral Detergent Fiber (NDF) content is 47.15%, suggesting that nearly half of the peel consists of structural fiber components, including cellulose, hemicellulose, and lignin, as shown in Figure 3.5 below. The Acid Detergent Fiber (ADF) is 17.15%, representing the tougher fraction of fiber that contains cellulose and lignin. The Acid Detergent Lignin (ADL) value is 9.00, and the cellulose content measures 8.15%, while the hemicellulose concentration is notably high at 30.00%.

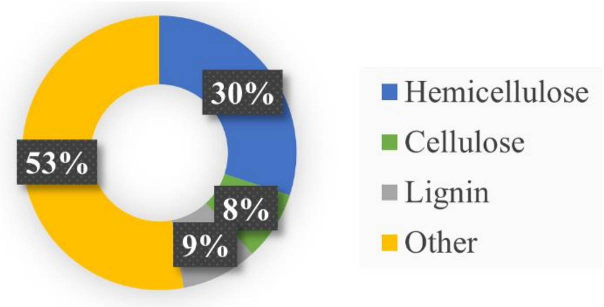


Figure 3.5. Cassava peel fiber content

3.1.3. Biogas production rate and yield of the different substrate/inoculum ratios

The AD test conducted on cassava peels at varying S/I ratios revealed notable differences in biogas generation over time. Cumulative biogas production, as presented in Figure 3.6, began promptly across all samples. However, the S/I = 1/3 configuration stood out early, with a steep rise in yield, indicating rapid microbial activity and high biodegradability. In contrast, the higher S/I ratios (1/2 and 1/1) exhibited slower initial biogas formation and a more gradual increase, suggesting substrate overload or inhibitory effects limiting efficiency. After the first week, all samples transitioned into a steadier production phase, with the 1/3 ratio maintaining superior output, highlighting it as the most favorable condition for cassava peel digestion. The substrate-to-inoculum (S/I) ratios of 1/1 and 2/1 produced the highest cumulative methane yields, particularly between days 14 and 28, as shown in Figure 3.7 below. Cellulose serves as a positive control and performs consistently, while the blank confirms negligible gas production from inoculum alone.

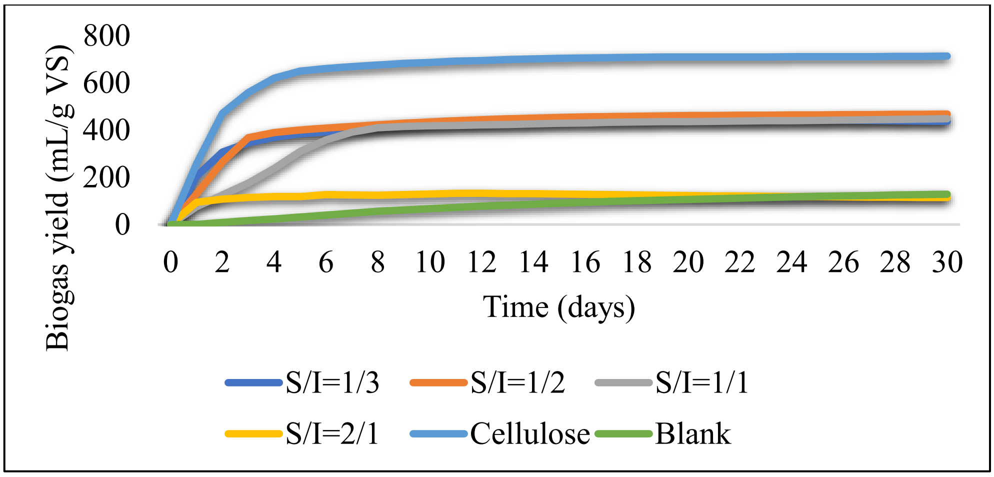


Figure 3.6. Cumulative biogas yield profiles

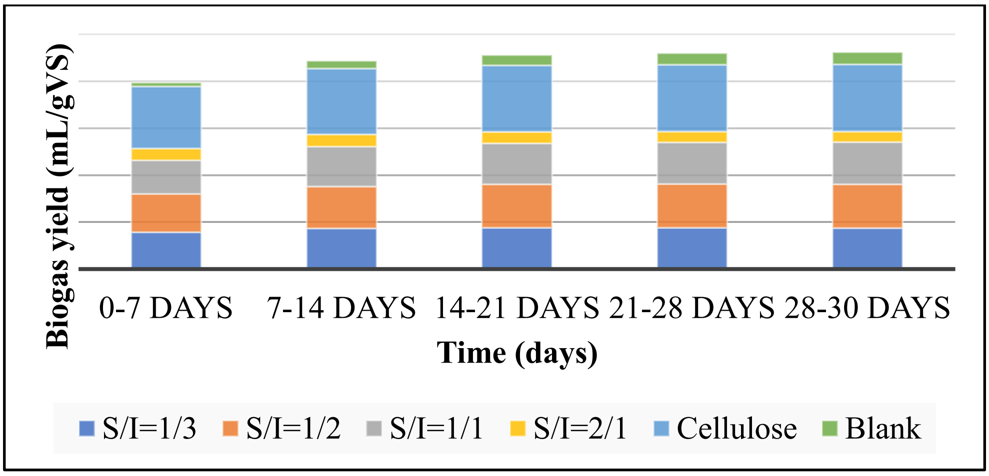


Figure 3.7. Weekly cumulative biogas yield

After performing the calculations, the final methane yields for each substrate-to-inoculum ratio revealed apparent variations in biodegradation performance: 469.5 ml/gvs for 1/2, 450.2 ml/gvs for 1/1, 433.9 ml/gvs for 1/3, and significantly lower at 112.7 ml/gvs for 2/1 (See Appendix E4: Final cumulative results of BMP tests).

3.1.4. Hydrogen production rate and yield

The Aspen Plus simulation, whose flowsheet is presented in Figure 2.3, demonstrates an efficient and nearly complete conversion of methane, leaving only trace amounts of methane and carbon monoxide in the product gas stream. The feed gas, composed of approximately 55.45% methane and 39.31% carbon dioxide by mass, yields a purified hydrogen stream with a purity of 99.99% (close to 100%) after passing through the PSA unit. This hydrogen product stream exhibited a mole flow rate of about 1.19 kmol/h, corresponding to a mass flow of 2.41 kg/h of high-purity hydrogen. Given the biogas feed mass flow of 23.48 kg/h, this equates to a hydrogen yield of approximately 0.10 kg H_2 per Nm^3 of biogas, or 2.26 g of H_2 per kg of biogas processed, accompanied by 30.77 kg/h of co-produced water. The flue gas stream comprised major by-products, including carbon dioxide (~0.79 kmol/h), nitrogen (~2.40 kmol/h), and oxygen (~0.43 kmol/h), reflecting the presence of oxidant from the burner air. Water vapor was also present, as expected, due to steam input and heat management requirements. Water vapor was present predominantly in the feed and flue gas, consistent with the steam requirements for reforming and process heat management. The detailed results are presented in Appendix E5: SMR process simulation results.

3.1.5. LCA results

3.1.5.1. LCA results of biogas production

The results presented in Appendix E6: LCA results of the AD process, indicate that CC potential is the dominant impact category, with a total of 13.64 kg CO_2-eq. AP is measured at 5.52×10^{-4} kg SO_2-eq, and PMF accounts for 2.01×10^{-4} kg PM2.5-eq. EP remains relatively low at 4.21×10^{-5} kg P-eq while POF contributes 1.45×10^{-4} kg NO_x-eq. Overall, the results highlight the environmental profile of biogas production across multiple impact categories, with the climate change impact emerging as the key ecological hotspot in the system. The summary results are presented in Appendix E6: LCA results of the AD process

3.1.5.2. LCA results of hydrogen production

The CC potential is estimated at 3.82 kg CO_2-equivalent per kg of H_2. AP reaches 0.0054 kg SO_2-eq per kg H_2, while PMF accounts for 0.00198 kg PM2.5-eq per kg H_2. POF contributes at 0.00292 kg NO_x-eq per kg H_2, and EP is measured at 3.34×10^{-4} kg P-eq per kg H_2. These results present the environmental profile of H_2 production from biogas across multiple impact categories. The CC potential stands out as the primary ecological hotspot in the system. The summary results are presented in Appendix E7: LCA results of the SMR process. Figure 3.8 provides an overview of the results between the two processes for a better understanding.

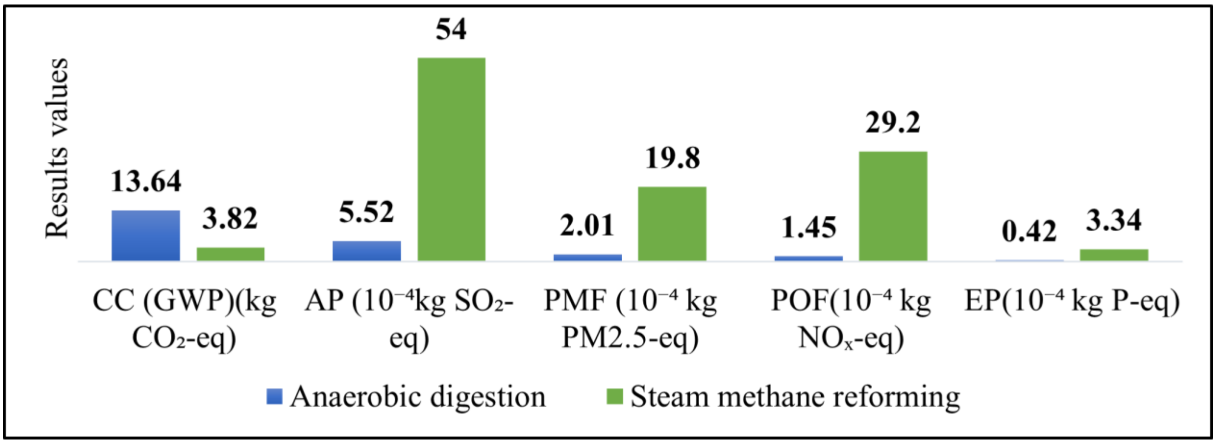


Figure 3. 8. Overview of AD & SMR processes results

3 2. Discussion

3.2.1. National potential of cassava peels

The graph's average for 2018–2022, listed as 1,158,857 tonnes, and its 2022–2023 value of 1,224,614 tonnes showed potential. The graph in Figure 3.1 shows a clear and steady increase in both cassava production and the volume of peels generated in Togo over recent years. Such continuous growth is highly significant for Togo's agri-food and energy sectors. The corresponding rise in peel generation provides a substantial and sustainable feedstock for industrial valorization in energy strategies, particularly in bioenergy production. Scientific studies, such as those conducted by Cuzin et al. [111] have demonstrated the technical feasibility and the strong biogas yield attainable from CP, reaching up to 0.6–0.7 Nm^3 biogas per kilogram of dry matter. Moreover, recent studies have reported high biogas yields from CP [73]. Harnessing this growing residue supply can not only help diversify Togo's rural economy through new value chains and job opportunities but also contribute to improved environmental management, reduced waste, and enhanced renewable energy output. [22] and guidelines indicate that leveraging CP for biogas production aligns with global recommendations for climate-smart, circular agriculture. This positive trajectory thus positions Togo to become a regional leader in both cassava value addition and sustainable bioresource management, reinforcing food security and the rural socio-economic fabric.

3.2.2. Characterization

The CP sample analyzed exhibited a remarkably high total solids (TS) content of 97.61%, indicating that the material was thoroughly dried and highly stable, with minimal moisture content (2.39%) as presented in the results. The volatile solids (VS) constituted the majority of the dry matter, suggesting a rich organic fraction suitable for biological conversion. These values are similar to those of Kusi et al. for VS content of 97% TS; however, the TS values reported were 31%, which is very low compared to the values in this study [23] . Amaza et al. found a value of 91.30±0.074 as TS, which is less than what is found in this study, certainly due to the nature (sweet) of the CP samples [112]. This highlights the high proportion of biodegradable organic material, suggesting strong potential for bioenergy applications such as AD. The relatively low AC and FC contents further support the peel's potential for energy recovery and feed applications, as they imply minimal inorganic residue and a composition typical of lignocellulosic biomass. The value of AC (6.74 %) is less than 8.93 ± 0.047%, reported by Amaza et al. [112], and higher than 3.0%, as reported by Kusi et al. [23]. However, for crops, AC typically ranges from 3% to 15%, and the AC of CP being within the range will allow for biogas generation, as noted by [113]. Meanwhile, fixed carbon (FC) accounted for only 2.45% of the dry matter, which aligns with values typically observed in lignocellulosic biomass. Overall, this composition highlights the suitability of cassava peels as a versatile, energy-rich agricultural waste product.

The mineral analysis (presented in Appendix E) revealed moderate levels of carbon, hydrogen, and nitrogen, with a high C/N ratio, demonstrating a slightly different profile compared to a higher carbon content of 48.7%, nitrogen at 1%, and phosphorus at 1.6% [12]. In comparison to Kusi et al., the CP analyzed in this study showed lower levels of carbon (42.4% TS), hydrogen (6.13% TS), and nitrogen, but slightly higher oxygen content and similar sulfur concentration [23]. These indicated slight differences in energy and nutrient profiles are likely due to varietal or environmental factors. The C/N ratio, calculated as 88.9, suggests the potential of cassava peels for bioenergy applications, aligning slightly with Kusi et al.'s results [23] of (83.38) but higher than the 19.10 obtained by Igbum et al. [114]. For optimal biogas generation, a C/N ratio of 25 to 30 is recommended. While this ratio exceeds the optimal range for AD, it suggests that CP could serve as a carbon-rich co-substrate, particularly when paired with nitrogen-heavy waste streams such as slaughterhouse effluents [58]. This aligns with previous recommendations for co-digestion strategies to balance nutrient profiles and mitigate ammonia inhibition. When the C/N ratio is low, it results in the formation of nitrogen in the form of NH_3, and a higher C/N ratio suggests a high possibility of inhibition.

The fiber composition, characterized by moderate hemicellulose and cellulose and slightly elevated lignin, contrasts with the values reported by Aripin et al. [115] at 37.0% hemicellulose, 37.9% cellulose, and a lower 7.5% lignin in peels processed for pulp and paper. Our results point to a substrate with limited immediate biodegradability. The lower cellulose and hemicellulose content in the samples from the present study suggests a potentially reduced amount of easily digestible carbohydrates, which are primary precursors for biogas production [116]. Conversely, the higher lignin content may hinder microbial access to fermentable carbohydrates, potentially reducing biogas yields unless pre-treatment methods are applied. This reinforces the need for mechanical, chemical, or biological enhancement techniques to improve digestibility [117].

This suggests that while CP remains a suitable substrate, the specific lignocellulosic composition observed in this study may require more intensive pre-treatment methods to enhance biodegradability and maximize biogas production.

Heavy metal concentrations were within acceptable limits and notably lower than those reported in composted cassava peels, suggesting favorable environmental conditions and minimal contamination. The gross calorific value further confirms the energetic viability of cassava peels, positioning them as a promising feedstock for renewable energy applications.

The present study revealed a distinct heavy metal profile within acceptable limits and notably lower than those reported in composted CP, suggesting favorable environmental conditions and minimal contamination. Obodai et al. [118] reported much higher Pb (30.97 mg/kg) and Cu (6.96 mg/kg) levels in composted cassava peels, suggesting better environmental or post-harvest conditions in our sample. The gross calorific value presented in the results (see Appendix E3) is slightly higher than the 15.92 MJ/kg reported by Adeboye et al. [119] likely due to their higher hydrogen and carbon contents, further confirming the energetic viability of cassava peels, positioning them as a promising feedstock for renewable energy applications. These values confirm the feasibility of CP as a viable biomass resource, consistent with calorific values established in studies on lignocellulosic feedstocks for renewable energy applications. Overall, the compositional profile of CP supports its use in bioenergy systems, particularly AD and thermal conversion. However, optimization strategies, such as co-digestion and pre-treatment, may be necessary to fully harness their potential.

3.2.3. Biogas and hydrogen production

3.2.3.1. Biogas production

The trend of biogas production is consistent with reports that optimal S/I ratios enhance microbial performance and digestion kinetics, whereas higher ratios, like 2/1, result in substrate overload and diminished yields due to microbial inhibition. These findings align with [120] who demonstrated that optimal S/I ratios enhance microbial efficiency and digestion kinetics. Compared to Mukhtar et al. who reported CP yields around 428 mL/g VS under mesophilic conditions, the present results suggest that Togo's CP has a high biogas potential, considering the current value of 469.5 mL/g VS, especially when properly pretreated [121]. Moreover, [122] emphasized that pretreatment methods could further boost yields by breaking lignocellulosic barriers. In contrast, according to the experimental results of a study, plantain peels yielded the highest biogas (468 ± 72 mL/g VS), followed by a mixture of yam, cassava, and plantain peels (362 ± 31 mL/g VS), and cassava peels yielded the least biogas (218 ± 19 mL/g VS) [23]. The biogas values corroborate studies showing that co-digestion with animal waste or pretreatments can further raise performance, aligning with regional strategies for sustainable energy and circular bioeconomy. The cellulose control confirms the strong biodegradability of cassava peels, while the blank validates the inoculum's minimal contribution. The biogas potential of CP in this study reached up to 469.5 mL CH_4/gVS for the optimized S/I ratio of 1:2, a value higher than what was recorded by Ismail et al., where biogas yields from CP were approximately 310 mL/gVS under mesophilic conditions [73]. This discrepancy is likely due to differences in substrate pretreatment and inoculum adaptation, as the authors highlighted the role of effective grinding and removal of inhibitory compounds such as cyanogenic glycosides in improving biodegradability and gas yield. This observation is further supported by the meta-analysis of Anacleto et al. where the pretreatment and substrate composition, such as the removal of recalcitrant lignin or an increase in surface area, significantly enhance methane productivity were directly confirmed [46] . This rationalizes why, despite both studies using CP, the more intensive drying and size reduction employed in this study led to higher yields.

In contrast, specific works have reported biogas yields of nearly 428 mL/gVS for CP, which, although lower than the present value, still reflect a favorable substrate profile [23]. The authors attributed any variability not only to pretreatment and inoculum, but also to the S/I ratios used, noting that sub-optimal ratios can result in acidification and microbial inhibition. This is confirmed in the review by Koch et al., who asserted that elevated S/I ratios or excessive substrate loading typically lower methane conversion due to process imbalance and VFAs accumulation, directly matching the sharp yield drop at an S/I ratio of 2:1 observed in the present experiments [88]. Additionally, the moisture content and VS concentration can cause yield variations among studies, with drier, organic-rich peels offering higher yields than those with elevated water or ash content [42]. This explains why the sun- and oven-dried samples in this study performed better. In the Togolese context, these findings offer vital opportunities. The valorisation of cassava peel waste into energy could address both the country's urgent rural energy poverty, with access rates as low as 26% in rural areas, according to research by INSEED [31] , and the environmental harms of indiscriminate dumping. The implementation of effective management strategies has the potential to curtail open burning practices, thereby reducing soil and water contamination. Concurrently, these strategies have the potential to facilitate the provision of affordable cooking gas and organic fertiliser using digestate.

3.2.3.2. Hydrogen production

The result of the H_2 production simulation in this study under similar operating conditions to those used by Phan et al. for 0.10kg/Nm^3, is approximately 43% lower than the average reported yield of 0.175 kg H_2/Nm^3 from the same studies that validated Aspen Plus models for biogas reforming and reported H_2 yields between 0.15 and 0.2 kg/Nm^3 [1] . As shown in Figure 3.9, the comparative analysis of H_2 yields across these data sources supports the validity of our simulation model. At the same time, the observed deviations underscore the impact of biogas composition, experimental variability on process performance, and the influence of real-world operational factors.

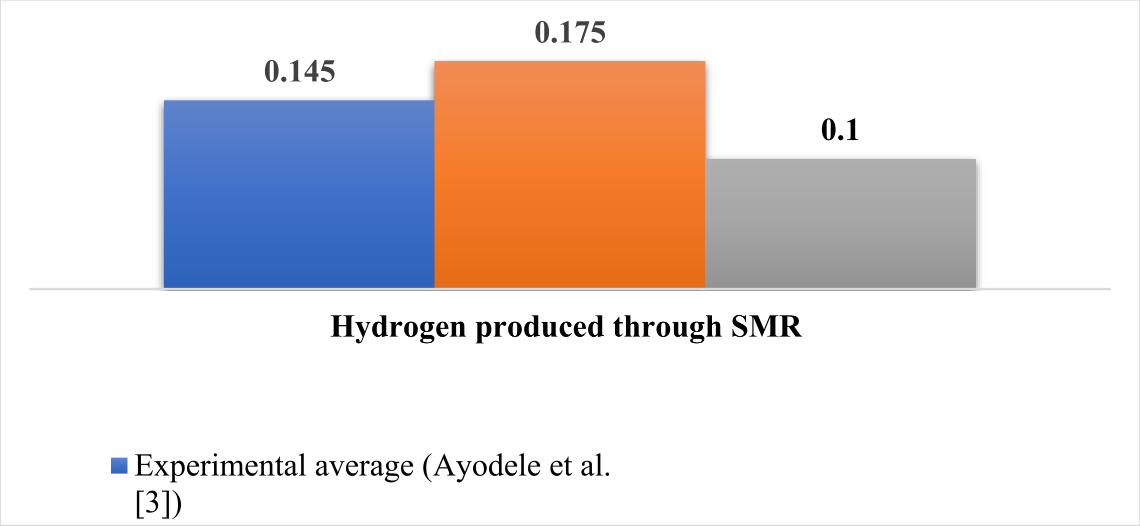


Figure 3.9: Validation of the simulation process

These deviations are attributed to a lower methane fraction or insufficient steam, an interpretation supported by Ganguli and Bhatt who demonstrated that both biogas quality and process configuration (S/C ratio, temperature, CO_2 content) are decisive for H_2 efficiency [123]. As Boscherini et al. demonstrated that a lower methane concentration in the feed gas reduces the only hydrocarbon substrate for steam reforming, directly limiting hydrogen formation [124]. Additionally, increased CO_2 content in biogas shifts reaction equilibria unfavourably and may inhibit catalyst activity, thereby diminishing overall conversion rates [125].

Then, to improve H_2 yield and align more closely with literature benchmarks, several recommendations emerge from the scientific community. The optimization of the biogas composition through pretreatment to increase methane content or CO_2 removal can significantly enhance performance [126]. Improved catalyst selection and reactor design optimization, including better heat integration and minimizing temperature gradients, have been shown by Sakthivel et al. to increase methane conversion rates and hydrogen selectivity directly [127] .

The utilisation of green H_2 is posited to generate clean industrial fuels and establish prospective export markets. Its incorporation into Togo's future energy mix has the potential to address chronic electricity shortages, reduce dependency on imported fossil fuels, and actively contribute to decarbonisation. Furthermore, as highlighted in the discussion by Dahsa et al. [128] the utilisation of H_2 can also supply the country's small-scale industries, such as cement and fertiliser production. This underscores the need to develop pilot plants based on cassava-derived biogas as a pivotal component of the nation's energy infrastructure. Furthermore, Togo's conversion of locally abundant feedstock into both biogas and hydrogen represents a tangible commitment to the Sustainable Development Goals (SDGs 7 and 13), offering a replicable model for energy-poor agrarian economies in Africa.

3.2.4. Biogas and hydrogen production LCA interpretation

3.2.4.1. Biogas production LCA interpretation

Methane emissions primarily drive the climate change impact of 13.64 kg CO_2-equivalent found in this study during AD, in addition to fossil CO_2 from energy inputs. The value obtained aligns closely with studies by Böhm et al. who reported climate footprints for agricultural residue-based biogas in the range of 10–30 kg CO_2-eq per functional unit and emphasized methane's dominant role at around 98% of total global warming potential [129] . This value is primarily due to methane emissions that occur during the process, which are recognized as critical emission hotspots within biogas systems. The AP, quantified at 5.52×10^{-4} kg SO_2-eq, stems from SO_2 and NO_x emissions that contribute to ecosystem acidification. This result is consistent with the range reported by Laurent et al., who documented acidification impacts between 1×10^{-4} and 1×10^{-3} kg SO_2-eq for various bioenergy pathways, mainly due to SO_2 and NO_x emissions influencing ecosystem acid-base balance [130]. PMF, at 2.01×10^{-4} kg PM2.5-eq, primarily comes from sulfur dioxide (SO_2), nitrogen oxides (NO_x), and direct particulate emissions linked to feedstock handling and biogas processing. Similar values and reasons were also reported by Hauschild et al., highlighting these emissions as significant contributors to local air quality concerns with direct implications for human health [131]. The POF category totaling 1.45×10^{-4} kg NO_x-eq, mainly originates from reactive nitrogen oxides and volatile organic compounds (VOCs) released during feedstock management and fugitive gas leaks, consistent with typical profiles of biogas systems and regulatory concerns about urban and regional smog formation. The EP (4.21×10^{-5} kg P-eq) remains relatively low, reflecting the low phosphate and nitrogen emissions from biomass handling and digestate application. This aligns with findings by Isabel et al. who observed eutrophication potentials ranging from 1×10^{-5} to 5×10^{-5} kg P-eq and noted lower nutrient-related emissions for cassava peel-based biogas compared to manure-heavy or intensive agricultural feedstocks [103] . Figure 3.10 presents a comparative analysis between the critical threshold values for environmental impacts and the results obtained from the LCA of biogas production.

The LCA of biogas production from CP reveals considerably lower burdens. These values remain substantially below established critical thresholds, suggesting that the biogas production process from CP poses limited ecological risks in these impact categories and can be considered environmentally acceptable within those dimensions. The results confirm the importance of integrated methane leakage control, air emission treatment, and nutrient management in digestate. This comprehensive understanding provides a reliable benchmark for assessing the environmental performance of AD of CP in Togo. It supports ongoing improvements through better operational practices and emission reduction strategies.

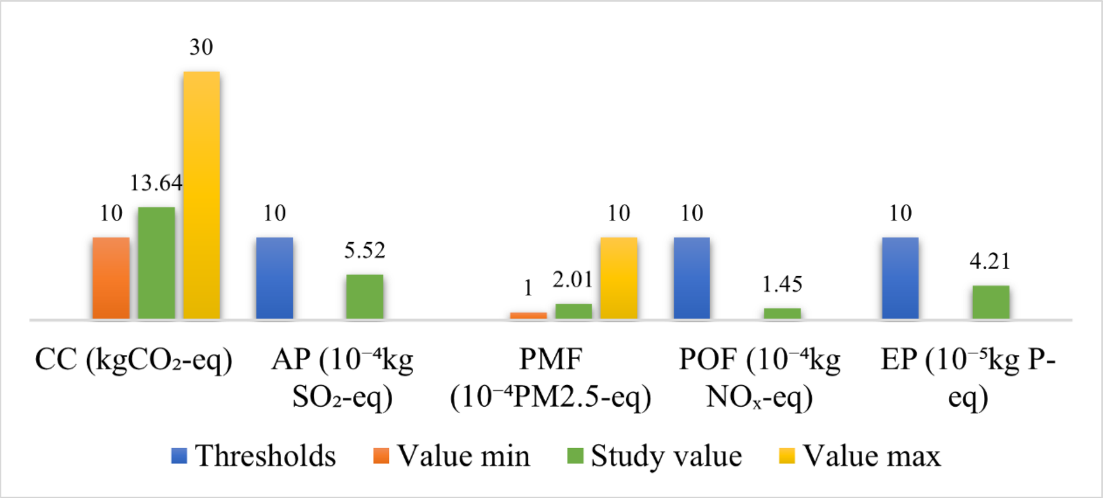


Figure 3.10: Positioning of cassava peel biogas within the reported emission range

3.2.4.2. Hydrogen production LCA interpretation

The CC potential accounting of 3.82 kg CO_2-eq per kg H_2 in this study is mainly caused by methane slip (~0.06 kg CH_4), whose strong radiative forcing effect made even small fugitive emissions necessary to control; this aligns with studies such as Kanz et al. [132], emphasizing methane management as key to maximizing climate benefits. This value falls within the lower-to-medium range reported in the literature for biogas-based hydrogen, which typically spans 2.3–6.6 kg CO_2-eq/kg H_2, depending on CH_4 management and energy sourcing. It is significantly lower than conventional natural gas SMR (8.3–12 kg CO_2-eq/kg H_2), according to the International Energy Agency (IEA) [133] and Martínez-Ramón et al. [134], demonstrating a reduction ranging between 59% and 68% compared to fossil-fuel-derived hydrogen. The comparatively low value in this study is attributed to the use of renewable feedstock and a limited CH_4 slip. However, in practice, higher slip rates could substantially increase the climate impact, as each kg of CH_4 equals 34kg of CO_2-eq. The AP, caused by sulfur dioxide and nitrogen oxides released during reforming and combustion [134], highlights the risk to soil and freshwater systems that can harm biodiversity and crop productivity if not mitigated. The value set at 0.0054 kg SO_2-eq/kg H_2 aligns well with values cited for biohydrogen (0.005–0.012) and is approximately 2–3 times lower than fossil SMR (0.01–0.015), reflecting both the lower sulfur content of biogas and the effectiveness of gas cleaning [135]. The value found in this study aligns with the range of 0.0015–0.003 from H_2 studies, mainly resulting from the combustion of auxiliary fuels. The PMF and the POF contribute to declining air quality, posing local to regional health risks through respiratory problems and ecological damage [135]. These findings highlighted the need for adequate controls on NO_x, SO_2, and volatile organic compounds. The measured POF of 0.0029 kg NO_x-eq/kg H_2 also matches biogas-based H_2 pathways (0.002–0.005 kg NO_x-eq/kg H_2) and is slightly lower than values from fossil fuel routes (0.004–0.008), again reflecting both feedstock effects and pollution control measures standard in biogas platforms. The modest EP, linked to phosphate and nitrogen discharges from biomass handling and digestate application [136], suggests nutrient runoff risks that could exacerbate algal blooms and further degrade aquatic ecosystems. This requires careful management of nutrients in upstream feedstock and waste treatment processes. The value obtained was at the lower end of the reported ranges for H_2 from wastes and residues (typically 3×10^{-4} to 6×10^{-4} kg P-eq/kg H_2), suggesting effective nutrient management and relatively low contributions from agriculture and runoff in this scenario [136]. Figure 3.11 presents a comparative analysis of the critical threshold values for environmental impacts and the corresponding results.

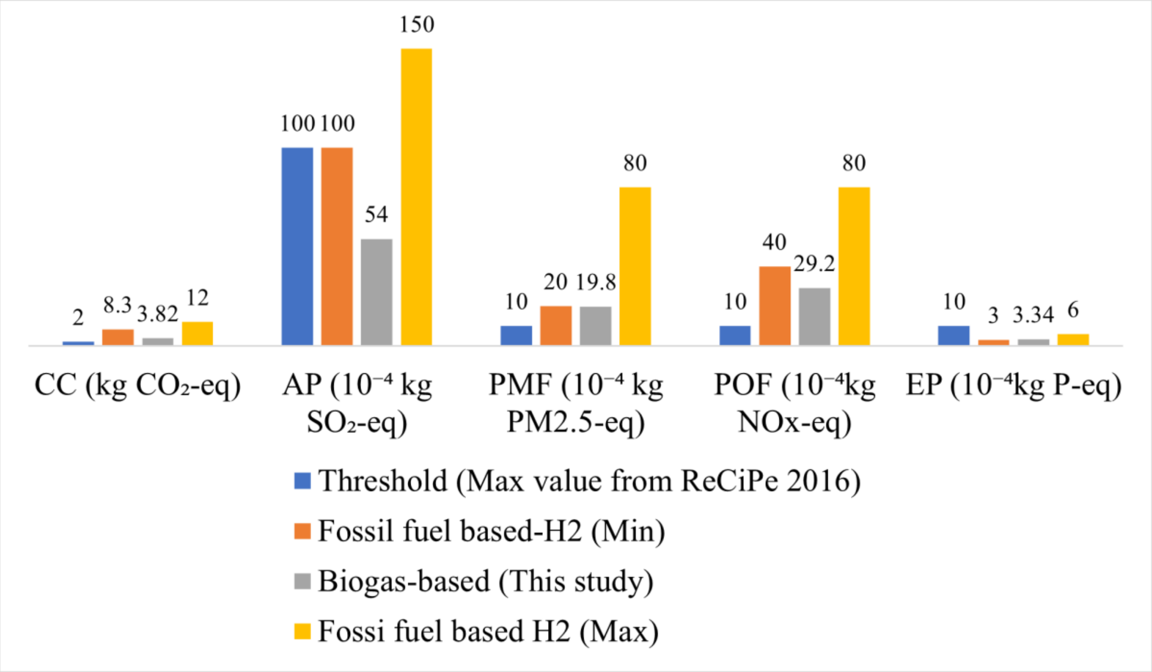


Figure 3.11: Biogas SMR vs. fossil fuels (ReCiPe 2016 Midpoint Indicators) comparison

These results suggest that while biogas-SMR hydrogen production has lower climate impacts than fossil fuel-based hydrogen, it presents complex environmental trade-offs that necessitate integrated strategies to mitigate methane emissions, control air pollutants, and manage nutrient flows to achieve genuinely sustainable hydrogen production.

The summary of these findings is presented in Figure 3.8, which compares environmental impacts between AD for biogas production and SMR for H_2 production. AD exhibits a significantly higher climate change (CC) impact (13.64 kg CO_2-eq) compared to SMR (3.82 kg CO_2-eq), primarily attributed to substantial fugitive methane emissions during biogas production, as supported by the literature. In contrast, SMR, when using biogas as feedstock, generally achieves a lower climate impact due to more efficient methane conversion and capture, assuming methane slip is effectively controlled.

However, for other impact categories such as acidification, particulate matter formation, and photochemical ozone formation, SMR shows higher impacts compared to AD. This results from

SMR’s energy-intensive conditions, including elevated fuel consumption and operating temperatures, which increase emissions of sulfur dioxide, nitrogen oxides, and particulates. These findings are consistent with the ones reported by IEA [137] that highlighted the trade-offs in air quality when comparing hydrogen from reforming versus direct biogas use. Regarding eutrophication potential, SMR has slightly elevated values linked to upstream nitrogen and phosphate releases during feedstock handling and conversion, mirroring trends reported in similar biomass conversion studies [138].

It is essential to note that the indicative environmental thresholds for these impact categories vary, with climate change having broader acceptable ranges compared to stricter limits for acidification and particulate emissions. Therefore, while SMR effectively reduces climate change impacts compared to AD, it tends to increase acidification and air pollution-related burdens, highlighting the complex environmental trade-offs inherent in renewable hydrogen technologies.

Overall, the compositional profile of CP supports its use in bioenergy systems, particularly AD and thermal conversion (SMR). However, optimization strategies, such as co-digestion and pre-treatment, may be necessary to fully harness their potential. H2 production simulated showed a good potential. The results highlight the importance of integrated life cycle assessment approaches in balancing reductions in greenhouse gas emissions with potential increases in other environmental impacts, thereby guiding process optimization and sustainable technology deployment.

➢ Recommendations

To fully harness the potential of cassava peels, several strategic actions are proposed:

- Policy support is essential to encourage investment in renewable bioenergy infrastructure, including financial incentives, capacity building, and development of regulatory frameworks that align with sustainable development priorities such as SDG 7 (clean energy access) and SDG 13 (climate action).
- Furthermore, life cycle thinking should be embedded in future project design to monitor and minimize environmental trade-offs and continuously promote resource efficiency.
- Lastly, engaging stakeholders through training and public awareness campaigns will foster the sustainable collection and utilization of cassava waste and enhance local acceptance of bioenergy technologies.

CONCLUSION & PERSPECTIVES

The present study evaluated the potential of cassava peels as a renewable feedstock for biogas and hydrogen production in Togo. The peels showed high organic content (91.03% volatile solids) and a carbon-to-nitrogen ratio of 88.9, confirming their suitability for anaerobic digestion. Biochemical methane potential (BMP) tests for biogas potential identified the 1:2 S/I ratio as optimal, yielding up to 469.5 mL CH_4/gVS. Hydrogen production via steam methane reforming, simulated using Aspen Plus software, achieved 99.99% purity with a yield of 0.10 kg/Nm^3. Life Cycle Assessment (LCA) revealed that CP valorization significantly reduces greenhouse gas emissions and fossil energy use, although SMR introduces higher acidification and particulate impacts. Overall, cassava peels offer a viable and sustainable pathway for integrated bioenergy systems, addressing energy insecurity, waste management, and climate goals in Togo.

Cassava peels represent a promising solution to address both energy insecurity and waste management challenges in Togo. Their high organic content and favorable biochemical properties make them suitable for biogas generation, while SMR enables conversion into high-purity hydrogen. The LCA results validate the environmental benefits of CP valorization, particularly in reducing climate change impacts. However, optimization is needed to improve hydrogen yields and mitigate secondary environmental effects. Additionally, co-digestion strategies and pretreatment methods are recommended to enhance process efficiency. Integrating CP-based bioenergy systems can contribute meaningfully to Togo’s energy transition and support national climate goals.

In sum, this work provides a foundation for leveraging cassava peels in Togo’s renewable energy agenda. It offers a replicable model for other agrarian economies aiming to address energy challenges through sustainable bioresource management, thereby advancing both environmental stewardship and socio-economic development.

➢ Future research

Future research could focus on innovative and strategic areas to accelerate the integration of cassava peels as bioenergy:

- Cost-effectiveness and market viability of the study
- Develop and test a large-scale system to assess real-world feasibility
- Combine solar or wind systems to enhance sustainability
- Explore enzymatic or biological pretreatment
- Initiate projects focused on wastewater treatment following cassava processing

References

---

[1] T. S. Phan, D. Pham Minh, F. Espitalier, A. Nzihou, and D. Grouset, “Hydrogen production from biogas: Process optimization using ASPEN Plus®,” International Journal of Hydrogen Energy, vol. 47, no. 100, pp. 42027–42039, Dec. 2022, doi: 10.1016/j.ijhydene.2022.01.100.

[2] D. Singh, P. Sirini, and L. Lombardi, “Green Hydrogen Production from Biogas or Landfill Gas by Steam Reforming or Dry Reforming: Specific Production and Energy Requirements,” Energies (Basel), vol. 18, no. 10, art. 2631, May 2025, doi: 10.3390/en18102631

[3] T. R. Ayodele, M. A. Alao, A. S. O. Ogunjuyigbe, and J. L. Munda, “Electricity generation perspective of hydrogen derived from biogas using food waste in south-western Nigeria,” Biomass Bioenergy, vol. 127, no. 2, art. 105291, Aug. 2019, doi: 10.1016/j.biombioe.2019.105291.

[4] D. M. C. Chen, B. L. Bodirsky, T. Krueger, A. Mishra, and A. Popp, “The world’s growing municipal solid waste: trends and impacts,” Environmental Research Letters, vol. 15, no. 7, art. 074021, Jul. 2020, doi: 10.1088/1748-9326/ab8659.

[5] D. C. Wilson and C. A. Velis, “Waste management - Still a global challenge in the 21st century: An evidence-based call for action,” Waste Management & Research, vol. 30, no. 8, pp. 755-757, Dec. 01, 2015, doi: 10.1177/0734242X15616055.

[6] D. W. Gafa and A. Y. G. Egbendewe, “Energy poverty in rural West Africa and its determinants: Evidence from Senegal and Togo,” Energy Policy, vol. 156, art. 112476, Sep. 2021, doi: 10.1016/j.enpol.2021.112476.

[7] G. Mutezo and J. Mulopo, “A review of Africa’s transition from fossil fuels to renewable energy using circular economy principles,” Renewable and Sustainable Energy Research, vol. 137, Art. 110609, Mar. 01, 2021, doi: 10.1016/j.rser.2020.110609.

[8] R. Yang, F. Wang, Z. Rao, C. Shen, and D. Li, “Advancing Sustainable Energy Solutions: Innovations in Clean Energy Applications and Conventional Energy Efficiency Upgrade,” Clean and low carbon energy, vol. 17, no. 10, art. 2441, May. 2024, doi: 10.3390/en17102441.

[9] M. Yasim and F. Buyong, “Comparison of experimental and theoretical biochemical methane potential generated by municipal solid waste,” Environmental Advances, vol. 11, art. 100345, Apr. 2023, doi: 10.1016/j.envadv.2023.100345.

[10] A. Vasavan, P. De Goey, and J. Van Oijen, “Numerical Study on the Autoignition of Biogas in Moderate or Intense Low Oxygen Dilution Nonpremixed Combustion Systems,” Energy and Fuels, vol. 32, no. 8, pp. 8768–8780, Aug. 2018, doi: 10.1021/acs.energyfuels.8b01388.

[11] A. A. Yussouff, W. A. Raji, S. Ajibade, S. O. Olowo, and A. O. Yussouff, “The Potential of Cassava Peel and Applicable Technologies for Sustainable Biogas-Bio Ethanol Production,”

Engineering and Technology Research Journal, vol. 3, no. 2, pp. 34–41, Sep. 2018, doi: 10.47545/etrj.2018.3.2.044.

[12] F. A. Aisien and E. T. Aisien, “Biogas from cassava peels waste,” Multidisciplinary Journal for Waste Resources and Residues, vol. 10, pp. 100–108, Jun. 2020, doi: 10.31025/2611-4135/2020.13910.

[13] A. Zappi, R. Hernandez, and W. E. Holmes, “A review of hydrogen production from anaerobic digestion,” International Journal of Environmental Science and Technology, vol. 18, pp. 4075-4090, Dec. 01, 2021, doi: 10.1007/s13762-020-03117-w.

[14] D. Pham Minh et al., “Hydrogen production from biogas reforming: an overview of steam reforming, dry reforming, dual reforming, and tri-reforming of methane,” Hydrogen Supply chain, pp. 111-166, 2018, doi:10.1016/B978-0-12-811197-0.00004-X.

[15] S. K. Dash, S. Chakraborty, and D. Elangovan, “A Brief Review of Hydrogen Production Methods and Their Challenges,” Energies, vol. 16, no. 3, art. 1141, Feb. 2023, doi: 10.3390/en16031141.

[16] J. Wang and Y. Yin, “Fermentative hydrogen production using various biomass-based materials as feedstock,” Renewable and Sustainable Energy Reviews, vol. 92, pp. 284- 306, Sept. 2018, doi: 10.1016/j.rser.2018.04.033.

[17] B. Zhu and C. Wei, “A Green Hydrogen Era: Hope or Hype?” Environmental Science & Technology, vol. 56, no. 16, pp. 11107–11110, Aug. 2022, doi: 10.1021/acs.est.2c04149.

[18] E. O. Fagbenle and D. O. Olukanni, “Production and purification of biogas from cassava peel using cow dung as inoculum,” Earth and Environmental Science, vol. 993, art. 012012, March 2022. doi: 10.1088/1755-1315/993/1/012012.

[19] F. Kemausuor, A. Addo, and L. Darkwah, “Technical and Socioeconomic Potential of Biogas from Cassava Waste in Ghana,” Biotechnology Research International, vol. 2015, pp. 1–10, Nov. 2015, doi: 10.1155/2015/828576.

[20] W. G. Adebayo, “Cassava production in Africa: A panel analysis of the drivers and trends,” Heliyon, vol. 9, no. 9, art. e19939, Sep. 2023, doi: 10.1016/j.heliyon.2023.e19939.

[21] “Ressources | Système Permanent d’Enquêtes.”, https://statagritogo.tg/stat/pages/ressources/advanced.html, accessed on May 19, 2025.

[22] FAOSTAT, “FAOSTAT.” 2025, https://www.fao.org/faostat/en/#data/QCL, accessed on May 19, 2025.

[23] J. Y. Kusi et al., “An Evaluation of Biogas Potential of Cassava, Yam and Plantain Peel Mixtures Using Theoretical Models and Hohenheim Biogas Yield Test-Based Experiments,” Energies (Basel), vol. 18, no. 4, art. 947, Feb. 2025, doi: 10.3390/en18040947.

[24] K. M. Oghenejoboh, H. O. Orugba, U. M. Oghenejoboh, and S. E. Agarry, "Value-added cassava waste management and environmental sustainability in Nigeria: A review," Environmental Challenges, vol. 4, art. 100127, August 2021, doi: 10.1016/j.envc.2021.100127.

[25] D. O. Olukanni and T. O. Olatunji, "Cassava waste management and biogas generation potential in selected local government areas in Ogun State, Nigeria," Recycling, vol. 3, no. 4, art. 58, 2018, doi: 10.3390/recycling3040058.

[26] Oparaku, F. N, Ofomatah, C. A, Okoroigwe, and C. E, "Biodigestion of cassava peels blended with pig dung for methane generation," Afr J Biotechnol, vol. 12, no. 40, pp. 5956–5961, Oct. 2013, doi: 10.5897/ajb2013.12938.

[27] A. Iulianelli et al., "Pure Hydrogen Production from Steam Reforming of Bio-Sources," International Journal of Membrane Science and Technology, vol. 2, no. 2, pp. 48–56, Dec. 2015, doi: 10.15379/2410-1869.2015.02.02.05.

[28] R. Gumisiriza, J. F. Hawumba, M. Okure, and O. Hensel, "Biomass waste-to-energy valorisation technologies: A review case for banana processing in Uganda," Biotechnology for biofuels, vol. 10, art. 11, January 2017, doi: 10.1186/s13068-016-0689-5.

[29] Ekop IE, Simonyan KJ, and Evwierhoma ET, "Utilization of Cassava Wastes for Value-Added Products: An Overview," International Journal of Scientific Engineering and Science, vol. 3, pp. 31-39, 2019.

[30] V. Okudoh, C. Trois, T. Workneh, and S. Schmidt, "The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review," Renewable and Sustainable Energy Reviews, vol. 39, pp. 1035-1052, November 2014, doi: 10.1016/j.rser.2014.07.142.

[31] T. Gmakouba, D. K. Dzidzienyo, S. Koussao, P. Tongoona, and I. K. Asante, "Identifying cassava production constraints, farmers' preferences, and cassava mosaic disease perceptions in Togo: insights for a participatory breeding approach," Agriculture & Food Security, vol. 13, no. 1, Dec. 2024, doi: 10.1186/s40066-024-00518-9.

[32] INSEED, "Togo - Enquête Harmonisée sur les Conditions de Vie des Ménages 2018-2019", Report generated on: September 1, 2022.

[33] T. Yenlide and M. K. N. Okey, "Inequality of opportunity in access to and consumption of modern energy in Togo: A parametric approach," Journal of Economic Inequality, vol. 22, no. 3, pp. 603–620, Sep. 2024, doi: 10.1007/s10888-023-09606-5.

[34] N. Nwokolo, P. Mukumba, K. Obileke, and M. Enebe, "Waste to energy: A focus on the impact of substrate type in biogas production," Processes, vol 8, no. 10, art. 1224, Oct. 2020 doi: 10.3390/pr8101224.

[35] P. Kohmuean, N. Boonrod, and A. Wongkoblap, “Biogas production from cassava waste: Effect of concentration,” IOP Conference Series: Materials Science and Engineering, vol. 778, art. 012115, Apr. 2020. doi: 10.1088/1757-899X/778/1/012115.

[36] Ukaegbu-Obi, “Bioconversion of Cassava Peels Via Anaerobic Digestion for Biogas Production,” International Journal of Research Publication and Reviews, vol 4, no. 8, pp. 1008-1014, August 2023

[37] I. Angelidaki, D. Karakashev, D. J. Batstone, C. M. Plugge, and A. J. M. Stams, “Chapter sixteen - Biomethanation and Its Potential,” Methods in Enzymology, vol. 494, pp. 327-351, 2021, doi: 10.1016/B978-0-12-385112-3.00016-0.

[38] Meegoda JN, Li B, Patel K, Wang LB. “A Review of the Processes, Parameters, and Optimization of Anaerobic Digestion,” International Journal of Environmental Research and Public Health, vol. 15, no.10, Oct. 2018, doi: 10.3390/ijerph15102224

[39] M. M. Uddin and M. M. Wright, “Anaerobic digestion fundamentals, challenges, and technological advances,” Physical Sciences Reviews, vol. 8, no. 9, pp. 2819–2837, Sep. 2023, doi: 10.1515/psr-2021-0068.

[40] Q. Sun, H. Li, J. Yan, L. Liu, Z. Yu, and X. Yu, “Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation,” Renewable and sustainable energy reviews, vol. 51, pp. 521-532, Nov. 2015, doi: 10.1016/j.rser.2015.06.029.

[41] Z. Rouhollahi, M. Ebrahimi-Nik, S. H. Ebrahimi, M. H. Abbaspour-Fard, R. Zeynali, and M. R. Bayati, “Farm biogas plants, a sustainable waste to energy and bio-fertilizer opportunity for Iran,” Journal of Cleaner Production, vol. 253, Apr. 2020, doi: 10.1016/j.jclepro.2019.119876.

[42] W. Czekała, M. Nowak, and W. Bojarski, “Characteristics of Substrates Used for Biogas Production in Terms of Water Content,” Fermentation, vol. 9, art. 449, May 01, 2023, doi: 10.3390/fermentation9050449.

[43] M. R. Atelge et al., “Biogas Production from Organic Waste: Recent Progress and Perspectives,” Waste Biomass Valorization, vol. 11, no. 3, pp. 1019–1040, Mar. 2020, doi: 10.1007/s12649-018-00546-0.

[44] A. Anukam, A. Mohammadi, M. Naqvi, and K. Granström, “A review of the chemistry of anaerobic digestion: Methods of accelerating and optimizing process efficiency,” Processes 7, no. 8, Aug. 01, 2019, doi: 10.3390/PR7080504.

[45] C. Zhang, H. Su, J. Baeyens, and T. Tan, “Reviewing the anaerobic digestion of food waste for biogas production,” Renewable and Sustainable Energy Reviews, vol. 38, pp. 383-392, 2014, doi: 10.1016/j.rser.2014.05.038.

[46] T. M. Anacleto et al., “Methane yield response to pretreatment is dependent on substrate chemical composition: a meta-analysis on anaerobic digestion systems,” Scientific Reports, vol. 14, art. 1240, 2024, doi: 10.1038/s41598-024-51603-9.

[47] D. Satterthwaite, “The implications of population growth and urbanization for climate change,” Environment & Urbanization, vol. 21, no. 2, pp. 545–567, Oct. 2009, doi: 10.1177/0956247809344361.

[48] A. Castellano-Hinojosa, C. Armato, C. Pozo, A. González-Martínez, and J. González-López, “New concepts in anaerobic digestion processes: recent advances and biological aspects,” Applied Microbiology and Biotechnology vol.102, pp. 5065–5076, Jun. 01, 2018, doi: 10.1007/s00253-018-9039-9.

[49] M. Laiq Ur Rehman, A. Iqbal, C. C. Chang, W. Li, and M. Ju, “Anaerobic digestion,” Water Environmental Research. vol. 91, no. 10, pp.1253-1271, Oct. 01, 2019, doi: 10.1002/wer.1219.

[50] S. Wang, G. L. Hawkins, B. H. Kiepper, and K. C. Das, “Treatment of slaughterhouse blood waste using pilot-scale two-stage anaerobic digesters for biogas production,” Renewable Energy, vol. 126, pp. 552–562, Oct. 2018, doi: 10.1016/j.renene.2018.03.076.

[51] S. Sarker, J. J. Lamb, D. R. Hjelme, and K. M. Lien, “A review of the role of critical parameters in the design and operation of biogas production plants,” Applied Sciences, vol. 9, no. 9, May 01, 2019, doi: 10.3390/app9091915.

[52] C. Zhang, H. Su, J. Baeyens, and T. Tan, “Reviewing the anaerobic digestion of food waste for biogas production,” Renewable and Sustainable Energy Reviews, vol. 38, pp. 383-392, 2014, doi: 10.1016/j.rser.2014.05.038.

[53] B. Fu, R. Conrad, and M. Blaser, “Potential contribution of acetogenesis to anaerobic degradation in methanogenic rice field soils,” Soil Biol Biochem, vol. 119, pp. 1–10, Apr. 2018, doi: 10.1016/j.soilbio.2017.10.034.

[54] L. M. Agneessens, L. D. M. Ottosen, M. Andersen, C. Berg Olesen, A. Feilberg, and M. V. W. Kofoed, “Parameters affecting acetate concentrations during in-situ biological hydrogen methanation,” Bioresour Technol, vol. 258, pp. 33–40, Jun. 2018, doi: 10.1016/j.biortech.2018.02.102.

[55] Zhe Lyu, Nana Shao, Taiwo Akinyemi, and William B. Whitman, “Methanogenesis’’, Current Biology, vol. 28, no. 13, pp. R727-R732, July 2018, https://doi.org/10.1016/j.cub.2018.05.021

[56] Zupančič and Grilc, “Anaerobic Treatment and Biogas Production from Organic Waste,” Management of Organic Waste.InTech, Feb. 01, 2012. doi: 10.5772/32756.

[57] Dr. Hilal Ezgi Toraman, Lesson 11: Additional Processes for Fuels from Biomass (11.1 Anaerobic Digestion), https://courses.ems.psu.edu/egee439/node/727, accessed on 22nd Oct 2025

[58] J. Yankyera Kusi et al., “Evaluation of Energetic Potential of Slaughterhouse Waste and Its Press Water Obtained by Pressure-Induced Separation via Anaerobic Digestion,” Energies (Basel), vol. 17, no. 22, art. 5522, Nov. 2024, doi: 10.3390/en17225522.

[59] Domínguez-Espinosa ME, Cruz-Salomón A, Ramírez de León JA, Hernández-Méndez JME, and Santiago-Martínez MG, “Syntrophy between bacteria and archaea enhances methane production in an EGSB bioreactor fed by cheese whey wastewater,’’ Frontiers in Sustainable. Food Systems, vol.7, art. 1244691, 2023, doi: 10.3389/fsufs.2023.1244691

[60] J. De Vrieze et al., “Inoculum selection is crucial to ensure operational stability in anaerobic digestion,” Appl Microbiol Biotechnol, vol. 99, no. 1, pp. 189–199, Jan. 2015, doi: 10.1007/s00253-014-6046-3.

[61] M. Srivastava, N. Srivastava, and R. Singh, “Clean Energy Production Technologies,” Bioenergy Research: Basic and Advanced Concepts, 2021, doi: 10.1007/978-981-33-4611-6

[62] P. Elefsiniotis and W. K. Oldham, “Influence of pH on the acid-phase anaerobic digestion of primary sludge,” Journal of Chemical Technology & Biotechnology, vol. 60, no. 1, pp. 89–96, 1994, doi: 10.1002/jctb. 280600114.

[63] L. Appels, A. Van Assche, K. Willems, J. Degrève, J. Van Impe, and R. Dewil, “Peracetic acid oxidation as an alternative pre-treatment for the anaerobic digestion of waste activated sludge,” Bioresour Technol, vol. 102, no. 5, pp. 4124–4130, Mar. 2011, doi: 10.1016/j.biortech.2010.12.070.

[64] E. Sánchez, R. Borja, P. Weiland, L. Travieso, and A. Martín, “Effect of substrate concentration and temperature on the anaerobic digestion of piggery waste in a tropical climate,” Process Biochemistry, vol. 37, no. 5, pp. 483–489, Dec. 2001, doi: 10.1016/S0032-9592(01)00240-0.

[65] J. N. Meegoda, B. Li, K. Patel, and L. B. Wang, “A review of the processes, parameters, and optimization of anaerobic digestion,” International Journal of Environmental Research and Public Health, vol. 15, no. 10, art. 2224, Oct. 11, 2018, doi: 10.3390/ijerph15102224.

[66] V. Moset, M. Poulsen, R. Wahid, O. Højberg, and H. B. Møller, “Mesophilic versus thermophilic anaerobic digestion of cattle manure: Methane productivity and microbial ecology,” Microb Biotechnol, vol. 8, no. 5, pp. 787–800, Sep. 2015, doi: 10.1111/1751-7915.12271.

[67] S. Weinrich and M. Nelles, DBFZ Report No. 40: Basics of Anaerobic Digestion - Biochemical Conversion and Process Modelling, pp. 9-76, ISBN: 978-3-946629-72-6

[68] L. Naik, Z. Gebreegziabher, V. Tumwesige, B. B. Balana, J. Mwirigi, and G. Austin, “Factors determining the stability and productivity of small-scale anaerobic digesters,” Biomass Bioenergy, vol. 70, pp. 51–57, Nov. 2014, doi: 10.1016/j.biombioe.2014.01.055.

[69] I. N. Azzahrani, F. A. Davanti, R. Millati, and M. N. Cahyanto, “Effect of Hydraulic Retention Time (HRT) and Organic Loading Rate (OLR) on the Nata de Coco Anaerobic Treatment Efficiency and its Wastewater Characteristics,” Agritech, vol. 38, no. 2, p. 160, Jul. 2018, doi: 10.22146/agritech.24226.

[70] K. Slimane, S. Fathya, K. Assia, and M. Hamza, “Influence of inoculums/substrate ratios (ISRs) on the mesophilic anaerobic digestion of slaughterhouse waste in batch mode: Process stability and biogas production,” Energy Procedia, vol. 50, pp. 57–63, 2014 doi: 10.1016/j.egypro.2014.06.007.

[71] A. Khadka et al., “Effect of the Substrate to Inoculum Ratios on the Kinetics of Biogas Production during the Mesophilic Anaerobic Digestion of Food Waste,” Energies (Basel), vol. 15, no. 3, Feb. 2022, doi: 10.3390/en15030834.

[72] S. Li, Y. Cui, Y. Zhou, Z. Luo, J. Liu, and M. Zhao, “The industrial applications of cassava: current status, opportunities and prospects,” Journal of Science & Food Agriculture, vol. 97, no. 8, pp. 2282–2290, Jun. 2017, doi: 10.1002/JSFA.8287.

[73] N. Ismail, N. F. Fauzi, A. Salehabadi, S. Latif, S. Awiszus, and J. Müller, “A study on biogas production from cassava peel and stem in anaerobic digestion reactor,” International Journal of Environmental Science and Technology, vol. 19, no. 3, pp. 1695–1704, Mar. 2022, doi: 10.1007/s13762-021-03222-4.

[74] T. Younus, A. Anwer, Z. Asim, and M. S. Surahio, “Production of Hydrogen by Steam Methane Reformation Process,” E3S Web of Conferences, vol. 51, art. 03003, 2018, doi: 10.1051/e3scconf/20185103003.

[75] W. W. Clark et al., “Hydrogen energy stations: Along the roadside to the hydrogen economy,” Util Policy, vol. 13, no. 1, pp. 41–50, 2005, doi: 10.1016/j.jup.2004.07.005.

[76] C. Coskun, M. Bayraktar, Z. Oktay, and I. Dincer, “Investigation of biogas and hydrogen production from wastewater of milk-processing industry in Turkey,” International Journal of Hydrogen Energy, vol 37, no.21, pp. 16498–16504, Nov. 2012, doi: 10.1016/j.ijhydene.2012.02.174.

[77] U. Izquierdo et al., “Biogas steam and oxidative reforming processes for synthesis gas and hydrogen production in conventional and microreactor reaction systems,” in International Journal of Hydrogen Energy, vol. 37, no.18, pp. 13829–13842, Sep. 2012, doi: 10.1016/j.ijhydene.2012.04.077.

[78] U. I. Amran, A. Ahmad, and M. R. Othman, “Kinetic-based simulation of methane steam reforming and water gas shift for hydrogen production using Aspen Plus,” Chemical Engineering Transactions, vol. 56, pp. 1681–1686, 2017, doi: 10.3303/CET1756281.

[79] M. Serhan et al., “Intermediate Temperature Water-Gas Shift Kinetics for Hydrogen Production,” AIChE Annual Meeting, Conference Proceedings, 2019. doi: 10.1039/x0xx00000x.

[80] D.-H. Hwang, Y.-S. Choi, and T.-W. Lim, “Performance analysis in water-gas shift reactor for hydrogen yield improvement,” Journal of Advanced Marine Engineering and Technology, vol. 47, no. 4, pp. 168–174, Aug. 2023, doi: 10.5916/jamet. 2023.47.4.168.

[81] M. A. J. Huijbregts et al., “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level,” International Journal of Life Cycle Assessment, vol. 22, no. 2, pp. 138–147, Feb. 2017, doi: 10.1007/s11367-016-1246-y.

[82] F. Cherubini, N. D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch, “Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations,” Resour Conserv Recycl, vol. 53, no. 8, pp. 434–447, Jun. 2009, doi: 10.1016/j.resconrec.2009.03.013.

[83] J. Cristobal-Garcia, F. Reale, S. Sala, and R. Pant, “Life cycle assessment for the impact assessment of policies,” JRC Technical Reports, 2016.

[84] M. C. Mwape, A. Parmar, F. Roman, Y. O. Azouma, N. M. Emmambux, and O. Hensel, “Determination and Modeling of Proximate and Thermal Properties of De-Watered Cassava Mash (Manihot esculenta Crantz) and Gari (Gelatinized cassava mash) Traditionally Processed (In Situ) in Togo,” Energies (Basel), vol. 16, no. 19, Oct. 2023, doi: 10.3390/en16196836.

[85] O. F. Odediran et al., “Awareness of Cassava Peel Utilization Forms among Cassava Processors in Rural Communities of Southwest, Nigeria,” International Journal of Applied Agriculture and Apiculture Research, vol. 11, no. 1-2, pp. 93-102, 2015.

[86] Adebayo K., Fabusoro E., and Fapojowo O. E., “Factors Determining Selective Adoption of the Cassava Grater and Screw Press in Southwest Nigeria,” An International Journal, vol.3, no. 1, pp. 40-51, 2008.

[87] F. Kemausuor, A. Addo, and L. Darkwah, “Technical and Socioeconomic Potential of Biogas from Cassava Waste in Ghana,” Biotechnol Res Int, vol. 2015, pp. 1–10, Nov. 2015, doi: 10.1155/2015/828576.

[88] K. Koch, S. D. Hafner, S. Weinrich, S. Astals, and C. Holliger, “Power and Limitations of Biochemical Methane Potential (BMP) Tests,” Front Energy Res, vol. 8, art. 00063, Apr. 2020, doi: 10.3389/fenrg. 2020.00063.

[89] M. Kawai, N. Nagao, N. Tajima, C. Niwa, T. Matsuyama, and T. Toda, “The effect of the labile organic fraction in food waste and the substrate/inoculum ratio on anaerobic digestion for a reliable methane yield,” Bioresour Technol, vol. 157, pp. 174–180, 2014, doi: 10.1016/j.biortech.2014.01.018.

[90] E. Elbeshbishy, G. Nakhla, and H. Hafez, “Biochemical methane potential (BMP) of food waste and primary sludge: Influence of inoculum pre-incubation and inoculum source,” Bioresources Technology, vol. 110, pp. 18–25, Apr. 2012, doi: 10.1016/j.biortech.2012.01.025.

[91] A. Rahbari, M. Ramdin, L. J. P. Van Den Broeke, and T. J. H. Vlugt, “Combined Steam Reforming of Methane and Formic Acid to Produce Syngas with an Adjustable H2:CO Ratio,” Industrial & Engineering Chemistry Research, vol. 57, no. 31, pp. 10663–10674, Aug. 2018, doi: 10.1021/acs.iecr.8b02443.

[92] G. Franchi, M. Capocelli, M. De Falco, V. Piemonte, and D. Barba, “Hydrogen production via steam reforming: A critical analysis of MR and RMM technologies,” Membranes (Basel), vol. 10, no. 1, art. 0010, Jan 2020, doi: 10.3390/membranes10010010.

[93] E. M. A. Mokheimer, M. I. Hussain, S. Ahmed, M. A. Habib, and A. A. Al-Qutub, “On the modeling of steam methane reforming,” Journal of Energy Resources Technology, Transactions of the ASME, vol. 137, no. 1, art. 012001, 2015, doi: 10.1115/1.4027962.

[94] J. Pryshlakivsky, C. Searcy, “Fifteen years of ISO 14040: a review,’’ Journal of Cleaner Production, vol. 57, pp. 115-123, 15 October 2013, doi: 10.1016/j.jclepro.2013.05.038

[95] B. Morero, R. Vicentin, and E. A. Campanella, “Assessment of biogas production in Argentina from co-digestion of sludge and municipal solid waste,” Waste Management, vol. 61, pp. 195–205, Mar. 2017, doi: 10.1016/j.wasman.2016.11.033.

[96] M. Teresa Costa-Campi and E. Trujillo-Baute, “trade-offs in energy and environmental policy,” Energy Policy, vol.104, pp. 415-418, 2017, doi: 10.1016/j.enpol.2017.01.053.

[97] H. Lin, A. Borrion, W. A. da Fonseca-Zang, J. W. Zang, W. M. Leandro, and L. C. Campos, “Life cycle assessment of a biogas system for cassava processing in Brazil to close the loop in the water-waste-energy-food nexus,” Journal of Cleaner Production, vol. 299, May 2021, doi: 10.1016/j.jclepro.2021.126861.

[98] N. I. H. A. Aziz and M. M. Hanafiah, “Life cycle analysis of biogas production from anaerobic digestion of palm oil mill effluent,” Renewable Energy, vol. 145, pp. 847–857, Jan. 2020, doi: 10.1016/j.renene.2019.06.084.

[99] Q. L. Wang, W. Li, X. Gao, and S. J. Li, “Life cycle assessment on biogas production from straw and its sensitivity analysis,” Bioresources Technology, vol. 201, pp. 208–214, Feb. 2016, doi: 10.1016/j.biortech.2015.11.025.

[100] R. A. Ibrahim, H. Inan, and I. S. Fahim, “A comparative cradle-to-gate life cycle assessment of three cotton stalk waste sustainable applications,” Scientific Reports, vol. 13, no. 1, Dec. 2023, doi: 10.1038/s41598-023-47817-y.

[101] T. Rehl, J. Lansche, and J. Müller, “Life cycle assessment of energy generation from biogas - Attributional vs. consequential approach,” Renewable and Sustainable Energy Reviews, vol. 16, no. 6, pp. 3766-3775, Aug. 2012. doi: 10.1016/j.rser.2012.02.072.

[102] N. Hansupalak, P. Piromkraipak, P. Tamthirat, A. Manitsorasak, K. Sriroth, and T. Tran, “Biogas reduces the carbon footprint of cassava starch: a comparative assessment with fuel oil,” Journal of Cleaner Production, vol. 134, no. Part B, pp. 539–546, Oct. 2016, doi: 10.1016/j.jclepro.2015.06.138.

[103] A. Isabel Nilsson, “Finding ways to develop a sustainable bioeconomy: The case of industrial cassava in Colombia: Environmental impact and food security insights from a combined life cycle assessment and interview study,” Degree Project in Energy and Environment, KTH Royal Institute of Technology, Stockholm, Sweden, 2023

[104] K. Rajendran, S. Aslanzadeh, and M. J. Taherzadeh, “Household biogas digesters-A review,” vol. 5, no. 8, art. 2911, 2012, Energies, doi: 10.3390/en5082911.

[105] N. Hajjaji, S. Martinez, E. Trably, J. P. Steyer, and A. Helias, “Life cycle assessment of hydrogen production from biogas reforming,” International Journal of Hydrogen Energy, vol. 41, no. 14, pp. 6064–6075, Apr. 2016, doi: 10.1016/j.ijhydene.2016.03.006.

[106] M. Abawalo, K. Pikoń, and M. Landrat, “Comparative Life Cycle Assessment of Hydrogen Production via Biogas Reforming and Agricultural Residue Gasification,” Applied Sciences (Switzerland), vol. 15, no. 9, art. 5029, May 2025, doi: 10.3390/app15095029.

[107] J. T. Hancock, “Oxygen: Highlights from the Papers Published in the Journal up to February 2024,” vol. 4, no. 1, pp. 117-121, Oxygen, Mar. 01, 2024, doi: 10.3390/oxygen4010007.

[108] D. Christianides et al., “Biogenic CO2 Emissions in the EU Biofuel and Bioenergy Sector: Mapping Sources, Regional Trends, and Pathways for Capture and Utilisation,” Energies (Basel), vol. 18, no. 6, art. 1345, Mar. 2025, doi: 10.3390/en18061345.

[109] K. Lehtoranta, H. Vesala, N. Flygare, N. Kuittinen, and A. R. Apilainen, “Measuring Methane Slip from LNG Engines with Different Devices,” Journal of Marine Science & Engineering, vol. 13, no. 5, art. 0890, May 2025, doi: 10.3390/jmse13050890.

[110] K. K. Kesari et al., “Wastewater Treatment and Reuse: a Review of its Applications and Health Implications,” Water, air & soil pollution, vol. 232, no. 208, art. 208, May 01, 2021, doi: 10.1007/s11270-021-05154-8.

[111] N. Cuzin, J. L. Farinet, C. Segretain, and M. Labat, “Methanogenic Fermentation of Cassava Peel Using a Pilot Plug Flow Digester technology, Bioresource Technology, vol. 41, no. 3, pp. 259-264, 1992, doi:10.1016/0960-8524(92)90011-L.

[112] I. B. Amaza, “Determination of proximate composition, amino acids, minerals and phytochemical profile of Cassava (Manihot esculenta) peel from sweet cassava variety grown

in Yobe State of North Eastern Nigeria," Nigerian Journal of Animal Production, vol. 48, no. 1, pp. 124–134, Feb. 2021, doi: 10.51791/njap.v48i1.2894.

[113] K. Parmar, "Biomass- An Overview on Composition Characteristics and Properties," IRA-International Journal of Applied Sciences, vol. 7, no. 1, p. 42, May 2017, doi: 10.21013/jas.v7.n1.p4.

[114] O. G. Igbum, A. C. Eloka-Eboka, and S. Adoga, "Feasibility study of biogas energy generation from refuse dump in a community-based distribution in Nigeria," International Journal of Low-Carbon Technologies, vol. 14, no. 2, pp. 227–233, Jun. 2019, doi: 10.1093/ijlct/ctz011.

[115] A. M. Aripin, A. Sari, M. Kassim, Z. Daud, M. Zainuri, and M. Hatta, "Cassava Peels for Alternative Fibre in Pulp and Paper Industry: Chemical Properties and Morphology Characterization," International Journal of Integrated Engineering, vol. 5, no. 1, pp. 30-33, 2013.

[116] Y. Li, Y. Jin, A. Borrion, and J. Li, "Influence of feed/inoculum ratios and waste cooking oil content on the mesophilic anaerobic digestion of food waste," Waste Management, vol. 73, pp. 156–164, Mar. 2018, doi: 10.1016/j.wasman.2017.12.027.

[117] K. O. Olatunji, N. A. Ahmed, and O. Ogunkunle, "Optimization of biogas yield from lignocellulosic materials with different pretreatment methods: a review," Biotechnology for Biofuels, vol. 14, art. 159, Dec. 01, 2021, doi: 10.1186/s13068-021-02012-x.

[118] M. Obodai et al., "Heavy metal and proximate composition associated with the composting of cassava (Manihot esculenta) peels used in the cultivation of mushrooms in Ghana," African Journal of Biotechnology, vol. 13, no. 22, pp. 2208–2214, May 2014, doi: 10.5897/ajb2014.13733.

[119] B. S. Adeboye et al., "Co-pyrolysis of cassava peel with synthetic polymers: thermal and kinetic behaviors," Waste Disposable & Sustainable Energy, vol. 3, no. 4, pp. 289–298, Dec. 2021, doi: 10.1007/s42768-021-00085-w.

[120] F. Raposo, R. Borja, M. A. Martín, A. Martín, M. A. de la Rubia, and B. Rincón, "Influence of inoculum-substrate ratio on the anaerobic digestion of sunflower oil cake in batch mode: Process stability and kinetic evaluation," Chemical Engineering Journal, vol. 149, no. 1–3, pp. 70–77, Jul. 2009, doi: 10.1016/j.cej.2008.10.001.

[121] A. Mukhtar, S. Latif, Z. Barati, and J. Müller, "Valorization of Cassava By-Products: Cyanide Content and Quality Characteristics of Leaves and Peel," Applied Sciences (Switzerland), vol. 13, no. 10, May 2023, doi: 10.3390/app13106340.

[122] W. Rogoski, G. N. Pereira, K. Cesca, D. de Oliveira, and C. J. de Andrade, "An Overview on Pretreatments for the Production of Cassava Peels-based Xyloligosaccharides: State of Art and

Challenges," Waste and Biomass Valorization, vol. 14, art. 2115-2131, Jul. 01, 2023, doi: 10.1007/s12649-023-02044-4.

[123] A. Ganguli and V. Bhatt, "Hydrogen production using advanced reactors by steam methane reforming: A review," Frontiers in Thermal Engineering, vol. 3, art. 1143987, Apr. 2023, doi: 10.3389/fther.2023.1143987.

[124] N. Majd Alawi, G. Hung Pham, A. Barifcani, M. Hoang Nguyen, and S. Liu, "Syngas formation by dry and steam reforming of methane using microwave plasma technology," Materials Science and Engineering, vol. 579, art. 012022, Aug. 2019. doi: 10.1088/1757-899X/579/1/012022.

[125] M. Boscherini, A. Storione, M. Minelli, F. Miccio, and F. Doghieri, "New Perspectives on Catalytic Hydrogen Production by the Reforming, Partial Oxidation and Decomposition of Methane and Biogas," Energies, vol. 16, no. 17, art. 6375, Sep. 01, 2023, doi: 10.3390/en16176375.

[126] S. Sakthivel, "Perspectives on CO2-Free Hydrogen Production: Insights and Strategic Approaches," Energy & Fuels, vol. 3, art. 156, Nov. 07, 2024, doi: 10.1021/acs.energyfuels.4c03156.

[127] M. J. Park, H. M. Kim, Y. J. Gu, and D. W. Jeong, "Optimization of biogas-reforming conditions considering carbon formation, hydrogen production, and energy efficiencies," Energy, vol. 265, art. 126273, Feb. 2023, doi: 10.1016/j.energy.2022.126273.

[128] R. Dahsa, M. Dymek, Y. Ben Belgacem, J. Lamloumi, C. Khaldi, and H. Bala, "Determination of H2O/H2 system exchange current densities on cycled hydride electrodes from overswitch potential jump at low and high charge/discharge rates," International Journal of Hydrogen Energy, vol. 48, no. 40, pp. 15203–15214, May 2023, doi: 10.1016/j.ijhydene.2022.12.315.

[129] J. Böhm, F. M. Holzheid, M. Schäfer, and T. Krexner, "Life cycle assessment of electricity from wind, photovoltaic and biogas from maize in combination with area-specific energy yields - a case study for Germany," Environmental Research Communication, vol. 6, no. 10, art. ad7dd9, Oct. 2024, doi: 10.1088/2515-7620/ad7dd9.

[130] A. Laurent et al., "Review of LCA studies of solid waste management systems - Part II: Methodological guidance for a better practice," Waste Management, vol. 34, no. 3, pp. 589–606, 2014, doi: 10.1016/j.wasman.2013.12.004.

[131] M. Z. Hauschild, Bjon Anders,"Cradle-to-gate and LCA'', Life Cycle Assessment - Theory and Practice, no. 1, pp. 605-631, 2018, doi.org/10.1007/978-3-319-56475-3.

[132] O. Kanz, K. Bittkau, K. Ding, U. Rau, and A. Reinders, "Review and Harmonization of the Life-Cycle Global Warming Impact of PV-Powered Hydrogen Production by Electrolysis," Frontiers in Electronics, vol. 2, art. 711103, Sep. 2021, doi: 10.3389/felec . 2021.711103.

[133] IEAGHG, “Low-Carbon hydrogen from Natural Gas: Global Roadmap’’, publication no. 2022-07, August 2022.

[134] N. Martínez-Ramón, M. Romay, D. Iribarren, and J. Dufour, “Life-cycle assessment of hydrogen produced through chemical looping dry reforming of biogas,” Int J Hydrogen Energy, vol. 78, pp. 373–381, Aug. 2024, doi: 10.1016/j.ijhydene.2024.06.288.

[135] S. Bakkaloglu and A. Hawkes, “A comparative study of biogas and biomethane with natural gas and hydrogen alternatives,” Energy Environmental Science, vol. 17, no. 4, pp. 1482–1496, Jan. 2024, doi: 10.1039/d3ee02516k.

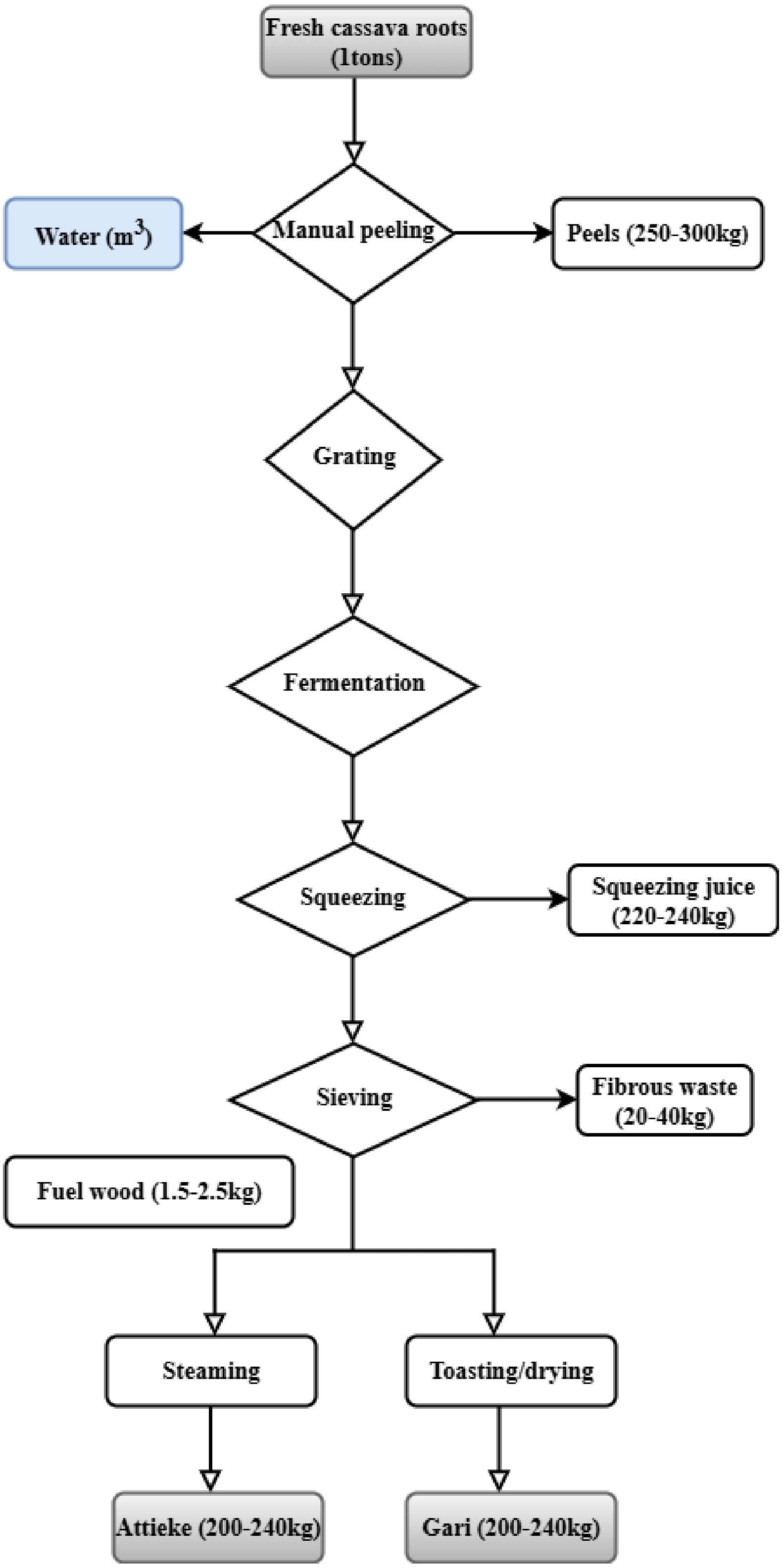
[136] S. Atilhan, S. Park, M. M. El-Halwagi, M. Atilhan, M. Moore, and R. B. Nielsen, “Green hydrogen as an alternative fuel for the shipping industry,” Current Opinion in Chemical Engineering, vol. 31, Mar. 01, 2021, doi: 10.1016/j.coche.2020.100668.

[137] IEA, “The Future of Hydrogen,”, Seizing today’s opportunities, 2019, accessed on 25th october 2025.

[138] A. Mio, E. Barbera, A. M. Pavan, A. Bertucco, and M. Fermeglia, “Sustainability analysis of hydrogen production processes,” International Journal of Hydrogen Energy, vol. 54, pp. 540-553, February 2024, doi: 10.1016/j.ijhydene.2022.11.044.

APPENDICES

Appendix A: Flow Chart of Attiéké and/or Garri Production with peel generation percentage



Source: Adapted from [29]

Appendix B: Kinetics involved in the hydrogen production simulation

Stage	Reaction kinetics	Sources
Reforming Reactor	$r_{SMR} = k_{SMR} \times P_{CH4}^{m} \times P_{H2O}^{n}$	[78]
HTWGS	$r_{HTWGS} = k_{HTWGS} \times P_{CO} \times P_{H2O}$	[79]
LTWGS	$r_{LTWGS} = k_{LTWGS} \times P_{CO} \times P_{H2O}$	[80]

In the table, r_{SMR}, r_{HTWGS}, and r_{LTWGS} are the reaction rate of respective stage in mol/s or mol/(m^3·s), and k_{SMR}, k_{HTWGS}, and k_{LTWGS} are the kinetic rate constant of respective stage.

P_{CH4}, P_{CO}, and P_{H2O} are the partial pressures of methane, carbon monoxide, and steam, respectively. The exponents m and n depend on catalyst properties and reaction conditions.

Appendix C: Pretreatment /Materials & methods

Appendix C1: Characteristics of inoculum & cellulose

Parameter (%)	Inoculum	Cellulose
MC	95.4	3.9
TS	4.6	96.1
AC	1.72	-
VS	2.8	96.02
FC	95.48	-

Appendix C2: Calculations for the BMP test setup

S/I	Inoculum (g)	$Q_{inoculum}$ (gVS)	Substrate (g)	$Q_{substrate}$ (gVS)	SC (gVS/l)
1:3	300	8.40	3.05	2.77	3.47
1:2	300	8.40	4.61	4.2	5.25
1:1	300	8.40	9.23	8.4	10.5
2:1	300	8.40	18.46	16.8	21

Appendix D: Formulas for biogas mass flow & steam mass flow calculations

Biogas mass flow rate

$$\text{Total biogas volume(L)} = \text{Biogas yield } (\frac{\text{L}}{\text{kgVS}}) \times \text{Mass VS processed(kgVS)}$$

$$\text{Total biogas moles} = 22.4 \left(\frac{\text{L}}{\text{mol}}\right) \times \text{Total biogas volume}$$

$$\text{Moles of component} = \text{Total biogas moles } \times \%\text{component}$$

$$\text{Mass of component} = \text{Moles X} \times \text{Molar mass of component}$$

$$\text{Biogas mass flow } (\frac{\text{kg}}{\text{day}}) = \sum \text{masses}$$

Steam mass flow rate

$$\text{Moles of Reactive Carbon } (\text{nC}_{\text{reactive}}) = \text{n}_{\text{CH4}} + \text{n}_{\text{CO2}}(\frac{\text{mol}}{\text{day}})$$

$$\text{Molar Flow Rate of Steam } (\text{n}^{\cdot}_{\text{H2O}})(\frac{\text{mol}}{\text{day}}) = \text{ S/C ratio} \times \text{nC}_{\text{reactive}}$$

$$\text{Mass Flow Rate of Steam } (\text{m}^{\cdot}_{\text{H2O}})(\frac{\text{kg}}{\text{day}}) = \text{n}^{\cdot}_{\text{H2O}} \times \text{Mass molar H}_2\text{O}$$

Appendix E: Results

Appendix E1: Comparison of root and tuber crop production in tonnes for 2023-2024 and 2022-2023

Culture	2022-2023	2023-2024	Variation of 2023-2024 compared to	Average 2018-2022	Variation of 2023-2024 compared to

			2022-2023 (%)		2018-2022 average (%)
Tubers	2,238,530	2,406,614	7.51	2,110,093	14.05
Cassava	1,224,614	1,326,783	8.34	1,158,857	14.49
Yam	984,614	1,050,387	6.68	923,794	13.70
Taro	19,355	19,511	0.81	18,214	7.13
Sweet potatoes	9,919	9,932	0.13	9,228	7.63

Source : [21]

Appendix E2: Comparison of root and tuber crop production in tonnes of each region from 2018 to 2024

Region	2022-2023	2023-2024	Variation of 2023-2024 compared to 2022-2023 (%)	Average 2018-2022	Variation of 2023-2024 compared to 2018-2022 average (%)
Maritime	416,369	449,631	8.00	399,507	12.5
Plateaux	307,131	434,694	9.5	370,377	17.4
Centrale	238,936	258,728	8.3	228,675	13.1
Kara	162,659	173,791	6.6	150,942	15.1
Savanes	9,546	9,939	4.1	9,356	6.2

Source : [21]

Appendix E3: CP characterization results

Proximate analysis		
Total Solids (TS)	97.61 (%FM) / 97.61 (%DM) / 100 (%TS)	%
Moisture Content (MC)	2.39	%FM

Volatile Solids (VS)	91.03 (%FM) / 93.26 (%DM) / 95.54 (%TS)	%
Ash Content (AC)	6.58 (%FM) / 6.74 (%DM) / 6.90 (%TS)	%
Fixed Carbon (FC)	2.39 (%FM) / 2.45 (%DM) / 2.51 (%TS)	%
Ultimate analysis		
Carbon (C)	42.4	% dry basis
Hydrogen (H)	6.13	% dry basis
Nitrogen (N)	0.477	% dry basis
Phosphorus (P)	0.12	% dry basis
Oxygen (O)	43.2	% dry basis
Sulfur (S)	0.4	% dry basis
C/N ratio	88.9	dry basis
C/P ratio	353.3	dry basis
Heavy metals		
Lead (Pb)	0.55	mg/kg
Manganese (Mn)	42.9	mg/kg
Copper (Cu)	3.55	mg/kg
Chromium (Cr)	21.1	mg/kg
Nickel (Ni)	8.04	mg/kg
Calorific value		
Gross calorific value	16,419 (as received) / 17,034 (dry)	KJ/kg
Net calorific value	15,043 (as received) / 15,698 (dry)	KJ/kg

Appendix E4: Final cumulative results of BMP tests

Final production (mL/gVS)	
1/3	433.9
½	469.5
1/1	450.2

2/1	112.7

Appendix E5: SMR process simulation results

Parameter	Value
Hydrogen purity	99.99 %
Hydrogen mole flow	1.19 kmol/h
Hydrogen mass flow	2.41 kg/h
Biogas feed rate	23.48 kg/h
Hydrogen yield	0.1 kg/Nm^3 biogas
Specific hydrogen yield	2.26 g/kg biogas
Co-produced water	30.77 kg/h
CO_2 in flue gas	~0.79 kmol/h
N_2 in flue gas	~2.40 kmol/h
O_2 in flue gas	~0.43 kmol/h

Appendix E6: LCA results of the AD process

Impact Category	Environmental Concern	Total impact
Climate Change	Global warming from GHG emissions	13.64 kg CO_2-eq
Particulate Matter Formation	Airborne fine particles affecting human health	2.01×10^{-4}kg PM2.5-eq
Photochemical Ozone Formation	Formation of ground-level ozone, a respiratory irritant	1.45×10^{-4}kg NO_x-eq
Acidification Potential	Ecosystem damage from acidic deposition	5.52×10^{-4}kg SO_2-eq
Eutrophication Potential	Water body impairment from nutrient loading	4.21×10^{-5}kg P-eq

Appendix E7: LCA results of the SMR process

Impact Category	Total impact
Climate Change	3.82 kg CO_2-eq/kg H_2
Acidification Potential	0.0054 kg SO_2-eq/kg H_2
Particulate Matter Formation	0.00198 kg PM2.5-eq/kg H_2
Photochemical Ozone Formation	0.00292 kg NO_x-eq/kg H_2
Eutrophication Potential	3.34×10^{-4} kg P-eq/kg H_2