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**Hydrogen Production Using Cashew Nutshells via
gasification for electricity generation in Guinea-Bissau**

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Declaration

I explicitly state that I have completed this thesis independently, relying solely on permitted, authorised sources and materials. I confirm that all information, data, and analysis included in this document have been obtained and utilised in strict accordance with the highest standards of academic honesty, ethical principles, and scholarly tradition. Additionally, I affirm that all materials, concepts, and findings not created by me are properly cited and referenced, reflecting my own work and intellectual effort.

Dedication

This is my master's thesis, respectfully dedicated to my God, parents, brothers, sisters, teachers, professors, all members of the WASCAL committee, friends, my pastors, and all those individuals who have stood steadfastly supporting me, emotionally, spiritually, morally, and economically, during my educational journey. Your unwavering guidance and endless motivation have been the cornerstones of this achievement. I am deeply grateful for pushing me beyond horizons and inspiring me towards the realisation of this milestone. It is with genuine hope that I believe this accomplishment fulfils the tremendous vision you envisioned for me and strengthens your trust in my capacity, even amid all the hardships I endured. And I thank God for all my answered prayers.

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Résumé

L'utilisation de déchets de coques de noix de cajou comme matière première pour la production d'hydrogène en Guinée-Bissau peut répondre à des préoccupations énergétiques et environnementales. Avec l'effort politique mondial axé sur la transition vers des sources d'énergie plus propres, l'hydrogène apparaît comme une alternative viable aux combustibles fossiles grâce à sa polyvalence et à ses émissions quasi nulles. Cependant, les sources renouvelables telles que le solaire et l'éolien sont confrontées à des problèmes d'intermittence, tandis que la Guinée-Bissau continue de souffrir d'un manque d'électricité dû à l'instabilité politique et à une gestion inadéquate des déchets. L'usine de noix de cajou d'Arrey Africa produit une grande quantité de déchets de noix de cajou non utilisés actuellement. Cette étude a proposé des solutions aux pénuries d'énergie et aux dommages environnementaux, notamment la transformation des déchets de noix de cajou en hydrogène, afin d'améliorer l'accès à l'énergie et de minimiser la pollution environnementale. Les coques de noix de cajou ont été collectées au Togo et leur caractérisation physico-chimique a été réalisée à l'Université de Rostock selon des procédures conformes aux normes ISO afin d'identifier leur composition élémentaire et immédiate. Le logiciel Aspen Plus est le logiciel le plus important pour cette étude. Il a été utilisé pour simuler le processus de gazéification avec les étapes suivantes: séchage, pyrolyse, gazéification et séparation. Catalyseurs hétérogènes K_2CO et CaO ont été proposés pour une application future, car ils peuvent maximiser le craquage du goudron, le reformage du méthane et le rendement en hydrogène. Un modèle cinétique basé sur six réactions majeures en régime permanent a été établi et validé par rapport aux données expérimentales avec une marge d'erreur de 8,79 % en utilisant RMSE. Les bonnes propriétés, qui comprennent une faible teneur en humidité de 6,3 %, une faible teneur en cendres, une teneur élevée en carbone et une teneur modérée en hydrogène avec respectivement 2 %, 55,7 % et 6,75 %, ont confirmé que les CNS sont un combustible de biomasse efficace. Les coquilles de noix de cajou disponibles pour la production d'hydrogène à l'usine d'Arrey Africa sont d'environ 1 215 tonnes par an. L'analyse de sensibilité a identifié la température comme le paramètre le plus influent sur le rendement en hydrogène, la pression ayant un effet négligeable. Sur la base de valeurs adaptées à l'étude expérimentale, la simulation a estimé la production d'hydrogène à 221.922 kg/h à partir de 1000 kg de CNS, combinée à l'efficacité des piles à combustible, proposée comme un moyen viable d'obtenir une énergie durable en utilisant l'hydrogène comme carburant, ce qui équivaut à une production d'énergie d'environ 26,630.64 MJ/h. La recherche suggère trois stratégies de gestion des CNSW : la planification, la formation et l'engagement des parties prenantes. Bien que les résultats soient encourageants, des limites sont liées à l'absence d'essais locaux, à l'omission de l'utilisation de catalyseurs dans la pratique et au manque d'analyse économique. Une validation et une optimisation pour l'application sont nécessaires.

Summary

The utilization of cashew nutshell waste as a feedstock for hydrogen production in Guinea-Bissau can address both energy and environmental concerns. With the political effort focusing globally on shifting towards cleaner energy sources, hydrogen emerges as a viable alternative to fossil fuels with its versatility and almost zero emissions, respectively. However, renewable sources such as solar and wind face intermittency concerns, whereas Guinea-Bissau continues to struggle with a lack of electricity, caused by political instability, and inadequate waste management. The Arrey Africa's cashew facility produces a high amount of CNSW, which is presently not being utilized. This study proposed solutions for energy shortages and environmental damages, the transformation of CNS into hydrogen, to enhance access to energy, and minimizing environmental pollution. The cashew nutshell was collected in Togo, and its physicochemical characterization, was carried out at the University of Rostock through ISO-standard procedures to identify its elemental and proximate composition. Aspen Plus software is the most important software for this study, it was used to simulate the hydrogen production based on the process of gasification with the following stages: drying, pyrolysis, gasification, and separation process. Heterogeneous catalysts, which included K_2CO_3 and CaO were proposed for future application, as they can maximize tar cracking, methane reforming, and hydrogen yield. A kinetic model based on six major reactions under steady-state conditions was established and validated against experimental data with an error margin of 8.79% using RMSE. The good properties, which include a low moisture content of 6.3%, a low ash content, high carbon content and moderate hydrogen content with 2%, 55.7% and 6.75% respectively, indicated as a results confirmed CNS is an effective biomass fuel. Cashew nutshells available for hydrogen production at the Arrey Africa facility are approximately 1,215 tonnes annually. Sensitivity analysis identified temperature as the most influential parameter on hydrogen yield, with the pressure having an insignificant effect. Based on adapted values to match the experimental study, the simulation estimated hydrogen production at 221.922 kg/h from 1000 kg of CNS, multiplied by LHV of hydrogen to obtain sustainable energy which was equivalent to an energy output of around 26,630.64 MJ/h, estimated theoretically. The research suggests three CNSW management strategies: Planning, education, and stakeholder engagement. Though the results are encouraging, limitations involve the absence of local testing, omission of catalyst use in practice, and lack of economic analysis. Validation and optimization for the application are required.

Abstract

Global development has made energy more vital across many sectors, including agriculture, industries, health, transportation, and communications, among others. Governments around the world are hoping to attain emissions reductions by converting power generation away from fossil fuels towards cleaner options such as biomass and hydroelectric power, supported by leading conversion technologies. This study characterizes biomass as a substitute for fossil fuels through the use of the gasification process in the production of hydrogen. Cashew nutshells are explored as a potential biomass feedstock. Guinea-Bissau is one of the world's largest producers of cashews, where production is increasing and the government actively supports local processing to add value and create jobs. Cashew nutshells are a good, renewable biobased material, providing a profitable byproduct for energy or chemical production. It refers to the hard outer shell encasing the cashew seed, commonly known as the cashew nut. This shell is considered waste and is a non-edible part of the nut, containing various compounds, including cashew shell liquid, which is toxic if ingested and potentially harmful to the environment if it is not managed correctly. This study aims to evaluate the hydrogen potential in Guinea-Bissau and to reduce the environmental hazards posed by cashew nutshell waste. Aspen Plus was utilised to predict the yields of hydrogen and other compounds through simulation based on kinetic modelling, employing a multi-stage gasification system comprising drying, pyrolysis, gasification, and gas separation. The simulation also assessed the influence of pressure and temperature on gas yields in the Rplug reactor. Cashew nutshells were evaluated based on two criteria: theoretical potential and mobilizable potential, with the latter reaching over 60% annually, corresponding to 1,215 tonnes. The conducted simulation indicated that introducing 1,000 kg/h of cashew nutshells into the system could generate approximately 221.922 kg/h of hydrogen without using catalytic agents. Based on this hydrogen mass flow rate and its energy content, expressed as LHV, the theoretical energy output of the fuel cell system would be around 26,630.64 MJ/h. For effective waste management, stakeholder engagement, education, and planning have been suggested as key strategies. This study concludes that cashew nutshells with cold gas efficiency and carbon conversion efficiency, which were respectively 84% and 93.6%, represent a promising and sustainable biomass resource for hydrogen production via gasification, with results demonstrating that high-temperature conditions can facilitate effective hydrogen generation without catalysts.

Keywords: Cashew nutshell, gasification, simulation, hydrogen, energy, Guinea-Bissau.

ACRONYMS AND ABBREVIATIONS

ASPEN: Advanced system for process engineering

CCUS: Carbon capture, utilization, and storage

CE: Carbon conversion efficiency

CNS: Cashew nutshell

Co: cobalto

CO: Carbon monoxide

CO₂: carbon dioxide

CH₄ Methane

CH₃ amoniaco

°C: Celsius temperature degree

GDP: Gross domestic product

GE: Gasification efficiency

LHV: Lower heating value

HHV: Higher heating value

bar: unit of pressure

MJ: Mega joule

mJ: micro joule

Mo: molybdenum

MP: Methane Pyrolysis

MWh: mega watt hour

m²: meter square

Na₂CO₃: Sodium carbonate

NaOH: Sodium hydroxide

Ni: Nickel

NO_x: Nitric oxide

U.S: United States

SCWG: supercritical water gas

S: sulphur

S: second

SWM: Sustainable waste management

WGS: water gas shift

Wt%: wet humidity

KOH: Potassium hydroxide

SAF: Sustainable aviation fuel

SMR: Steam methane reforming

&: Symbol of and

%: Percentage

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Introduction

1. Background

Nowadays, with tremendous progress in almost all aspects of life, energy has become essential due to its importance in various sectors, such as agriculture, industry, health, transportation, and communication, and so on. Recent political efforts to reduce greenhouse gas emissions have incorporated the idea of transition, which refers to changes in electricity production from petroleum-based fuels to more environmentally friendly sources like biomass and hydroelectricity, by using crucial conversion technologies. This transition, therefore, involves the use of advanced technologies such as solar panels, wind turbines, hydroelectric power plants, and various biomass conversion methods to generate energy. These efforts demonstrate a commitment to increasing energy supply while supporting environmental conservation and making significant advances in decreasing reliance on oil and its derivatives [1]. However, it is important to recognize some challenges linked to renewable energy sources, particularly the issue of intermittency related to solar, hydro, and wind energy [2]. Concerning all these challenges mentioned, according to Marjani et al.[3], hydrogen has emerged as a promising alternative for providing clean, efficient, and cost-effective electricity. It facilitates better energy conservation and offers independence from the time of day and the seasons. Nazar et al.[4], confirmed that hydrogen is widely recognized as a cornerstone of decarbonization efforts due to its abundance, environmental compatibility, diverse production pathways, and broad applicability. According to Díaz González & Pacheco Sandoval [5], One potential approach involves the utilisation of biomass as an energy source to replace fossil fuels. Biomass can be converted into gaseous fuel through a process known as gasification, which is regarded as more environmentally friendly. Biomass gasification has proven to be a cost-effective method for extracting energy, as it can use cashew nut shells as a potential biomass. According to Sierra-Baquero et al [6], in recent years, Guinea-Bissau has become one of the world's leading producers of cashew nuts, with production expected to increase in tonnes in the coming years. The government actively encourages local cashew processing to enhance value addition and create jobs. however, this processing results in residues known as cashew nutshells, which are considered waste.

2. Problem statement

According to Díaz González & Pacheco Sandoval [5], Guinea-Bissau faces significant issues related to a lack of electricity and soil contamination caused by inadequate waste management, including waste from cashew nutshells. The electricity shortage is a pressing

concern that has persisted since the country gained independence in 1974. As the population has grown and expanded, coupled with ongoing political instability, the energy sector has encountered serious challenges in terms of infrastructure and the reliable supply of electricity to consumers. This situation is a direct result of the country's chronic political instability. The energy sector, which is crucial for its functionality, has deeply affected other sectors such as health (primarily due to insufficient lighting in hospital facilities), industry (which is hindered by a lack of large industrial enterprises), the environment and economy (largely due to the continued reliance on fossil fuels from other countries for energy supply and the effect on climate change are visible). Moreover, in the agricultural sector, particularly regarding cashew nuts, waste management practices are inadequate, resulting in severe consequences that directly impact the environment and daily life. The compounds of the cashew nutshell, combined with insufficient treatment, lead to increased contamination in cultivation areas, fields, water sources, and air pollution from the uncontrolled burning of this waste. This situation leads to the premature deaths of birds and poses health risks to humans due to the toxic smoke generated by these practices [7], [8], [9]. Based on the relevant points mentioned earlier, such as issues related to the lack of electricity and soil contamination caused by improper treatment of cashew nut waste, this study aims to find practical solutions to improve access to electricity and reduce cashew nutshell waste hazards. Guinea-Bissau also has a few associated issues in terms of considering producing hydrogen from cashew nutshells by gasification. Most prominent among them is limited local data; there is little evidence aimed at Guinea-Bissau regarding how much hydrogen is producible by CNS and whether this is applicable in terms of using it to power electricity locally. The insufficiency of local data creates a disconnect in terms of integrating waste-to-energy systems. Concerning the process modelling, Aspen Plus, among other tools, has been employed elsewhere. There is minimal published work that simulates CNS gasification of producing hydrogen under conditions that are representative of Guinea-Bissau, by considering feedstock variability, moisture content, ash content, locally available gasifying agents, and operating limitations. These technical constraints are related to environmental, waste, and energy issues. Few studies correlate cashew nutshell-based syngas, in particular, hydrogen production with real strategies for reducing and utilizing CNS wastes, taking into consideration country resources and disposal practices. Finally, there is insufficient guidance regarding how to utilize CNS-based hydrogen production in the energy plans of Guinea-Bissau. Grid constraints, finance systems, and explicit policy guidance make it difficult to understand how CNS-to-hydrogen can contribute to sustainable power generation in Guinea-Bissau.

3. General objective:

- To assess the hydrogen potential in Guinea-Bissau, as well as to mitigate the hazards of cashew nutshell waste on the environment.

3.1. Specific objectives:

- a) Evaluate the potential of cashew nut Shells as a biomass resource.
- b) Investigate the theoretical hydrogen potentials through the simulation using Aspen Plus.
- c) Assess the theoretical energy estimation.
- d) Discuss strategies for effective waste management.

4. Research questions

- a) What is the potential of cashew nutshells for hydrogen production via gasification in Guinea-Bissau?
- b) How can cashew nutshells via gasification improve energy access in Guinea-Bissau?
- c) What is the feasibility and efficiency of hydrogen for electricity generation in Guinea-Bissau?
- d) How to mitigate hazards related to the cashew nutshell waste?

5. Structure of the thesis

This master's thesis consists of three chapters, which include: Statement of knowledge, materials/methods, and results/discussion, in addition to the introduction, conclusion, study limitations, and references. The introduction outlines the research background, the problem statement, the research objectives (both general and specific), and the research questions.

Chapter 1. Provides a comprehensive summary of research conducted on cashew nut production in West African countries, with a focus on Guinea-Bissau. It defines key terms such as cashew nutshell, hydrogen, gasification, catalysts, and the optimisation process. It classifies types of gasifiers and discusses existing models. The chapter compares two catalyst types, such as homogeneous and heterogeneous, and how each can be utilised to produce hydrogen. At the end, it identifies the challenges related to biomass gasification and some applications of hydrogen.

Chapter 2. Outlines the materials and methods. This chapter provides a clear description of the study process, starting with an overview of the study area, feedstock characterisation, hydrogen potential assessment, feedstock analysis, kinetic model, application of the model simulator, assumptions, and the sequence of modelling.

Chapter 3. This chapter presents and discusses the results collectively, with particular emphasis on model validation, the two parameters temperature and pressure, which influence four main compounds of syngas, especially their impact on hydrogen yield, and the three main strategies developed for effective waste management.

Chapter 1. State of knowledge

Introduction

Biomass gasification is a promising clean energy technology that converts organic waste into syngas, particularly hydrogen, which is essential for decarbonising various sectors. The process is influenced by numerous technical and operational factors and still faces challenges such as tar production and ash management, necessitating ongoing research and optimisation. Cashew nutshell, a by-product of agricultural processing, offers a viable and sustainable biomass source, especially abundant in West Africa. Using CNS in gasification provides dual benefits: clean hydrogen production and economic development in regions, especially in countries like Guinea-Bissau, which are rich in biomass but face energy shortages. This approach can support both climate objectives and energy development sustainability.

1.1. Cashew nutshell as a biomass

Due to its high fruit consumption, the cashew tree (*Anacardium occidentale*) is a perennial plant widely cultivated in many tropical and subtropical regions. This tree is known as the cashew, which refers to its kidney-shaped fruit rich in fatty acids, proteins, and carbohydrates. The cashew tree belongs to the anacardiaceous family and is an evergreen species that can grow to heights of 8 to 20 metres, depending on soil and climate conditions. It comprises six genera and around 400 species of trees and shrubs characterised by branches with alternate leaves and resin production. It begins to flower in its third year and reaches full production by the eighth year, with a productive lifespan lasting 25-50 years. It thrives at altitudes up to 600 metres, in temperatures ranging from 15-35°C, and with annual rainfall of 600-3800mm. The cashew tree adapts well to dry conditions if its roots can access soil moisture and prefers deep, sandy soils, although it can grow in most soil types except those that are very dry during the nut maturation phase. The cashew tree is native to the tropical regions of Brazil and Mexico [10], [11].

Cashew nutshell, a part of the cashew tree or a byproduct of cashew processing, is recognised as one of the most versatile, renewable, biobased materials. It refers to the hard outer shell that surrounds the cashew seed, commonly known as the cashew nut. This shell is regarded as waste and is a non-edible part of the cashew nut, containing many compounds, including the oil called cashew shell liquid, which is toxic if ingested. It also contains four main components: anacardic acid, cardanol, cardol, and 2-methyl cardol. Depending on the extraction methods used, these constituents vary in concentration. The nutshell is often removed during processing, allowing the cashew seed to be extracted and prepared for use. In small-scale processing operations, shell residue makes up approximately 67.5% of the total nut weight, which can be utilised as a fuel source to generate thermal energy [12].



Figure 1: (A) the cashew tree, (B) leaves of the cashew tree, (C) the flowers of the cashew tree, (D) the cashew fruit with the nut, and all these figures A, B, C, and D are adopted from Otálora et al,[13]. The figure (E) is the cashew nutshells collected in Togo, Sokodé region

1.2. Potential of cashew nuts in West Africa

West Africa, also known as Western Africa, is the westernmost region of Africa. The United Nations defines Western Africa as the 16 countries located in West Africa, including: Benin, Burkina Faso, Cape Verde, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, The Gambia, and Togo. The population of West Africa is estimated at around 466,527,806 people, according to World Population Review [14].

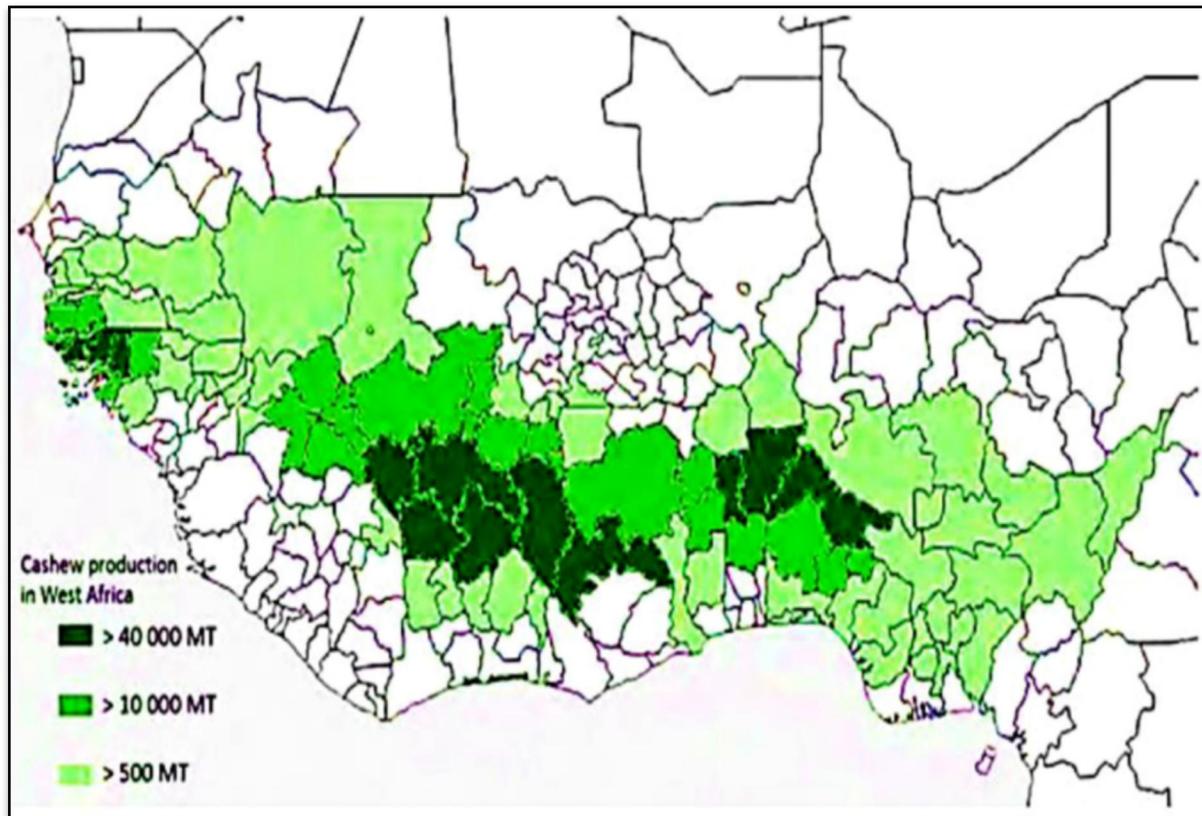


Figure 2: West African countries with more cashew nut potential in million tonnes, adopted from [15]

West Africa was regarded as the leading producer of cashew nuts in the world in 2018. The raw cashew nuts harvested in West Africa accounted for around 49% of the global supply. Since 2014, cashew has become the second most important crop after cocoa in terms of export value in West African countries. It is one of the key agricultural commodities that has significantly boosted Africa's GDP, foreign exchange earnings, and overall worth, driven by the increasing demand for raw cashew nuts. There are three main regions in West Africa where cashew is cultivated: the central region, which includes the Ivory Coast, Ghana, Burkina Faso, Guinea, Mali, and Togo; the eastern region, comprising Nigeria and Benin; and the western region, consisting of Guinea-Bissau, Senegal, and The Gambia. The most

prominent cashew-growing countries span these three regions, notably the Ivory Coast, Nigeria, Guinea-Bissau, Benin, and Ghana [16].

1.3. Potential of cashew nuts in Guinea-Bissau

West Africa is richly endowed with potential resources for renewable energy supply, and Guinea-Bissau is among the most resource-rich countries for energy generation. Recently, cashews have become the primary agricultural product of Guinea-Bissau due to the favourable soil and climate conditions, which are suitable for cashew cultivation. The export of cashew nuts accounts for between 85% and 90% of the country's total exports. To meet global demand, cultivating cashews (*Anacardium occidentale*) has become the primary economic activity for many rural families, comprising a significant portion of the population, as part of government initiatives. The process is manual, and efforts to boost productivity focus on expanding the cultivated land. Guinea-Bissau has established itself as the fifth-largest producer and exporter of cashew nuts worldwide, ranking among the top three producers and exporters in Africa. Approximately one-third of its land is covered by cashew trees. Due to the absence of a processing industry, Guinea-Bissau manages to export nearly 100% of its annual cashew nut production [17] [18] [6].

1.4. Concept and some properties of hydrogen

Hydrogen is a chemical element, a non-metal with the symbol H its molecular formula is H_2 (diatomic gas). It is a clean-burning fuel its main properties are presented in **Table 1**. Hydrogen is a colourless, odourless, tasteless, flammable gaseous substance that is the simplest of the family of chemical elements in the universe, and makes up only about 0.14% of earth's crust by weight. Hydrogen has three known isotopes, the most abundant being the main isotope mass of one called Protium (H or 1_1H), the mass two isotope is named Deuterium, or heavy hydrogen (2_1D or 2_1H) constitutes 0.0156% of the ordinary mixture of hydrogen and Tritium with the symbol (3_1T or 3_1H) one proton and two neutrons in each nucleus, and constitute about 10^{-15} to 10^{-16} percent of hydrogen. There are two types of molecular hydrogen known as Ortho and Para. These differ in the magnetic proton interaction due to the protons' spinning motions. In Orthohydrogen, the spins of both protons are aligned in the same direction, and in Parahydrogen, the directions of the spins are different. The relationship of spin alignment determines the magnetic properties of atoms [17] [18].

Table 1: The physicochemical Properties of Hydrogen are adopted from [21]

| Properties | Value |
|---------------------------------|-------------------------|
| Density at 25°C and 1.01325 bar | 0.089 kg/m ³ |
| Molecular weight | 2.016 g/mol |

| | |
|---|---|
| Viscosity at 25°C and 1.01325 bar | $0.89 \times 10^{-5} \text{ Pa}\cdot\text{s}$ |
| The diffusion coefficient in air | $6.1 \times 10^{-5} \text{ m}^2/\text{s}$ |
| Boiling point | -252.95 °C |
| Critical pressure | 13.0 bar |
| Critical temperature | -239.95 °C |
| Lower heating value | 120 MJ/kg |
| Autoignition temperature | 585 °C |
| Lower flammability limit | 4% (by volume in air) |
| Upper flammability limit | 75% (by volume in air) |
| Adiabatic flame temperature in air | 2044.85 °C |
| Minimum spark ignition energy | 0.02 mJ |
| Diffusion in pure water at 25°C and 1.01325 bar | $5.1 \times 10^{-9} \text{ m}^2/\text{s}$ |
| Research octane number | >130 |
| Thermal conductivity | $182 \times 10^{-3} \text{ W/m}\cdot\text{k}$ |
| Quenching distance | 0.64 mm |
| Density(liquid) at -253 °C and 1 bar | 70.79 kg/m^3 |
| Energy density (ambient cond, LHV) | 0.01 MJ/L |
| Specific energy (liquefied, LHV) | 8.5 MJ/L |
| Flame velocity | 346 cm/s |

1.4.1. Hydrogen production pathways

As it is known, there are many options for producing hydrogen from fossil fuels and renewable resources, depending on the biomass type, the need for it, and the purpose behind it, according to the U.S. Department of Energy's Hydrogen Program Plan [22], hydrogen can be produced from various domestic or forested renewable resources, as well as nuclear and fossil fuels, in large, centralised plants or smaller facilities close to the point of use. Hydrogen production methods are diverse, differing in their efficiency, processes, and environmental impacts. The most common method is Steam Methane Reforming, which accounts for approximately 80% of global hydrogen production. This process involves high-temperature reactions between natural gas, primarily methane and steam, producing hydrogen and carbon monoxide. Although SMR is cost-effective and well-established, it generates significant CO₂ emissions, categorizing it as a source of grey hydrogen. Similarly, partial oxidation produces

grey hydrogen through high-temperature reactions using limited oxygen but yields less hydrogen than SMR.

Emerging technologies are paving the way for more sustainable hydrogen production options. Turquoise hydrogen is produced via MP, which generates solid carbon instead of CO_2 , thereby reducing emissions and generating marketable byproducts like carbon nanotubes. Although still in the development stage and not yet commercially available, this method demonstrates significant potential for cleaner hydrogen. Conversely, brown and black hydrogen, produced from coal via gasification, are highly carbon-intensive, emitting up to 20kg of carbon dioxide by every kilogram of hydrogen produced. Despite their environmental impacts, these methods remain widely used in countries rich in coal, like China, although innovations like combining biomass with coal through co-gasification can improve hydrogen yields and waste management. Biomass and blue hydrogen provide promising low-carbon and transitional solutions for hydrogen production. Biomass gasification can be either thermochemical or biological, with thermochemical methods showing greater potential for scalability methods showing better potential for scalability. While some CO_2 emissions are involved in biomass-based hydrogen production, it can be considered carbon neutral when lifecycle emissions are fully accounted for. Blue hydrogen, produced from fossil fuels such as grey or brown hydrogen, incorporates (CCUS) technologies. Although it still depends on fossil resources, blue hydrogen significantly reduces emissions, serving as a practical bridge towards greener energy systems during the global energy transition [23].

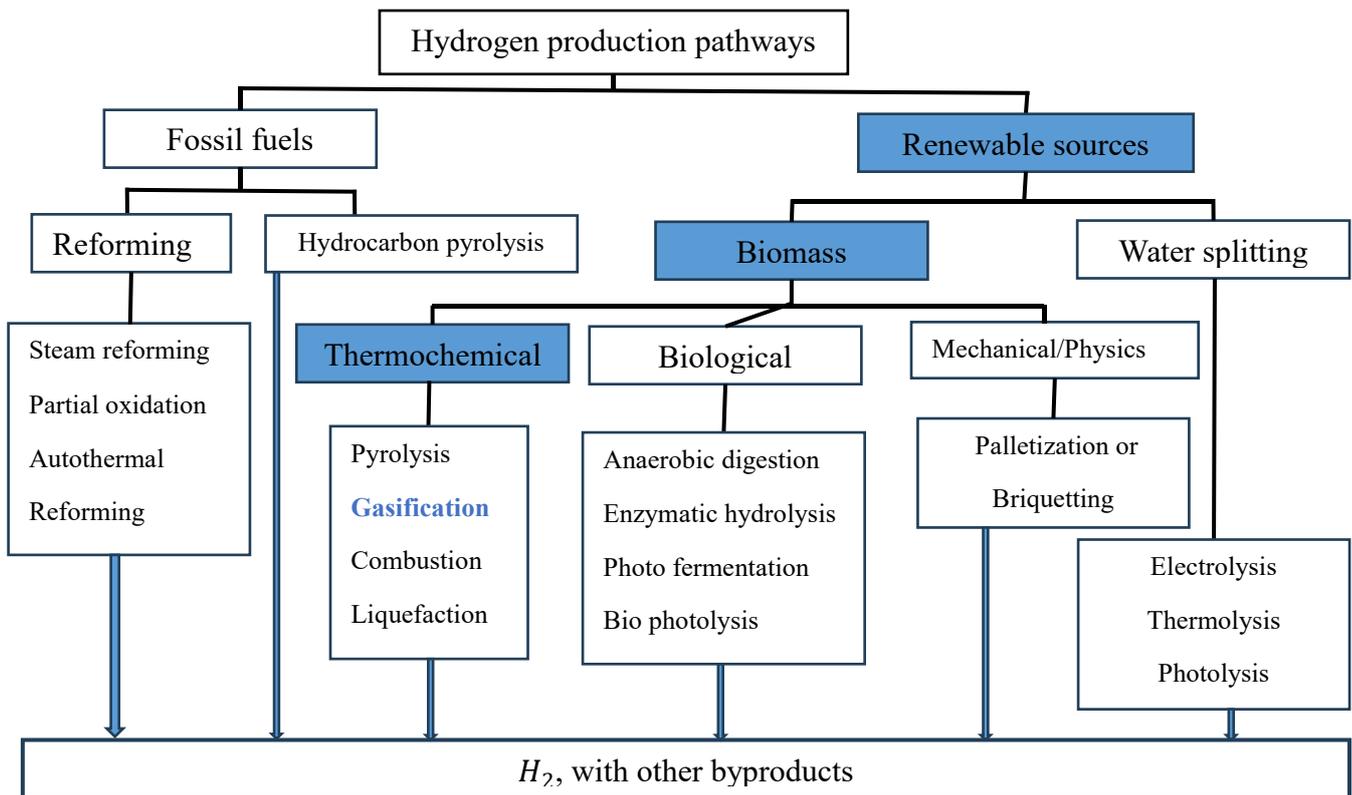


Figure 3: The hydrogen production pathways are adopted from,[22], [23], [24], [25].

1.5. Biomass gasification

The Gasification of carbon-rich materials may have been witnessed in human history as early as the invention of fire. In an oxygen-deficient environment, the ignition and burning of smoke are caused by smouldering materials such as coal, wood, straw, grass, and other organic matter. In 1792, the first industrial gasification system designed to produce electricity was documented. During the Second World War, there was a pressing need to find new feedstock due to the shortage of fossil fuels. This led to the development of the wood gas generator, which powered various motor vehicles, including agricultural machinery, trucks, buses, and cars. And then, when fossil fuels became abundant after WWII, the price automatically fell; only Sweden continued to pursue advancements in gasification technology, where they included the gasifiers into their strategic emerging plans in 1956 [23] [24]. Gasification is one of the thermochemical processes, it consists of partial oxidation of materials rich in carbon in a restricted oxygen atmosphere to produce gas fuels, known as syngas or synthesis gas. The syngas is composed of carbon monoxide (CO) and hydrogen (H_2) as the most abundant with a small quantity of carbon dioxide CO_2 , nitrogen (N_2), methane (CH_4) and other light hydrocarbons. The final products depend on several factors, including materials used, gasification technology adopted, and gasifier agents used, like air and steam [28]. According to Lian et al.[24], gasification is an intensive process of energy

that involves multiple reactions, including pyrolysis, char gasification, combustion of carbon residues, and cracking or reforming of tar, where the biomass is used as a feedstock and operates at high temperatures between 700°C to 1000°C. To Garcia et al.[30], thermal composition occurs in three primary stages. The first stage happens at a low temperature, from 30 to 200°C, and involves minimal mass loss, due to water and light volatile evaporation. The second stage, spanning 200°C to 400°C, involves the breakdown of hemicellulose, cellulose, and lignin, with the peak approximately at 330°C. The third stage, occurring around 500°C, pertains to the decomposition of carbon, reaching its maximum at this temperature. According to Buckner et al.[25], gasification is an advanced technology to convert biomass to syngas fuels under different atmospheres (Oxygen, air, steam, H_2 , CO_2 ...). The product syngas can also be used as precursors to synthesize valuable chemicals via Fisher-Tropsch reactions. This process as well can also be observed with two visual phenomena; firstly, thermal decomposition on the outer surface of the solid phase to release volatile and combustible components, which join thermal reactions in the gas phase, and second, the formation of flames. Differing from direct combustion, gasification limits the process at the first step to produce syngas.

The goal of the gasification process is to produce high-quality synthesis gas with a low tar level and toxic substances like ammonia, chlorine, and sulfur dioxide. Biomass type, reactor type, and operating parameters are the factors that affect the gasification process. Biomass with the ash content of less than 2% is not suitable for internal combustion, as it produces high tar, but it is best for updraft gasifiers. Downdraft Gasifiers are suitable for low-moisture biomass, and the tar gas that they generate is lower, though cooling is needed due to high operational temperatures. Fluidised Bed Gasifiers support a wide biomass range and produce a better quality of gas at a higher cost. Higher temperatures improve carbon conversion, reduce tar, and optimal management is crucial to initially increase hydrogen. Increasing pressure automatically decreases the tar and leads to an alteration of gas composition, potentially increasing nitrogen and carbon dioxide but reducing combustible gases. And gasifier agents are considered another parameter that influences the gasification process, such as air provides heat, producing moderate tars. Oxygen enhances carbon conversion and reduces tar, and the steam increases calorific value and hydrogen content. While raising calorific value reduces levels of gaseous such as CO_2 . Higher air/fuel ratio values can lower calorific value, but, particularly with steam, enhance hydrogen production and reduce tar, and

the optimal ratio is typically between 0.2 to 0.4, the range that helps in balancing energy content, hydrogen production, and tar reduction [5].

1.5.1. Some of the challenges in biomass gasification

Biomass gasification involves the thermochemical conversion of raw biomass materials (cashew nutshell, firewood, sawdust, wheat straw, and rice straw) into synthetic gas. The feedstock is typically shaped or crushed before being fed into a gasifier operating under deficient oxygen conditions [31]. Within the gasifier, pyrolysis, cracking, and reforming reactions produce syngas suitable for various applications, including heating, electricity generation, liquid fuel synthesis, and centralized gas supply systems. Lignocellulose biomass, especially crop residues, contains highly crystalline cellulose, hemicellulose, and lignin, which form a dense, complex chemical structure. These mentioned characteristics lead to the challenges related to the reduction of heating value by high oxygen content around 40 wt%, low energy density between 15-20 MJ/kg, which limits the transportation and storage. The complex structure results in high energy input during the gasification, excessive tar formation, and operational issues such as pipeline clogging and corrosion [32].

1.5.1.1. Biomass pretreatment

Pretreatment aims to modify the physical and chemical properties of biomass, thereby improving its reactivity and gasification performance. It reduces volatile matter, enhances grindability, increases energy density, and decreases the formation of undesirable byproducts like tar and ash. This process disrupts the fibre content matrices, decreases polymer crystallinity, and enlarges the effective surface area, facilitating more efficient gasification [31]. Non-lignocellulose biomass, such as sewage sludge and food waste, often contains high levels of nitrogenous compounds that produce pollutants such as NO_x , NH_3 , and hydrogen cyanide (HCN) during gasification. Pretreatment methods targeting nitrogen reduction help mitigate emissions. In addition, high moisture content increases energy consumption, making dewatering and drying essential before gasification. The pretreatment technologies are broad, including Physical, Chemical, physicochemical and biological pretreatment. Where physical pretreatment methods involve particle size reduction via mechanical crushing or microwave irradiation. These techniques increase surface area and decrease polymerization, but face limitations including inconsistent particle quality, high energy consumption, and equipment maintenance costs. Chemical approaches use acids, alkalis, ionic liquids, or organic solvents to hydrolyze chemical bonds, reduce crystallinity and promote biomass degradation and is an effective pretreatment method. Challenges include high chemical costs, environmental pollution from wastewater, and the need for the separation of solid and liquid after pretreatment, reagent recovery and biomass drying, these processes increase equipment costs and energy demand. This approach combines high temperature, pressure, and chemical reagents to effect physical and chemical modifications simultaneously. Torrefaction,

hydrothermal treatment, and steam explosion are the techniques that fall into this category. This process its success depends heavily on biomass particle size, crystallinity, high operating temperature, pressures raised, system complexity and costs. And the biological methods utilize microbial metabolism or enzymes to alter biomass structure. Anaerobic digestion of biomass like corn straw enhances the porosity, reduces inert components, increases gas yield, and significantly decreases tar production. This process offers cost advantages up to 44% cost savings and 25% higher net profits when combined with the thermochemical process, especially gasification [32].

1.5.1.2. Tar removal

Tar is a dark, highly viscous liquid, containing approximately 30% to 70% of water which is miscible with it. The presence of water negatively impacts syngas production when reintroduced into the gasifier. To mitigate this, researchers often dry the tar further before recycling it, thereby reducing its water content. In this experimental setup, a small quantity of tar enters the furnace, burns alongside the syngas, and produces soot. Over time, this soot hardens into a rock-like formation around the syngas outlet, leading to a blockage. The maximum allowed concentration in a reliably operated internal combustion engine should be less than $0.1\text{g}/\text{Nm}^3$. Tar compounds can lead to operational issues such as pipeline corrosion and blockage, as mentioned earlier, making their removal from syngas a necessary step before downstream processing. Tar elimination remains one of the most significant challenges in the effective utilization of produced syngas [33].

1.5.1.3. Ash handling

The large quantities of biomass ash that have been produced present significant handling and environmental challenges due to the high moisture content and mixture variability of biomass fuels. It is a dense material that can cause health and safety hazards during collection and transportation, especially since it contains reactive alkali metals that hydrate and pose tissue risks. The ash tends to accumulate in the combustion chamber, leading to operational issues, particularly fouling, slagging and agglomeration, because of low fusion temperatures caused by alkaline content, which fuse and adhere to equipment surfaces. Excessive ash production can reduce the boiler efficiency, increase maintenance costs, and cause plant shutdowns, rapidly escalating with rising biomass usage driven by increasing energy demand. Environmentally, biomass ash contains toxic trace elements such as mercury, lead, arsenic, and cadmium, which contaminate soil and water, increasing salinity and risking aquatic and plant life. Serious ecological concerns can be caused by the rise of large ash volumes, especially when ash is part of the landfill, potentially polluting waterways and air quality due to dust. Regulations and control technologies like the bag filters and electrostatic precipitators are implemented to mitigate these impacts, but current handling systems remain inadequate,

requiring advancements in storage, dewatering, and post-treatment to manage ash efficiently and reduce environmental risks while supporting the growing biomass energy sector [34].

1.6. Gasifiers classification

Gasification is a process that converts biomass or fossil fuels into synthetic gas. It is the process that takes place in reactors known as gasifiers, which vary in form and size, each offering distinct benefits and drawbacks. The suitable gasifiers depend on several factors, including the biomass type and its moisture content, as well as the gasification agents used (air, steam, or oxygen). In addition, the important factors include the gasifier operating temperature and the heat transfer mode, which can be either direct, meaning where the gasifier generates its heat or indirect, where heat is derived from an external source, such as circulating steam or an inert material [35]. The following **Figure 4** shows the gasification process flow that takes place inside the gasifier.

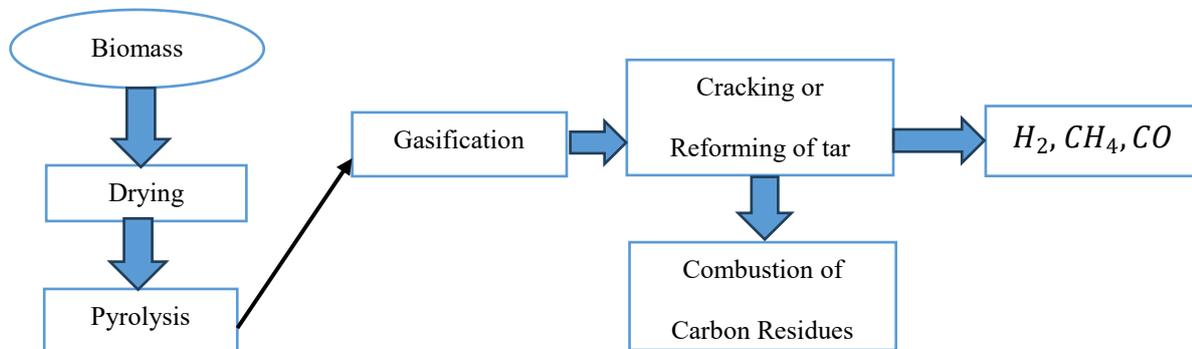


Figure 4: The scheme represents the flow step of the gasification process adopted from [24], [35].

According to Lian et al.[24], typical gasification reactors are categorized into entrained flow gasifier, fixed bed gasifier, and fluidized bed gasifier, as shown in the **Table 2**. For biomass gasification, Cvetinović et al.[36], said the most commonly preferred technologies are fluidized and fixed bed gasifiers, which have been developed and are currently in commercial operation by numerous companies. And according to them, in comparison, biomass entrained flow gasifiers have largely remained in the research phase; their technology is extensively utilized in industrial-scale coal gasification processes that include chemical synthesis, with capacities reaching several hundred MWh. Entrained flow gasification is favoured in these applications due to its higher availability, greater throughput, and superior quality of the produced syngas [36].

Table 2: Gasifiers types with their advantages and challenges

| Types of Gasifiers | Average tar levels in product gas (g/Nm ³) | Advantages | Challenges |
|--------------------|--|------------|------------|
| | | | |

| | | | |
|---------------------------|--------|--|--|
| Updraft | 10-150 | Simple construction High carbon conversion efficiency | Large tar production Potential channelling Low dust levels in gas Small feed size |
| Downdraft | 0.01-6 | Simple and robust construction High carbon conversion efficiency Only traces of tar in the product gas Cleaner gas is produced relative to the updraft. Gasifiers may be banked for long periods Low ash carry-over | Limits to scale up capacity High exit gas temperature Low thermal efficiency |
| Circulating Fluidized bed | 1-30 | High mixing and gas-solid contact High carbon conversion Good temperature control Can handle materials with different characteristics | Loss of carbon in the ashes Dragging of dust and ashes Restrictions on the size Relatively low process temperature to avoid phenomena of bed fluidisation High investment and maintenance costs. |
| Bubbling Fluidized Bed | 1-23 | Flexible process High carbon conversion Good ability to scale up High volumetric capacity | Corrosion and attrition problems Lower tar production Loss of carbon in the ashes High product gas temperature Restricted solid-gas contact, Complex technology and difficult control, Safety issues High start-up and investment |

| | | | |
|----------------|-----|---|--|
| | | | costs |
| | | | Requires the reduction of particle size and preparation supply |
| Entrained Flow | 0.2 | High gasification temperature Fast conversion of biomass takes place | The ash melts onto the gasifier walls, and is discharged as molten slag, High cost of materials of construction |

1.7. Gasification process optimization

Optimization techniques, according to Ahmad A. A et al.[37], can be utilized to identify the ideal conditions and/or geometric parameters that achieve the extreme of specified objective functions within predefined constraints. The objectives of an optimization process may include maximizing product yield or purity of end products, maximizing profit, minimizing the time of production, determining the optimal process configuration for maximum operational efficiency, selecting suitable catalysts to facilitate the process, selecting the best combination of raw materials to maximize profit, or minimizing the carbon emissions while meeting demand targets. According to Faizan & Song [38], once the catalysts have been successfully developed, their catalytic performance in biomass gasification should be evaluated within a well-designed gasifier. The design of the gasifier itself plays a crucial role in maximizing catalytic efficiency and yield. To optimize the reaction conditions, the gasifier must be made to order to specific requirements, considering factors such as moisture content, feedstock flow rate, ash content, particle size, shape, and operational needs.

1.7.1. Gasification catalysts

Catalysts are essential in biomass conversion, with their structural features and active sites influencing reaction efficiency, product specificity, and durability. These active sites are the main regions where chemical reactions occur, affecting the pathways and rates of biomass decomposition, deoxygenation, and hydrogenation processes. Gaining insight into the nature of the active site is vital for designing catalysts with high activity, selectivity, and lasting performance. The catalyst's effectiveness depends significantly on the density, strength, and accessibility of these active sites. During biomass conversion, there are different types of active sites, such as acidic, basic, and metallic, which drive various reaction pathways. Acidic

sites, often present in zeolites and metal oxides, facilitate dihydrogen, deoxygenation, and cracking, which are the key to upgrading bio-oil and lowering oxygen levels. The basic sites, such as those in alkali metal-doped catalysts, aid in CO_2 adsorption and biomass intermediate gasification, boosting syngas production and composition. Metallic active sites, especially involving transition metals like Ni , Co , and Mo , are crucial for hydrogenation and hydrodeoxygenation, improving the yield of hydrocarbon energy fuels [39]. According to Siddiqui et al.[40], in biomass gasification, choosing the right catalyst is crucial for achieving a high syngas ratio, increased hydrogen content, reduced tar formation, and optimal carbon conversion efficiency. To address these challenges, selecting a catalyst that effectively facilitates reforming reactions and meets practical demands is important. Ideally, such a catalyst should be affordable, highly capable of cracking tar, resistant to deactivation from carbon fouling and sintering, easy to regenerate, resistant to wear and attrition, and capable of reforming methane efficiently. To Alptekin & Celiktas [2], a catalyst is a substance that, when added in small amounts, speeds up a chemical reaction without itself being changed chemically. Effective catalysts lower the activation energy needed for gasification, thereby reducing both temperature and duration of the process, and achieving higher carbon conversion rates, which are advantageous for gasification. They also help decrease the necessary operating temperature and reduce tar formation during gasification.

1.7.2. Homogeneous catalysts

According to Faizan & Song [38], the impact of alkali metals like $KHCO_3$, K_2CO_3 , Na_2CO_3 , and $NaOH$ as catalysts on biomass SCWG has been widely documented. These catalysts are typically used to facilitate water gas shift (WGS) reactions. For example, $NaOH$ enhances hydrogen production and improves the efficiency of biomass gasification in the WGS process. Theoretically, hydrogen is generated during WGS when hydroxylated carbonyl compounds undergo decarbonylation, releasing CO and carboxylic acids to produce H_2 . Moreover, KOH enhances WGS reactivity in the presence of formic acid as an intermediate. While alkali catalysts can significantly boost hydrogen output, issues such as corrosion, scaling, and blockages in the system may also be caused by them.

1.7.3. Heterogeneous catalysts

Heterogeneous catalysis is crucial for biomass conversion, providing durable and reusable catalytic systems that enable selective transformation of complex biomolecules. Heterogeneous catalysts are typically solid, making them easier to separate and recycle. These catalysts, often made of metal oxides, zeolites, or carbon-based materials, improve reaction rates and process efficiency by offering active sites for chemical reactions. Gasification depends on heterogeneous catalysts to optimize syngas production by minimizing tar formation and increasing hydrogen output. Alkali and alkaline earth metal

catalysts, like calcium oxide (CaO) and potassium carbonate (K_2CO_3), boost the efficiency of gasification by promoting tar cracking and carbon dioxide reforming reactions [39].

1.7.4. Catalyst comparison

Homogeneous catalysts have demonstrated better catalytic performance than heterogeneous catalysts, primarily because they offer more active sites and eliminate barriers associated with physical transfer processes. Additionally, highly soluble homogeneous catalysts are easier to pump and tend to be more cost-effective compared to their heterogeneous counterparts. Heterogeneous catalysts are commonly employed in small-scale, complex, and large-scale industrial processes. This type of catalysis offers several benefits over homogeneous catalysts, including easier recovery after the reaction, a higher number of active sites that enhance efficiency during gasification, and increased selectivity toward producing desired products in specific reactions. Numerous studies documented in the existing literature have explored heterogeneous catalysis using various feedstocks [39], [40].

Table 3: List the gasifier types, their advantages, challenges and average tar level, is adopted from [24]

| Homogeneous | Heterogeneous |
|---|--|
| Same phase as the reaction medium. | Usually, a distinct solid phase |
| Insensitive to fatty acid and water content. | |
| Often difficult to separate | Readily separated |
| Expensive and difficult to recycle | Less expensive, readily regenerated and recycled |
| Not diffusion controlled | May be diffusion controlled |
| High selectivity | Lower selectivity |
| Short life and requires an extensive purification step. | Long life and fewer purification steps |

1.8. Modelling approaches for gasifiers

The gasifiers are constructed based on either experimental data or computational simulations. Important operating factors that greatly influence the gasification process include the flow rate of the feedstock and gasifying agent, the equivalence ratio, reactor temperature, and reactor pressure. Any alteration in these parameters significantly affects the composition of the produced gas and, consequently, the performance of the gasifier. Mathematical models are essential for accurately representing the chemical and physical processes within a gasifier [41]. Crucial factors in these models include pressure, temperature, flow velocity, density,

and species concentration. Fluid flow, molecular movement, and radiation are interdependent variables that vary dynamically due to ongoing chemical reactions. A model in the gasification process is considered effective depending on its realistic representation of various factors. Model formulation is crucial; trying simplification can lead to inaccuracies. Despite possible errors, mathematical models offer valuable insights into how to design, operate, and input factors impact gasifier performance. They also provide a cost-effective alternative to experimental methods. The main modelling techniques include broad thermodynamic, reaction kinetics, computational fluid dynamics(CFD), and data-driven modelling [35]. Kinetic and thermodynamic modelling is essential in biomass conversion processes to optimize catalyst design and improve process efficiency. Reaction kinetics offer valuable information about reaction rates, activation energies, and mechanisms of catalyst deactivation, which is essential for developing efficient and long-lasting catalytic systems. In contrast, thermodynamic modelling forecasts equilibrium product distributions, phase behaviour, and energy needs, helping to determine the best reaction conditions [39].

1.8.1. Thermodynamic modelling

The Gibbs free energy minimization principle forms the basis of equilibrium modelling, often referred to as zero-dimensional modelling. A gasifier achieves its most stable composition at chemical equilibrium, characterized by increased entropy and minimized Gibbs free energy. As a result, equilibrium models provide a standard for designing gasifiers, offering reliable predictions of the final composition and monitoring process parameters such as pressure and temperature. Equilibrium modelling can be classified into two categories: Stoichiometric and non-stoichiometric. Where the stoichiometric equilibrium models depend on all the chemical reactions and substances involved, while non-stoichiometric models focus solely on minimizing the Gibbs free energy system without specifying the exact reaction mechanism. Additionally, the moisture content and elemental composition of the feed must be determined, which can be achieved using the final analytical data from the feed [35]. Shaji et al. [42], utilized thermodynamic modelling through the Gibbs free energy minimization method to determine the specific energy needed (Energy per unit mass of syngas) for complete tar degradation. They also analyzed the post-tar reformulation composition of syngas, focusing on the concentrations of hydrogen and carbon monoxide, as different amounts of air were introduced into the reaction system. The raw syngas examined herein included tar, CO_2 , H_2 , CO , CH_4 , C_2H_4 , H_2O , O_2 , and N_2 . The tar investigated consists of a mixture of benzene (C_6H_6), toluene (C_7H_8), naphthalene ($C_{10}H_8$), phenol (C_6H_6O). The thermodynamic analysis assessed the impact of adding 0%, 5%, 10%, 15%, 20%, and 30% air on the raw syngas mass flow rate.

1.8.2. Kinetic modelling

Kinetic models offer insights into numerous factors that equilibrium models cannot address. These models are grounded in kinetic mechanisms that detail the chemical processes involved in biomass gasification, playing a vital role in the design, assessment, and enhancement of the gasifiers. They can predict various parameters, including residence time, gasifier design, fuel feeding rates, and the reactor hydraulics, by incorporating factors such as density, feedstock flow rate, particle size, temperature, pressure, and gasifier height. A methodology was developed that accounts for various operational variables, which were expanded to analyze syngas composition in downdraft gasifiers. However, they found limitations, including the overestimation of methane concentrations due to simplifications regarding oxygen consumption. These models are enhanced by introducing a variable char reactive factor to improve alignment with experimental data [35].

1.9. Application of hydrogen

About 96% of the world's hydrogen is produced from natural hydrocarbons, with only 4% generated through water electrolysis currently. Conventional hydrogen manufacturing relies heavily on significant mineral resources and energy inputs, and during this process contributes to environmental pollution [43]. The capacity of hydrogen to efficiently store and transport energy makes it a crucial element for the future of global energy systems. Its unique and adaptable properties enable various industrial applications vital for sustainability and energy efficiency, including: The chemical industry, metallurgy, transportation, the energy sector, and agriculture and food production. The main application of Hydrogen nowadays is in ammonia production. Using the Haber-Bosch process, which combines hydrogen and nitrogen to produce ammonia, is fundamental for manufacturing fertilizers that support modern agriculture. In addition, hydrogen is utilized in oil refineries to remove impurities like sulphur from crude oil, thereby enhancing fuel quality [44].

Linde [45], reported that, the steel industry accounts for around 5% of global CO_2 emissions, prompting key players like ArcelorMittal Europe to aim for a 30% reduction by 2030 and achieve carbon neutrality by 2050. Hydrogen is increasingly seen as a crucial solution for decarbonizing steel manufacturing, as it can replace fossil fuels in processes like DRI production and blast furnace operations, reducing emissions by up to 20%. Tests have shown that heating steel with hydrogen does not compromise its quality, paving the way for full-scale adoption in rolling mill furnaces.

Hydrogen plays a crucial role in chemical manufacturing, particularly in the production of ammonia and methanol, which are among the most significant industrial chemicals. The use of green hydrogen in these processes contributes significantly to reducing harmful emissions. Over 190 million tons of ammonia are produced annually worldwide, making green hydrogen a major sustainable alternative. In addition, hydrogen is vital for petrochemistry for the

desulphurization processes, further supporting industry decarbonization. Cryogenic technology enables the storage and transportation of liquid hydrogen, essential for scaling up green chemical production and industrial applications.

Transportation (road and public transit) accounts for around a quarter of global energy-related CO₂ emissions, with road vehicles contributing 70%, including cars, trucks, buses, and two- and three-wheelers. Hydrogen offers a powerful, zero-emission alternative to conventional fuels, especially for heavy-duty and public transit vehicles that return regularly to refuelling stations. Hydrogen-powered buses, trains, and trucks are already proving effective in reducing urban pollution. The Aberdeen fleet is the hydrogen buses a notable example. Hydrogen also underpins the future of airport transport and logistics, powering forklifts, buses, and trucks with green hydrogen. Its adoption in public transit accelerates infrastructure development, making decarbonization more achievable and effective across urban environments. Aviation remains one of the most challenging sectors for decarbonization, responsible for about 2.8% of global CO₂ emissions, and with emissions projected to triple if current trends continue. To address this, hydrogen offers promising solutions through the development of SAF produced via power-to-liquid processes, utilizing green hydrogen combined with renewable carbon sources. Hydrogen-based propulsion technologies, such as fuel cells and hydrogen combustion, are being explored by industry leaders like Airbus with projects like zero_e. Additionally, hydrogen plays a role in decarbonizing airport operations and logistics, replacing fossil fuel-powered equipment with green hydrogen solutions. For the wider renewable energy landscape, P2X tech enables the conversion of excess renewable electricity into versatile energy carriers like hydrogen, which can be stored, transported, and utilised across various sectors.

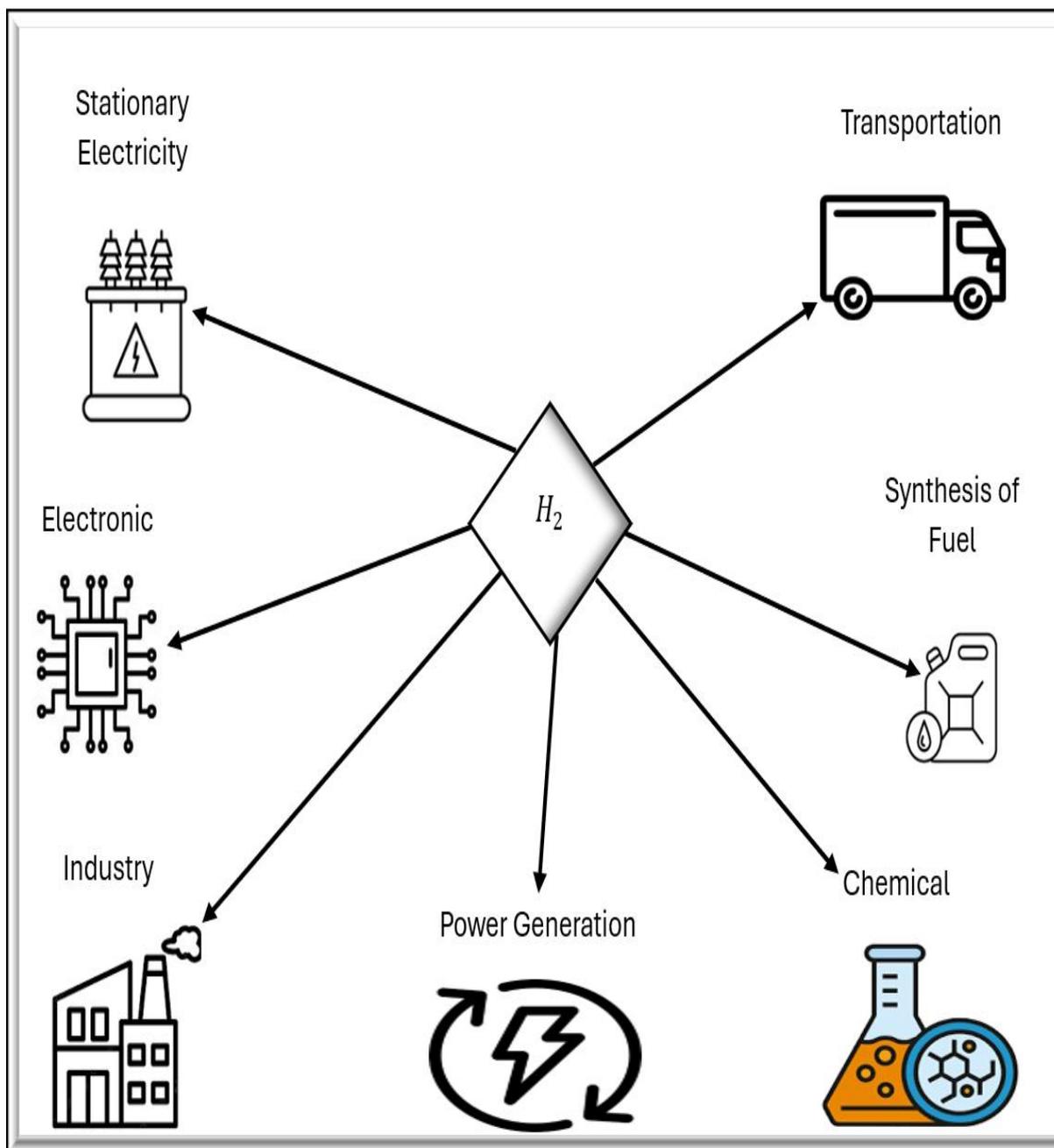


Figure 5: The hydrogen application adopted from [2]

Conclusion

Biomass gasification is a key element in renewable energy technology capable of producing rich syngas from organic materials, contributing significantly to energy transition goals. Cashew nutshells, abundant in countries like Guinea-Bissau and other West African nations, represent a valuable yet underutilised biomass resource. This study concludes that integrating CNS into hydrogen production via gasification can address two major challenges currently facing Guinea-Bissau: agricultural waste management and energy insecurity.

Chapter 2. Materials and methods

Introduction

Guinea-Bissau is one of the smallest countries in West Africa, but it is a vibrant country agriculturally, with concerns regarding cashew tree cultivation, bordered by Senegal and Guinea-Conakry. A nation with ample cashew production but poor energy infrastructure for renewable energy. Although there are more than 15 cashew processing facilities, cashew nuts are still available in massive amounts. Since CNS have high energy values, they can be used to produce hydrogen through biomass gasification. Through the utilisation of Aspen Plus and kinetic modelling, the study determines the viability of the process by conducting feedstock characterisation, simulation modelling, and sensitivity analyses analysis.

2.1. Study area

Guinea-Bissau is located in West Africa (12° 00' N, 15° 00' W), between Cape Roxo (latitude 12° 20'), Ponta Cajete (latitude 10° 59' N) and the meridians 13° 38' and 16° 43' W bordering the North Atlantic Ocean. It also borders Senegal to the north and Guinea-Conakry to the southeast. Guinea-Bissau is among the smallest countries on the continent, covering a total area of 36,125 square kilometers. Its population is estimated to be about 2,151,000 inhabitants. The population growth rate is 2.5% annually, increasing pressure on public resources and services. The geography primarily consists of coastal plains, with the Guinean forest savanna mosaic and Guinea mangroves as the main eco-regions [46] [47]. Regarding cashew nut processing, ANCA [48], reported that Guinea-Bissau has over 15 processing facilities for cashew nuts, with an estimated annual capacity of approximately 26,050 tonnes per year. These processing plants are in various sectors of different regions. This study relies on Arrey Africa, a medium-scale plant located in the Bula sector of the Cachéu region, which has a capacity of 3,000 tons per year of cashew nut processing. According to ACA [49], Arrey Africa uses Brazilian technology and operates without steam instead heating cashew nut shells directly in brick furnaces. This process causes CNSL within the nuts to swell and overflow, allowing its recovery for export. The remaining shells have two uses; about 40% are burned internally to fuel the furnaces, while the remaining shells are sent to the Noba Sabi distillery, where they are used as biomass fuel for their boiler, which also utilises sugarcane bagasse. This boiler produces superheated steam with a capacity of approximately 130 kW, mainly for onsite electricity.

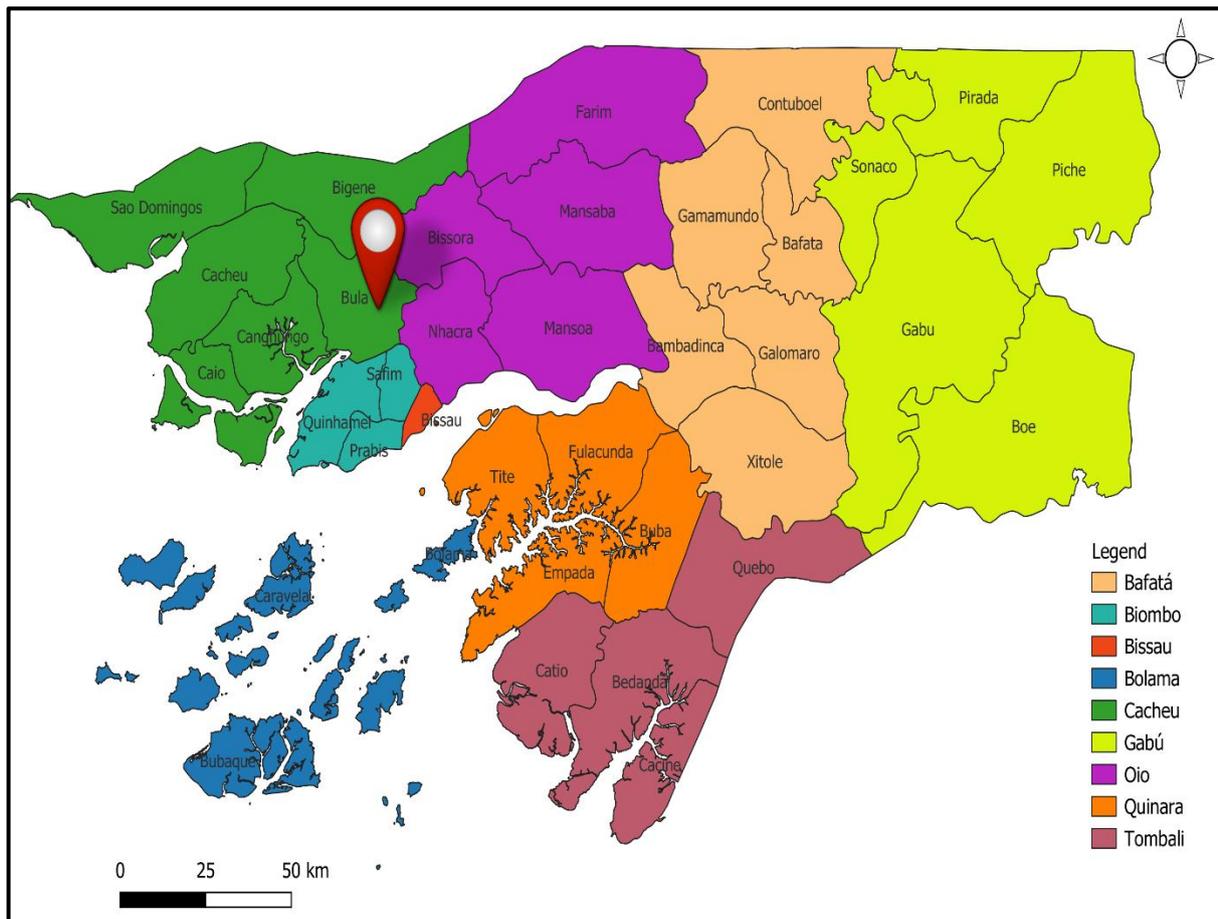


Figure 6: The map of Guinea-Bissau that locates the Arrey Africa cashew nut processing center

2.2. Data and cashew nutshells collection

For this present study, data were collected systematically from a diverse range of academic sources with a higher reputation, including well-established research platforms such as Google Scholar, Scopus, ResearchGate and others that are considered in the academic field. This extensive collection of relevant literature was considered to ensure a comprehensive and valuable foundation of information, thereby enriching the analysis and providing a strong understanding of the field and the topic under investigation. Cashew nutshells were collected as waste materials from the Sokodé region.

Figure 7: Cashew nutshells collected from Sokodé in Togo, specifically in an agro-industrial complex named Cajou du Center.

In Togo, concretely from the agro-industrial complex known as Cajou du Centre, the collection took place on 14th February 2025. Several key factors were considered to ensure the quality and suitability of the cashew nutshell waste for laboratory analysis, including the freshness of the waste, the collection not being more than three months after harvest, and the storage conditions, which were carefully managed to prevent deterioration. All these precautions serve a single purpose: to preserve the integrity of the samples and guarantee the reliability of the study.



2.3. Feedstock characterization

For the characterization of the CNS, its laboratory analysis was conducted at the University of Rostock, within the Agrar- und Umweltwissenschaftliche Fakultät, following the **DIN EN ISO 21663 (2021-03)** standard. The sample designated as 088-CS-25 comprises cashew nutshells and is classified as a derived fuel. It was received in a single bag within one container on 22 May 2025. A total of 70 g of the sample was used for testing, calculated on a dry basis, according to **DIN EN ISO 21656 (2021-06)**, section 8.2, which states that zero ingredients contribute to ash. The sample was ground to a nominal top size of 1 mm or less, based on the **ISO 21646** standard. Since the analysis focuses on dry basis samples, moisture content was measured according to **ISO 21660-3**. Equipment calibration involved following the manufacturer's instructions, stabilising the furnace and analyzers, and using 3 to 5 standards with increasing concentrations of the element. Calibration accuracy was verified

with a known standard, and performance was monitored through replicate analysis. Samples were weighed and processed following operational guidelines, and the results will be expressed as percentages of total C, H, N, and S. After calibration, calculations were performed based on the following equations below:

$$w_d(C) = w_d(C) \times \frac{100}{100 - w_{ad}(H_2O)} \quad (1)$$

$$w_d(N) = w_d(N) \times \frac{100}{100 - w_{ad}(H_2O)} \quad (2)$$

$$w_d(S) = w_d(S) \times \frac{100}{100 - w_{ad}(H_2O)} \quad (3)$$

$$w_d(H) = \left(w_d(H) \frac{w_{ad}(H_2O)}{8,94} \right) \times \frac{100}{100 - w_{ad}(H_2O)}, \quad (4)$$

An elemental Vario MACRO cube elemental analyzer was used for the measurement of Oxygen content, it was determined by difference according to **DIN 51733 (DIN 2016)** using the following formula:

$$O (\%) = 100 - C(\% db) - H (\% db) - N (\% db) - S (\%db) - Ash (\% db) \quad (5)$$

where **db** is dry basis.

Where: **d** → is dry basis, **ad** → is as determined, and **w_{ad}(H₂O)** → is the moisture content of the general analysis sample when analyzed.

For the proximate analysis, the determination of ash content was carried out according to **ISO 21656-2021** standard. A clean, empty dish was initially heated in a furnace at around 550°C for at least 1 hour to burn off all organic material. The dish was then cooled in a desiccator to prevent moisture absorption and weighed accurately to the nearest 0.1mg. These steps allow for precise measurement of the organic dry matter, which is crucial for analysing the composition and stability of CNS. The other values related to the proximate analysis, which included, have been provided from the Lab of the University of Rostock as well based on the following standard **ISO 250527**.

2.4. Assessment of hydrogen potential

Before assessing the hydrogen potential, the feedstock estimation is an important step to carry out in first step. Where the estimation of cashew nutshells' potential as a feedstock was based on the following parameters, including both theoretical and mobilizable estimations. The theoretical biomass potential is defined as the total maximum amount of terrestrial unprocessed biomass available within fundamental biological and physical constraints limits [50]. Mobilizable refers to the remaining part of biomass potential after considering the possible uses available under certain technical conditions related to existing technologies, or it refers to the fraction of the theoretical potential [51].

2.4.1. Theoretical estimation

Assessing the theoretical potential of cashew nutshells is a crucial step. Firstly, it is essential to determine the residue-to-product crop ratio of the biomass residue, such as cashew nutshells. This information can be found in the literature review. The RPR indicates the ratio of waste or byproduct generated from a specific process to its total output yield. RPR serves as an indicator of the potential amount of residue available for energy production [52]. The theoretical estimation has been carried out using the adapted equation below:

$$T_{pi} = A_{ai} \times RPR_i \quad (6) \quad [52]$$

Where: T_{pi} is the theoretical potential of a crop i , A_{ai} is the annual average yield of the crop i and RPR_i represent the RPR of the crop i .

2.4.2. Mobilizable estimation

Biomass is considered the solar energy stored in chemical form within plant and animal materials. It is one of the most valuable and adaptable resources on Earth, providing not only food but also energy, building materials, paper, textiles, medicines, and chemicals [53]. According to ACA [49], The cashew nutshells used by the Arrey Africa company, after processing, constitute about 40% of the total processed annually, leaving substantial residues in the storage area. This study considers the remaining 60% as a recoverable fraction to estimate the potential that can be mobilized. The technical potential calculation consider: Competing uses of crop residues, including animal feed, housing, and industrial applications. The estimation was performed using the adapted equation below:

$$M_{pi} = T_{pi} \times R_f \quad (6) \quad [51]$$

Where: M_p is the mobilizable potential of crop i , R_f refers to the recoverability of crop i based on several technical conditions.

2.4.3. Modelling and simulating hydrogen production

The design of a model for hydrogen production via gasification is one of the specific objectives of this study. The model is created through Aspen Plus to predict synthesis gases, particularly hydrogen from biomass gasification, taking into consideration gasification agents. Four main stages are involved in the biomass gasification model, which include drying, decomposition and pyrolysis, gasification, and the separation stage. According to Zina. J & Gogoro. G. B.[54], the developed Aspen Plus software model involves the following steps: specification of steam class, selection of property method, determination of the system component from data databank, specification of the conventional and non conventional components, specifying the process flowsheet by using unit operation blocks and connecting material and energy streams, defining feed streams (flow rate composition, and thermodynamic condition) and specifying unit operation blocks(thermodynamic condition and chemical reactions).

2.4.3.1. Kinetics modelling

A kinetic model estimates the gas yield and product composition in a gasifier over a specific volume and time, providing profiles of gas composition and temperature, along with overall performance under given operating conditions and configuration. Both reaction kinetics and hydrodynamics are considered in the gasifier. This approach is particularly important when long residence times are required for complete conversion, which occurs at low reaction temperatures with slow reaction rates. Generally, kinetic modelling is more accurate and suitable than equilibrium models at lower operating temperatures Baruah. D & Baruah. D. C [55]. The six chemical reactions that occur in OXI and RED reactors enable the conversion of biomass into desirable products such as CO , CO_2 , CH_4 , H_2 , H_2O . Based on the investigation of the theoretical hydrogen potential using Aspen Plus software, its validation will depend on comparison with other studies. Kinetic modelling in biomass gasification is vital for improving the efficiency of both the product and the reactor, reducing tar and pollutant formation, and scaling up from small to large scales. This model uses equations based on the principles of reaction kinetics to predict the concentration profiles of biomass.

The base of this model in biomass gasification relies on established rate laws that relate the rate of reactions, such as CO oxidation, methane partial oxidation, reforming of char, SMR, WGS, Boudourd, to the concentrations where the temperature is involved. A general biomass component occurs in gasification at the pyrolysis stage, and it is presented as an equation below:



[56]

In this model, the reactions are simplified by assuming that all responses are irreversible, which reduces to six denoted reactions, as shown in **Table 4**.

The description of each of the six reactions mentioned is made by using the Arrhenius equation to account for the temperature dependence of the reaction rates. According to the Arrhenius law, the rate constant K_r for each reaction, it is given by:

$$K_r = A \exp\left(-\frac{Ea}{RT}\right) \quad (8) [57]$$

Where: A is the pre-exponential factor, Ea is the activation energy, R is the universal gas constant, and T is the absolute temperature expressed in kelvin as a unit.

Thermogravimetric analysis is a dependable technique used to investigate the mechanisms and kinetics of biomass gasification [58]. TGA is a widely used thermal technique that measures how a mass of material changes with temperature, giving crucial insights into its thermal decomposition and stability. The primary output, the thermogravimetric (TG) curve, plots mass loss against temperature or time, revealing processes like decomposition, evaporation, or desorption. Beyond observing mass loss, TGA is valuable for studying reaction kinetics by analyzing the shape of the TG curve, the slope indicates the reaction rate. Kinetic analysis can be performed using isothermal or dynamic methods, with the former maintaining a constant temperature to assess reaction speed directly through differential thermal analysis (DTA) or differential thermal gravimetry (DTG) [59]. According to Smith et al.[60], after K_r was calculated by the Arrhenius equation, a kinetic model employing detailed reaction kinetics for all involved reactions is developed. The kinetic reaction rate for the species i in reaction r is expressed as:

$$r_{i,r} = K_r \prod_{i=1}^n [c_{i,r}]^{a_{i,r}} \quad (9) [60]$$

Where: $r_{i,r}$: represents the rate of reaction, $\prod_{i=1}^n [c_{i,r}]^{a_{i,r}}$ indicate the multiplication of the overall species, $c_{i,r}$: represents the volume substance concentration $a_{i,r}$: represents the total number of atoms entering the reactor, n : represents the element of ultimate analysis, r : reaction index, and i Species index.

2.4.3.2. Kinetic data collection

The main chemical reactions that occur in gasification and their exponent component are presented in the following **Tables 4** and **5**, and they were collected from the literature with some adjustments to facilitate the simulation process.

Table 4: Kinetic parameters of the main chemical reactions used in this gasification, adopted from [61]

| Reaction n° | Reactants-->Products | Reactions Names | A | E(J/Kmol) |
|----------------|--------------------------------|-----------------|----------|-----------|
| R1 | $CO + 0.5O_2 \rightarrow CO_2$ | CO oxidation | 2.24e+12 | 1.7e+0.8 |

| | | | | |
|----|---------------------------------------|---------------------------|----------|----------|
| R2 | $CH_4 + 1.5O_2 \rightarrow CO + H_2O$ | Methane partial oxidation | 5.01e+11 | 2.00e+08 |
| R3 | $C + H_2O \rightarrow CO + H_2$ | Reforming of char | 42.5 | 1.42e+08 |
| R4 | $CH_4 + H_2O \rightarrow CO + 3H_2$ | SMR | 5.92e+08 | 2.09e+08 |
| R5 | $CO + H_2O \rightarrow CO_2 + H_2$ | WGS | 2.35e+10 | 2.88e+08 |
| R6 | $C + CO_2 \rightarrow 2CO$ | Boudourd | 2224 | 2.20e+08 |

Table 5: Kinetic parameters of the main chemical reactions used in this gasification, adopted from [61]

| Reaction n° | H2 | O2 | CO | CO2 | CH4 | H2O | C |
|-------------|----|------|----|-----|-----|-----|---|
| R1 | - | 0.25 | 1 | 0.5 | - | - | - |
| R2 | - | 0.8 | - | - | 0.7 | - | - |
| R3 | - | - | - | - | - | 1 | 1 |
| R4 | - | - | - | - | 0.5 | 1 | - |
| R5 | - | - | 1 | - | - | 1 | - |
| R6 | - | - | - | 1 | - | - | 1 |

2.4.3.3. Key assumptions adopted in the model and with the table package properties used

The following lines of assumptions are applied to simplify the calculations:

- The global system is assumed to be in steady-state conditions, where the stream class is MIXCINC and the flow basis is in mass.
- The release of volatile compounds occurs immediately during the drying stage.
- Ash is ignored in the mass balances and the reaction schemes in this model.
- The model assumes that there is no heat exchange between the reactors or the flowing channel with the environment.
- As the char C_nH_mO it is a complex compound; it is replaced by carbon.
- Neither the pump nor the Valve is considered during the modelling.

Table 6: Package properties used

| Attributes | Specifications |
|------------------------|---------------------------------|
| Biomass | Proximate and ultimate analysis |
| Density mode | DCOALIGT |
| Enthalpy mode | HCOALGEN |
| Fluid-dynamic Packages | PENG-ROBINSON |
| Steam class | MIXCINC |

2.4.4. Model description

The gasification process using cashew nutshells is modelled in Aspen Plus software, treating CNS as biomass, a non-conventional component not available in the Aspen Plus database. The characterisation of cashew nutshells presented in **Table 9** was utilised in the model. For biomass and ash properties, packages were selected, and non-conventional solids were defined using the HCOALGEN and DCOALIGT modules, as outlined in the work of. Zina. J & Gogoro. G. B [54]. The selection of the Peng-Robinson equation of state was made as the method for predicting various component properties on a global scale, according to Zina J. & Gogoro G. B [51]. About 30% of studies utilised Peng-Robinson as the method for physical properties in biomass gasification simulations. Peng-Robinson, the equation of state, is used for nonpolar or mildly polar mixtures [58]. All these definitions are included within Aspen Plus's property environment.

The simulation begins by introducing a feed of 1000kg/hr of non-conventional biomass solid at standard conditions, 25 °C and 1 atm of temperature and pressure, respectively. The initial product after the drying stage is dried biomass with a mass fraction corresponding to the biomass composition. The process operates continuously, utilising a shortcut dryer that functions at 105 °C, with moisture content specified on a wet basis, and vapour-liquid phases are the valid phases considered during drying. Proximate and ultimate analyses are defined as component attributes, and all values sum to 100%. The yield component is based on calculations within reactors known as the Ryield and Rgibbs reactors, both operating at 800 °C and 1 bar. These reactors are used for decomposition and pyrolysis stages, where the Ryield reactor handles decomposition to form heavy gaseous species and generates the RGibbs block for subsequent reactions, converting conventional components into lighter gases. The steam products after the Rgibbs block reactions are represented as VOL- PD. Before reaching the gasification stage, the steam products pass through a splitter called SEP, which separates solid and gaseous components. The gaseous mixed flow from the products enters the Mixer, while carbon and ash exit the bottom of the separator as CISOLID and NC SOLID. The Mixer combines the mixed gases with three additional feeds- carbon, steam (after water conversion), and air. Steam flows at 300kg/hr with a water mass fraction of 1,

and air is modelled as consisting of 21% oxygen and 79% nitrogen, with a total flow of 200kg/hr at standard conditions of 25 °C and 1.01325 bar, which means this present study applied both as gasifying agents. According to Magtoto, Keynty Boy V. et al.[62], mixing steam and air as a gasifying agent improves the quality of the resulting syngas, and depending on the gasifying agents used its energy content can vary from (10-16 MJ/kg) and (4-7 MJ/kg), respectively. Two Rplug-flow reactors, named OXI and RED, based on their functions, model the six selected reactions occurring during gasification, with POWERLAW kinetics previously chosen.

Two heat exchangers serve different purposes: one functions as a cooler to lower the temperature after the reduction stage, and the other converts water into steam fed into the mixer at 400 ° C. Both water and steam are input at 300 kg/hr. The final products, obtained after separation, include hydrogen and undesired byproducts (UP), as shown in **Figure 7**. For validation, the study employs RMSE to calculate the percentage of error, comparing the results with other experiments presented in **Figure 9**, as it better represents model performance than alternative methods [63]. The following equation was used for the error calculation:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2} \quad (10) \quad [64]$$

Where: **RMSE**: root mean square, Y_i value from literature or experiment, \hat{Y}_i the predicted value from the simulation model, and n : the number of compounds considered during the error evaluation.

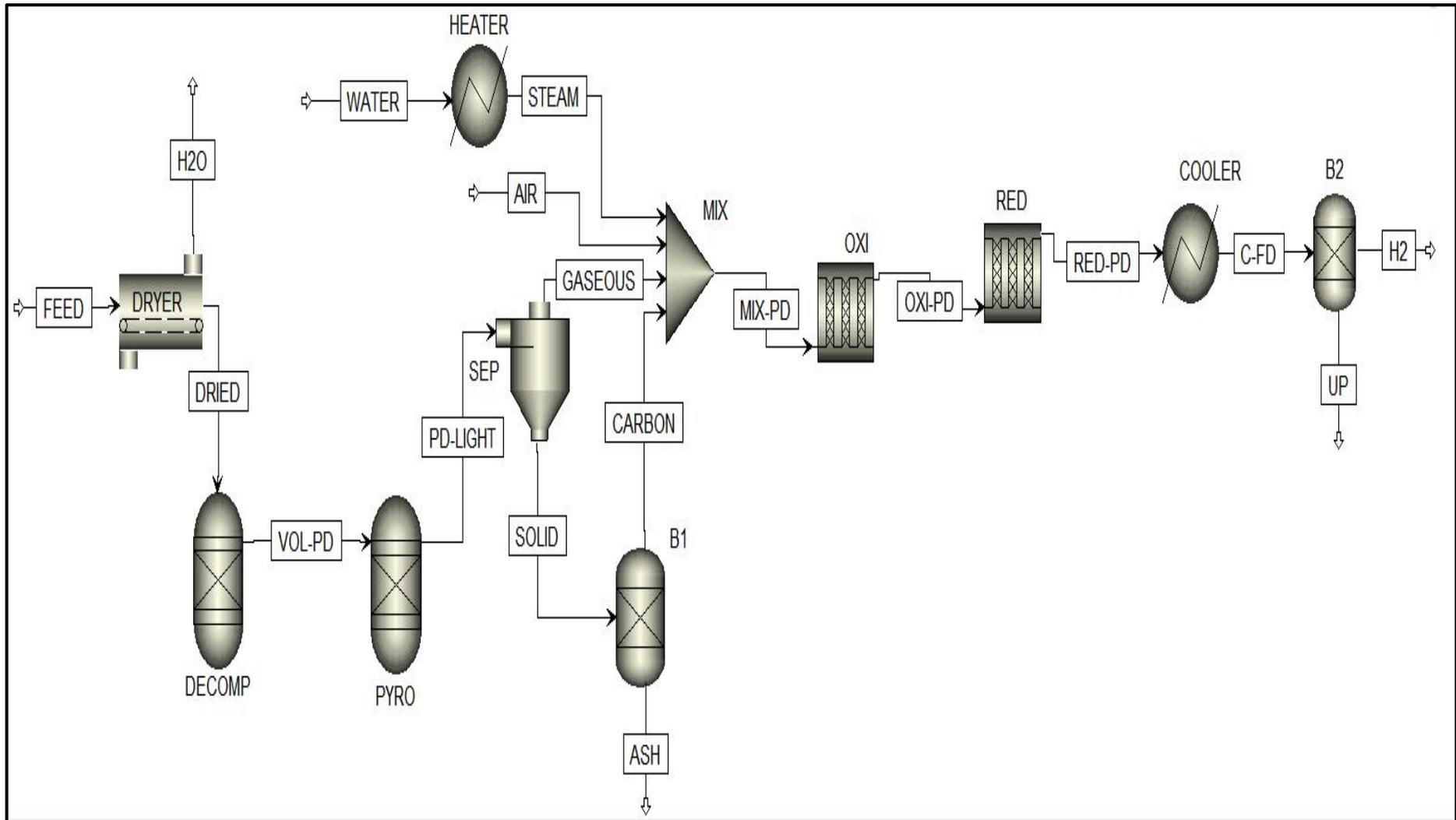


Figure 7: Aspen Plus flowsheet simulation of gasification using CNS as a feedstock

Table 7: Block description and its operation conditions

| Block Information | | Operating conditions | | Description |
|--------------------------|--|----------------------|----------------|--|
| Default ID in Aspen Plus | Assigned unit operations for block ID in the flowsheet | Temperature (°C) | Pressure (bar) | Unit operation Description |
| Dryer | Dryer | 105 | 1.01325 | Drying the biomass to eliminate a specific amount of moisture |
| OXI | Rplug | 800 | 1.01325 | There is a Rplug block that runs the two main reactions, which calculate the kinetics of oxidation. |
| RED | Rplug | 800 | 1.01325 | There is a Rplug block that runs the four main reactions and calculates the kinetics of the reduction zone. |
| Decomp | Ryield | 700 | 1.01325 | Specified the component yield of each compound, which means converting the non-conventional component into tar, char, and conventional components. |
| PYRO | RGibbs | 700 | 1.01325 | It is where the reaction among conventional components takes place through Gibbs free energy minimisation. |
| Exchanger1 | Heater | 300 | 1.01325 | Changing the state of water from liquid to steam by increasing the temperature from 25°C to 300°C. |
| Exchanger2 | Cooler | 30 | 1.01325 | Dropping down the temperature of 700°C from RED reactor to 30°C |

| | | | | |
|---------------|------------------|------------|----------------|---|
| Mixer | Mixer | 800 | 1.01325 | Mixing various gas compounds, such as steam, nitrogen, carbon, and gases produced from pyrolysis. |
| Split | Separator | 700 | 1.01325 | The separation of the gas compound from the solid compound. |
| Sep B1 | Separator | 30 | 1.01325 | Separator for the carbon-rich solid from the ash that will be produced. |
| Sep B2 | Separator | 30 | 1.01325 | Separator of hydrogen with gas products represented by UP in the model. |

Table 8: Feed steam in different conditions of temperature and pressure.

| Feed stream | Component | Temperature(°C) | Pressure (bar) | Flow rate(kg/hr) |
|------------------------|-------------------------|------------------------|-----------------------|-------------------------|
| Water | H2O conventional | 25 | 1.01325 | 300 |
| Cashew Nutshell | NC biomass | 25 | 1.01325 | 1000 |
| Air | Nc biomass | 25 | 1.01325 | 200 |
| Steam | conventional | 300 | 1.01325 | 300 |

2.4.5. Sensitivity analysis

After modelling and simulating the synthesis gas production, conducting a sensitivity analysis is a vital step. During the gasification process, especially in producing hydrogen and other gaseous compounds, parameters such as temperature, pressure, gasifying agents, and their types and quantities (as in this study, air and steam) significantly influence the system's behaviour and overall process performance. The sensitivity analysis aims to identify which of these parameters has a greater effect on a specific stage of the process, particularly in the composition of the final products. The sensitivity analysis was carried out using the flowsheeting options in the model analysis tool, Aspen Plus software 14.

Sensitivity analysis was carried out in a specific block, namely the Rplug RED block, which calculates the kinetics of the reduction zone as described in **Table 7**. In the Vary window, besides selecting temperature and pressure as the main variables for the Rplug block, Block

var was also chosen. The operating conditions for the block were assumed based on range within the specified lower and upper limits, considering the temperature and pressure used in the reactor block. For a pressure effect study on the steam reduction, RED-PD, the variable was varied at 10 points. The pressure ranged from 1 bar to 10 bar throughout the process within the reactor block. The temperature varied from 300°C to 800°C, with fluctuations occurring at 10 different points during the process. These variations systematically enable the assessment of how pressure and temperature affect the reaction kinetics inside the block.

2.5. Theoretical assessment of energy potential from H_2

The availability of hydrogen after running the simulation model is important for energy estimation. As shown in **Table 9**, the energy content of CNS was higher, which depends on the energy potential. However, 22.5 MJ/kg and 20.9 MJ/kg correspond to the HHV and LHV of cashew nutshell, respectively, reflecting their energy content before conversion. The prediction made by simulation using Aspen Plus shows how can be effectively produced from CNSL produced from CNS. According to Kojima & Masakuni Yamaguchi [65], a hydrogen energy carrier is a specific type of liquid hydrogen that transports large quantities of hydrogen from one place to another, while an energy carrier is a substance that can generate mechanical work or heat according to the following standard **ISO 13600**. Currently, there are three types of H_2 energy carriers, which include ammonia, liquid H_2 , and an organic hydride (methylcyclohexane, which has been considered in Japan). According to Ohi [66], hydrogen can be converted into electrical and thermal energy through thermochemical (combustion engines and turbines) or electrochemical (using fuel cells) processes. Engines can combust hydrogen in the same manner as natural gas, while fuel cells use the chemical energy of hydrogen directly to produce electricity and thermal energy. Hydrogen engines are particularly impressive, as evidenced by their use in the space shuttle Orbiters. These fuel cells are the supporting pillar of the hydrogen economy and have the potential to revolutionise national energy systems by providing clean, efficient, and versatile power from local renewable sources. They can perform well across a wide range of capacities, from watts to megawatts, and can achieve total efficiencies of up to 80%. In the economic aspect, Nowotny & Veziroglu [67], listed the hydrogen economy among the reasons for hope to solve the world's problems; however, to them, the hydrogen economy is relatively low-cost, and hydrogen available on the market at present is already priced lower than oil. The amount of energy that can be generated per hour theoretically, which means despite the use of any types of machines is obtained through the following formula:

$$E_{H_2} = m_{H_2} \times LHV_{H_2} \times \eta \quad (11)$$

[51]

Where: E_{H_2} : is the energy generated, which can vary based on the means used, m_{H_2} : the mass of hydrogen, LHV_{H_2} : represent the lower heating value of hydrogen produced through simulation, η : represent the efficiency of conversion means.

For the evaluation of the gasification process, Magtoto, Keynty Boy V. et al.[62], have used carbon conversion efficiency (CCE) and cold gas efficiency (CGE), in order to evaluate the performance of the gasification process. Where the CCE reflects the percentages of carbon atoms of biomass that have been converted to syngas. According to Shi et al.[68], cold gas efficiency indicates the energy conversion efficiency from biomass feedstock to syngas.

Both are defined, as well, in the following formulas below:

$$CGE = \frac{LHV_{Syngas} \times Q_{syngas}}{LHV_{biomass} (MJ/kg) \times Biomass\ fed} \times 100\% \quad [69] \quad (12)$$

$$CCE = \frac{Carbon\ element\ in\ syngas\ (in\ mass\ fraction)}{Carbon\ element\ in\ feedstock\ (in\ dry\ basis)} \times 100\% \quad [68] \quad (13)$$

$$LHV_{syngas} = \frac{(H_2\% \times H_{LHV}) + (CO\% \times CO_{LHV}) + (CH_4\% \times CH_{4LHV})}{100\%} \quad [69] \quad (14)$$

Conclusion

Considering the higher recoverable fraction observed at the Arrey Africa processing facility, it is essential to confirm that CNS constitutes a suitable and plentiful feedstock to produce clean hydrogen. The simulation results demonstrate that operational parameters, including temperature and pressure, significantly influence hydrogen yield. Consequently, Guinea-Bissau emerges as an optimal candidate for the deployment of biomass-to-hydrogen technologies, thereby supporting both local energy security and the global effort toward decarbonisation. Cold gas efficiency and CCE are presented as the major parameters to evaluate the performance of gasification.

Chapter 3. Results and Discussion

Introduction

For turning waste into the energy, CNS is a strong candidate due its favourable characteristics, which are it dries easily, does not carry much moisture or ash, it has plenty of useful volatile matter, and contains significant carbon and hydrogen. Which means it can clean burn and efficiently. Involving communities and local stakeholders, educating residents, and planning waste handling, in a way that protects the environment while creating jobs it is important.

3.1. Feedstock characterization

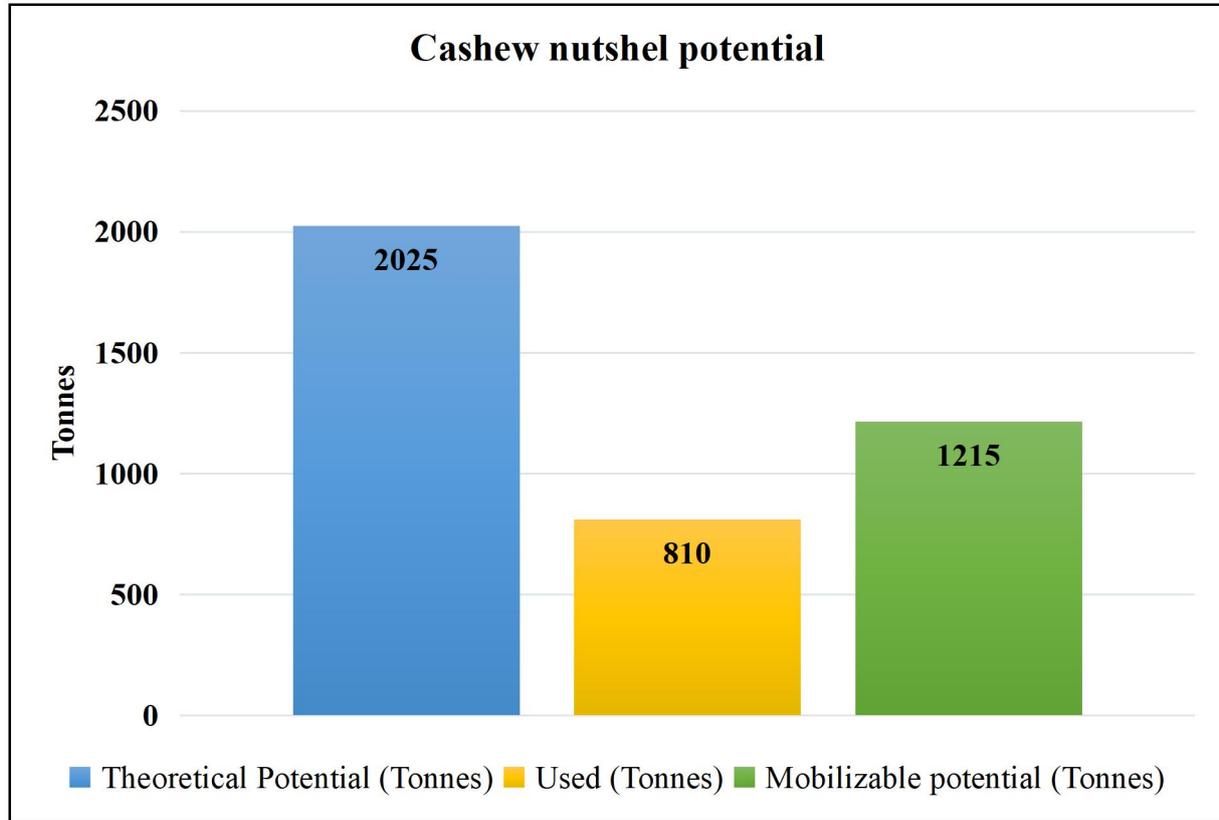
The proximate and ultimate analysis of CNS, through the dry basis results presented in the **Table 9**, reveals its potential as an efficient and environmentally friendly renewable energy source. Excellent drying characteristic is demonstrated with a low moisture content of 6.3%, which means that the combustion efficiency is elevated, automatically reducing the energy needed to evaporate water. The 3.5% of the fixed carbon indicates lower char production, resulting in short-time burn fuels. As the ash content is lower, around 2% minimizes issues related to slagging and disposal, confirming that cashew nutshells are an environmentally favourable fuel. However, with 55.7% and 6.75 corresponding to carbon and hydrogen, respectively, it provides a strong basis for energy release, while the 35% of oxygen facilitates combustion. And as the nitrogen and sulphur were present, the lowering value, such as 0.44% and 0.03% respectively, which means a lower environmental impact due to minimal emissions.

Table 9: Cashew nutshell characterization conducted at the laboratory of the University of Rostock

| Properties | Elements | Values |
|--------------------|-------------|--------|
| Proximate analysis | C (%) | 55.7 |
| | H (%) | 6.75 |
| | N (%) | 0.44 |
| | S (%) | 0.03 |
| Ultimate analysis | O (%) | 35 |
| | AC (%) | 2 |
| | FC (%) | 3.5 |
| | MC (%) | 6.3 |
| | VM (%) | 88.2 |
| | HHV (MJ/kg) | 22.5 |
| | LHV (MJ/kg) | 20.9 |

3.2. Theoretical and mobilizable potential CNS estimation

The evaluation of the potential of cashew nutshells at Arrey Africa Company was conducted based on the company's production capacity and the residues-to-product ratio obtained from the literature, as mentioned earlier in the methodology. This assessment is to estimate both



the

Figure 8: The cashew nutshells' potential in the Arrey Africa facility, located in the Bula sector of Guinea-Bissau

theoretical and mobilizable amounts of CNS, which serve as feedstock for hydrogen production. Arrey Africa annually processes over 3,000 tonnes of cashew nuts. For the theoretical potential, we considered the total amount stored across all storage facilities in the complex, after all the collections. This amount is estimated to be around 2,025 tonnes, as shown in the **Figure 8**, and is assessed by multiplying 67.5% of the RPR by the company's total processing capacity, following the described methodology. A recoverable factor of 60% was applied to multiply the theoretical amount to assess the mobilizable potential, which is thrown into nature and then considered losses during the collection. Based on the calculations, the estimated annual availability of CNS suitable for hydrogen production at Arrey Africa is approximately 1,215 tonnes per year, as demonstrated in **Figure 8**.

3.3. Validation of the model

Model validation is a crucial step that demonstrates the accuracy and reliability of the developed model, which is based on a comparison with experimental work found in the literature. Within the model process design, the data obtained from the lab analysis at the University of Rostock were introduced to run the model. **Table 10**, presents the feedstock characterization, which was considered in experimental work.

Table 10: Feedstock characterization of experimental results used to validate the predicted model, adopted from[70]

| Experiments | | | | |
|-----------------------|-----------------|-------------------|--------------|----------------|
| Feedstock used | | Parameters | Rice | Plastic |
| Proximate | analysis | MC (%) | 5.1 | 0.02 |
| | | FC (%) | 4 | Nd |
| | | VM (%) | 68.9 | 99.4 |
| | | AC (%) | 22 | 0.6 |
| | | HHV(MJ/K) | ---- | ---- |
| | | LHV(MJ/Kg) | ---- | ---- |
| Ultimate | analysis | C (%) | 35.34 | 85 |
| | | H (%) | 4.56 | 14.2 |
| | | N (%) | 0.63 | ---- |
| | | S (%) | Nd | 0.2 |
| | | O (%) | 59.47 | ---- |
| Sources | | | [70] | |

The experience reported by Bhurse et al.[70], was set up with a two-stage downdraft gasification reactor with a throat and tar trap, both stages measuring 4 mm in thickness and 44 mm in diameter, was utilized for the experiment. The first phase mimics drying and pyrolysis of rice husk to yield tar and volatile gases, which are carried into the second phase by nitrogen flow. The second phase is for tar destruction and may include catalysts or char to maximize tar cracking and yield cleaner producer gas. Temperature in both phases is separately regulated using thermocouples and PID controllers.

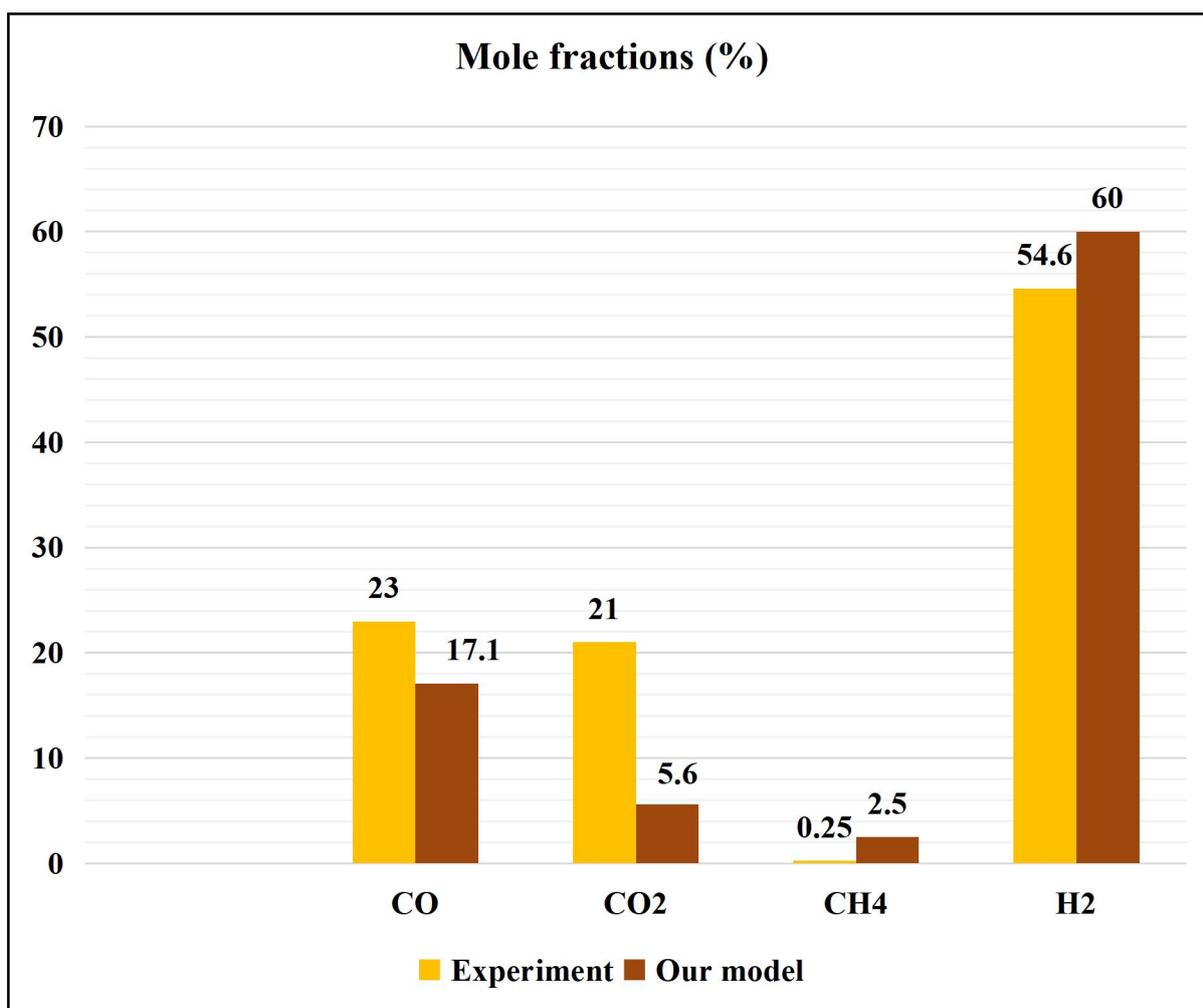


Figure 9: Experimental vs model prediction of hydrogen production using CNS via gasification process

The design of the reactor enables accurate control of gas flow at the interface of stages through nozzles that inject inert gas. Reactor insulation reduces heat loss, gases are led through a tar trap immersed in ice for tar condensation, with vents and sampling points. Rice husk, sized to $<1000\ \mu\text{m}$ and dried, was used as biomass, charged with 50g per batch and heated at 25 kg/min to 500°C , where tar formation is at its maximum. Gaseous products (CO, H₂, CH₄, and CO₂) were also analysed by gas chromatography to assess the influence of secondary reactions on tar yield.

Figure 9, shows the comparison between experimental data and model predictions, where the predictive model was designed to improve simulation inputs, so they better reflect the experimental conditions. The biomass feedstock utilised was 1,000 kg, and the reactor type employed was Downdraft, modelled at 800°C and 1.013bar for both baseline modelling and

sensitivity analyses. During these analyses, the temperature ranged from 300°C to 800°C, and the pressure varied from 1 bar to 10 bar. The study included two gasifier scenarios: one with a steam feed of 300 kg/h and another with an air feed of 200 kg/h. After running the model, some predicted values closely matched the experimental results, while others displayed significant discrepancies. The absolute estimation error was approximately 8.79%, which is acceptable considering the biomass types and their characterization, as shown in **Tables 9 and 10**, which present notable discrepancies in ultimate and proximate analysis results of feedstocks characterization. As illustrated in **Figure 9**, the system predicted a higher amount of H₂ and CO gases than other gases for both experimental and predicted data models.

3.4. Influence of dual parameters on biomass gasification process

After conducting the sensitivity analysis using Aspen Plus software, based on the two main parameters considered in this study, pressure and temperature, both of which may or may not have a visible influence on hydrogen yield during hydrogen production using CNS via gasification in a downdraft gasifier. Additionally, analysing these different parameters through Aspen Plus software V.14 improves the understanding of their behaviours, which can guide future decisions to select the best parameters for increasing hydrogen yield.

3.4.1. The influence of temperature on the four main gas compounds

Figure 10, shows the influence of temperature on product gases in the gasification process using CNS. According to Novandri Tri Setioputro et al.[71], in biomass gasification, temperature is one of the most critical parameters that can control gas composition, tar concentration, reaction rate, and ash accumulation. Low temperature gasification produces high tar content and low syngas, for example *CO* and *H₂* content in the product of gas. On the other hand, high-temperature gasification results in higher *CO* and *H₂*, while reducing the tar content.

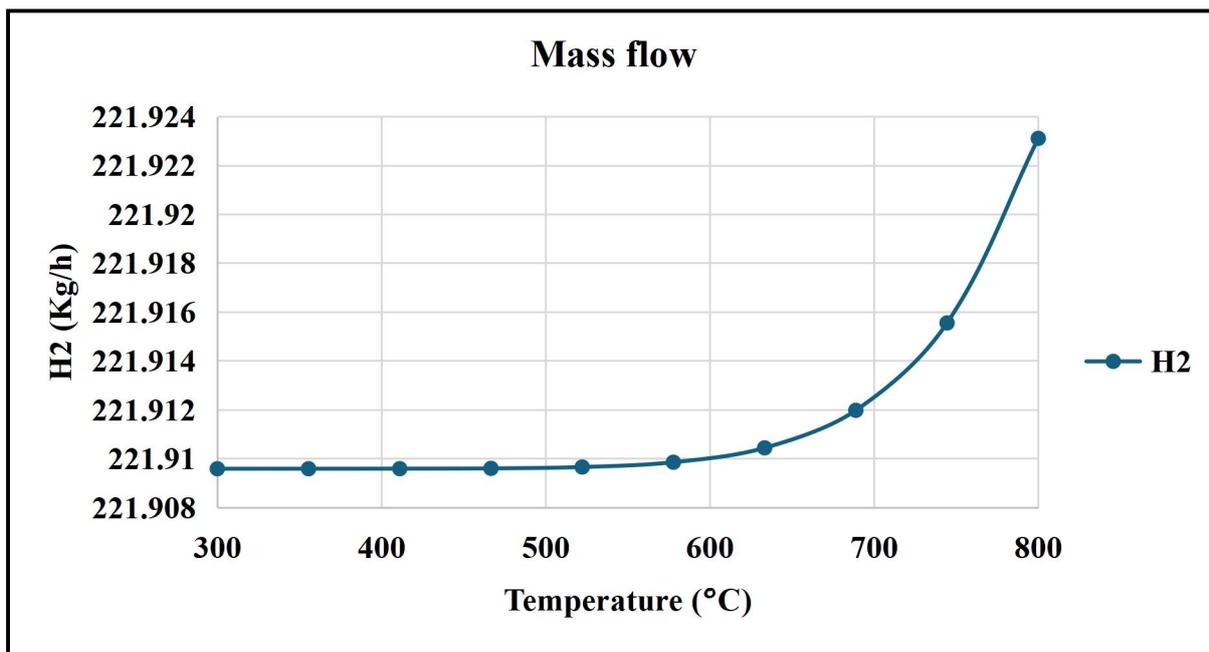


Figure 10: The influence of temperature on hydrogen gas production simulated, using CNS via gasification.

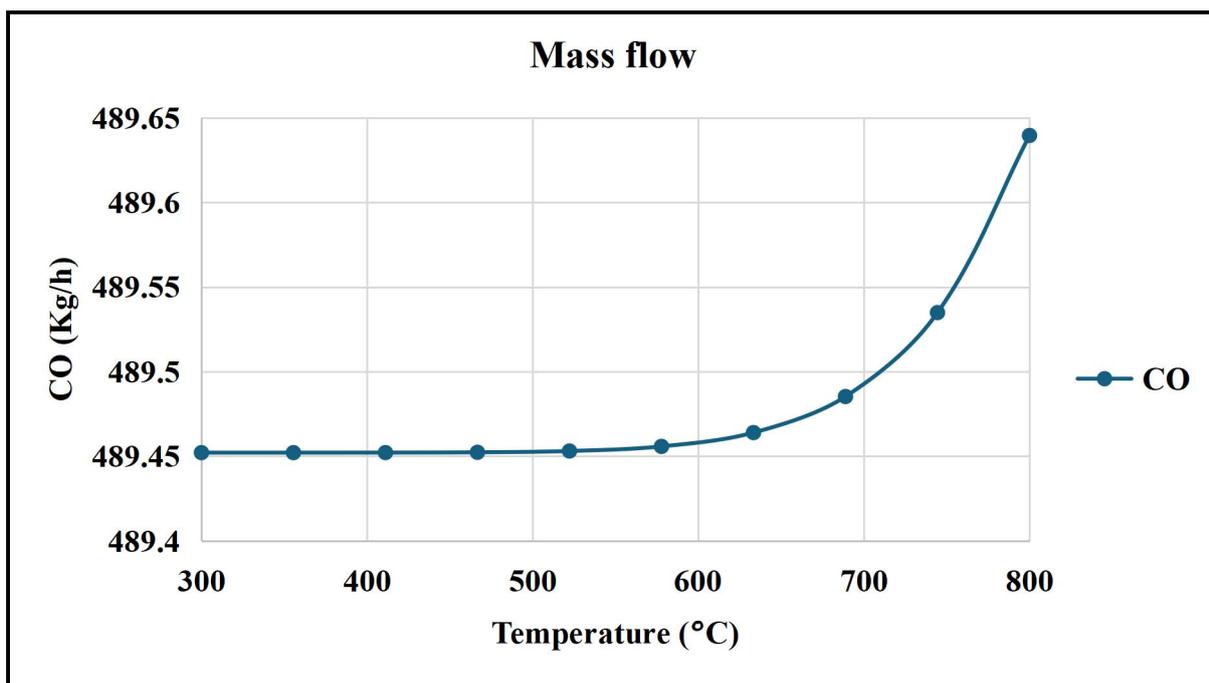


Figure 11: The influence of temperature on carbon monoxide gas production simulated using CNS via gasification.

This present study, as illustrated in **Figures 10 and 11** above, examines the influence of temperature by increasing the reactor temperature from 300°C to 800°C. The H_2 and CO yields rise from below 221.91kg/h to 221.924kg/h, and from 489.45kg/h to 489.65kg/hr, respectively.

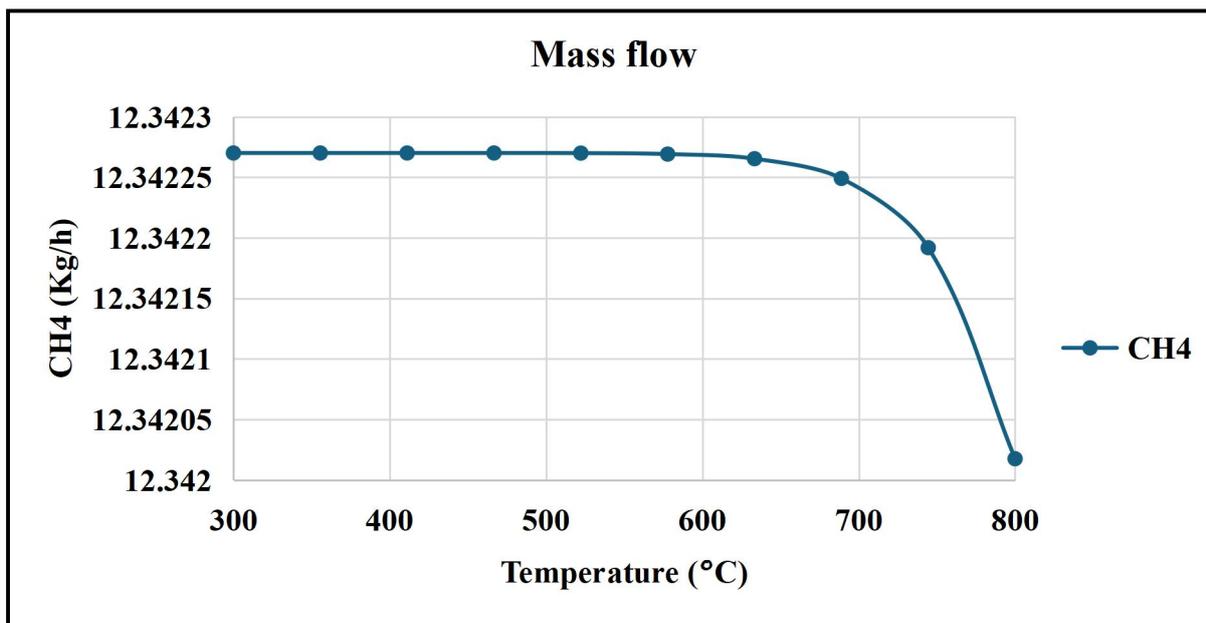


Figure 12: The influence of temperature on methane gas production simulated using CNS via gasification.

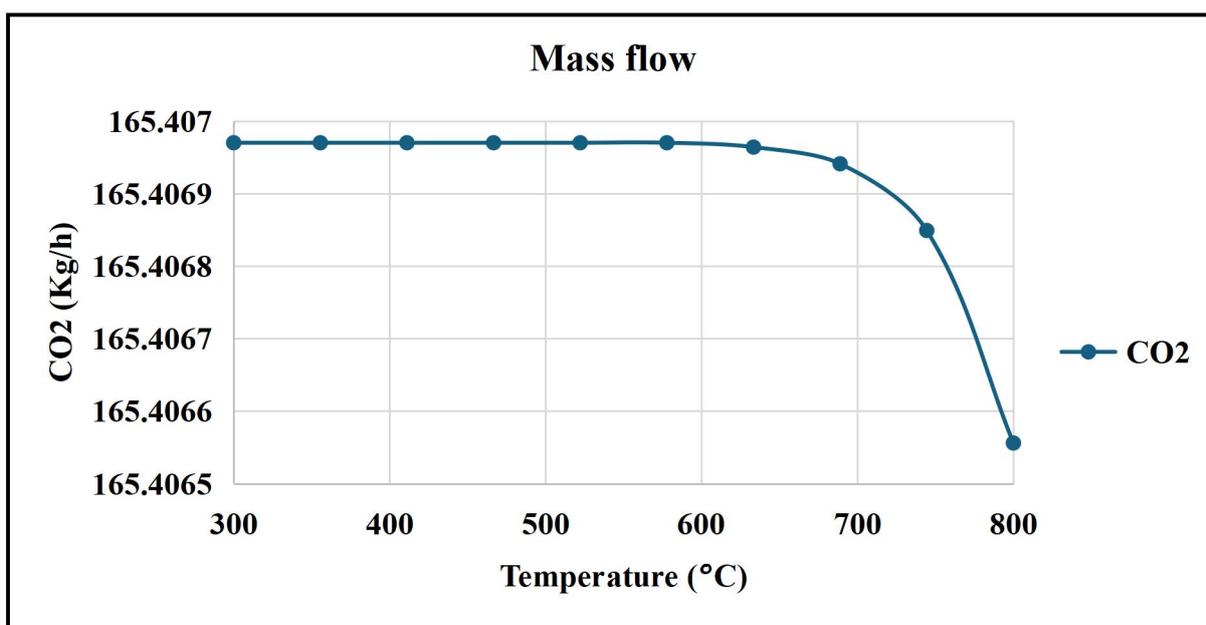


Figure 13.: The influence of temperature on carbon dioxide gas production is simulated using CNS via gasification.

As shown in **Figures 10** and **11**, the temperature influences the hydrogen and carbon monoxide positively, in contrast with the other two compounds, which are CO_2 and CH_4 illustrated in the **Figures 12** and **13** above decreased from 165.407kg/h to 165.40655 kg/h, and 12.34227 to \approx 12.342kg/hr, respectively, by increasing the reactor temperature from 300°C to 800°C as well.

3.4.2. The influence of pressure on the four main gas compounds

The influence of pressure on synthetic gas has been investigated in so many studies but with the use of different methods or processes. After an experimental work on SCW, Üremek Cengiz et al.[72], reported that the decreasing pressure promoted hydrogen yields while decreasing the methane yields. And they conclude that as the pressure decreased, higher yields of aqueous were obtained.

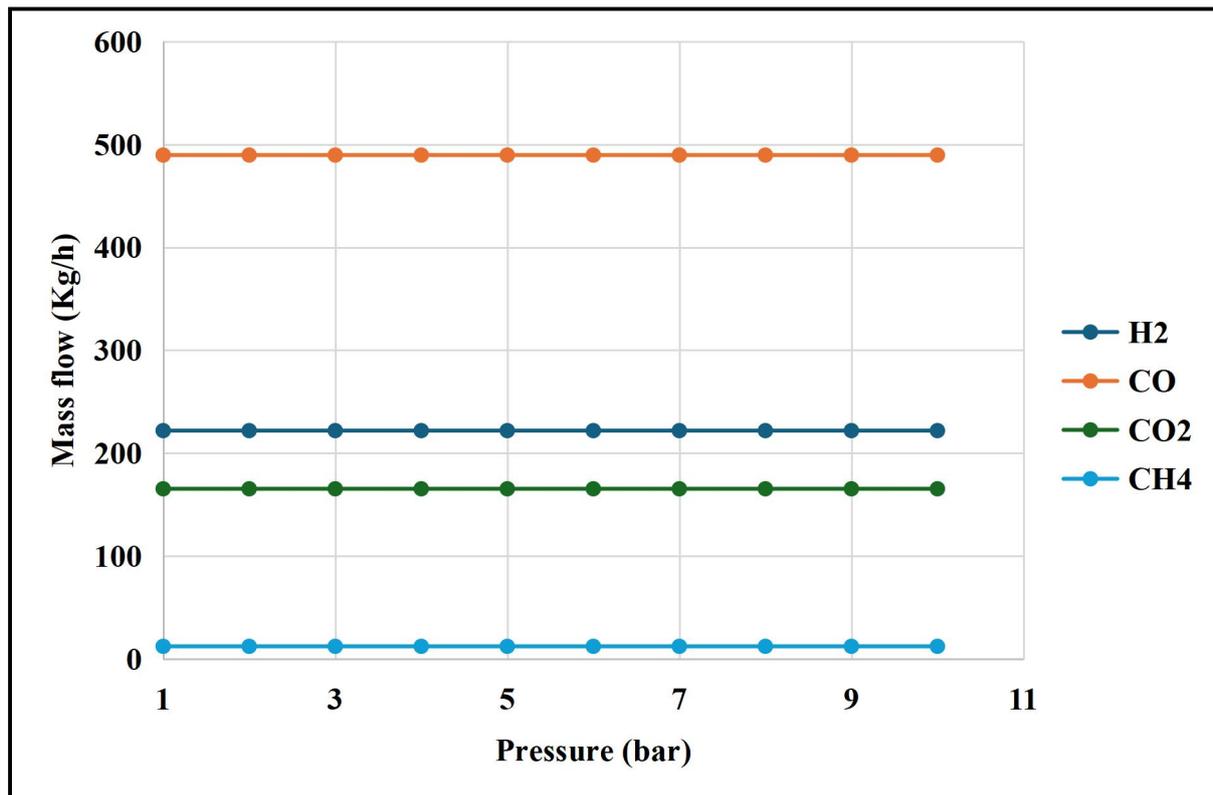


Figure 14: The influence of pressure on the synthetic gas production was simulated, using CNS via gasification.

According to Ardila et al.[73], an increase in the partial pressure of hydrogen had a detrimental effect on hydrogen yield in the fermentation process. Increasing pH_2 up to 3bar had no inhibitory effect on H_2 production, and following the WGS reaction, all CO presented in the system were converted into H_2 with a selectivity higher than 95%. Kumar & Das [74], in their investigation of the effect of temperature and pressure on hydrogen production from steam reforming of biogas with $Pd - Ag$ membrane reactor, reported that the H_2 generation decreases in percentage with the increase of system pressure from 1 to 20 bar. In the same perspective, the results obtained through TG-DTA have confirmed that after introducing a catalyst in the system and at the same time lowering the temperature to 100°C and the pressure at 1bar, the system generates a higher amount of hydrogen. To this present study, the **Figure 11** illustrates the pressure during the synthetic gas production, which referring H_2 ,

CO_2 , CH_4 , and CO . The reactor temperature was estimated over $800^\circ C$, and the pressure based on the simulated sensitivity was about 1 bar to 10 bar, respectively for the lower and upper limitation in the operating conditions. During the observation, it was observed that as the pressure increased, all the components remained constant, which means the pressure does not influence the yields of these four main compounds mentioned.

3.4.3. Influence of dual parameters, which include temperature and pressure

During the experiment of Kumar & Das [74], effect of temperature and pressure on hydrogen generation from sodium borohydride through thermolysis using a catalyst is examined. The study investigated how temperature and pressure influence the amount of hydrogen produced. The temperature range covers from $100^\circ C$ to $500^\circ C$, while pressure varies from 1 bar to 20 bar. Hydrogen production was lowest at $100^\circ C$ and 20 bar. Increasing the temperature and decreasing the pressure improved hydrogen generation. As shown in the study, at $500^\circ C$ and 20 bar, hydrogen accounted for about 0.92 wt%. When the pressure was reduced to 10, 5, and 1 bar at the same temperature, hydrogen production increased further, reaching approximately 4.38 wt% at $500^\circ C$ and 1 bar. Guo et al.[75], reported that at relatively high pressure, hydrogen yields, GE, and CE increase a little.

Figure 15, illustrates how temperature and pressure affect the H_2 yields during H_2 production using CNS via gasification in a downdraft gasifier. The sensitivity analysis was carried out on the RED reactor, where temperature varied from $300^\circ C$ to $800^\circ C$ and the pressure from 1 bar to 10 bar, as shown in **Figure 15**. During the study, temperature had the most significant influence on H_2 yield. The effect of pressure appeared minimal on H_2 yield. Pressure ranged from 1 bar to 10 bar, and H_2 level remained unchanged, as shown in **Figure 15**, which presents the mass flow. It was observed that the hydrogen yields improved, reaching 221.922 kg/h, when temperatures ranged from $650^\circ C$ to $800^\circ C$.

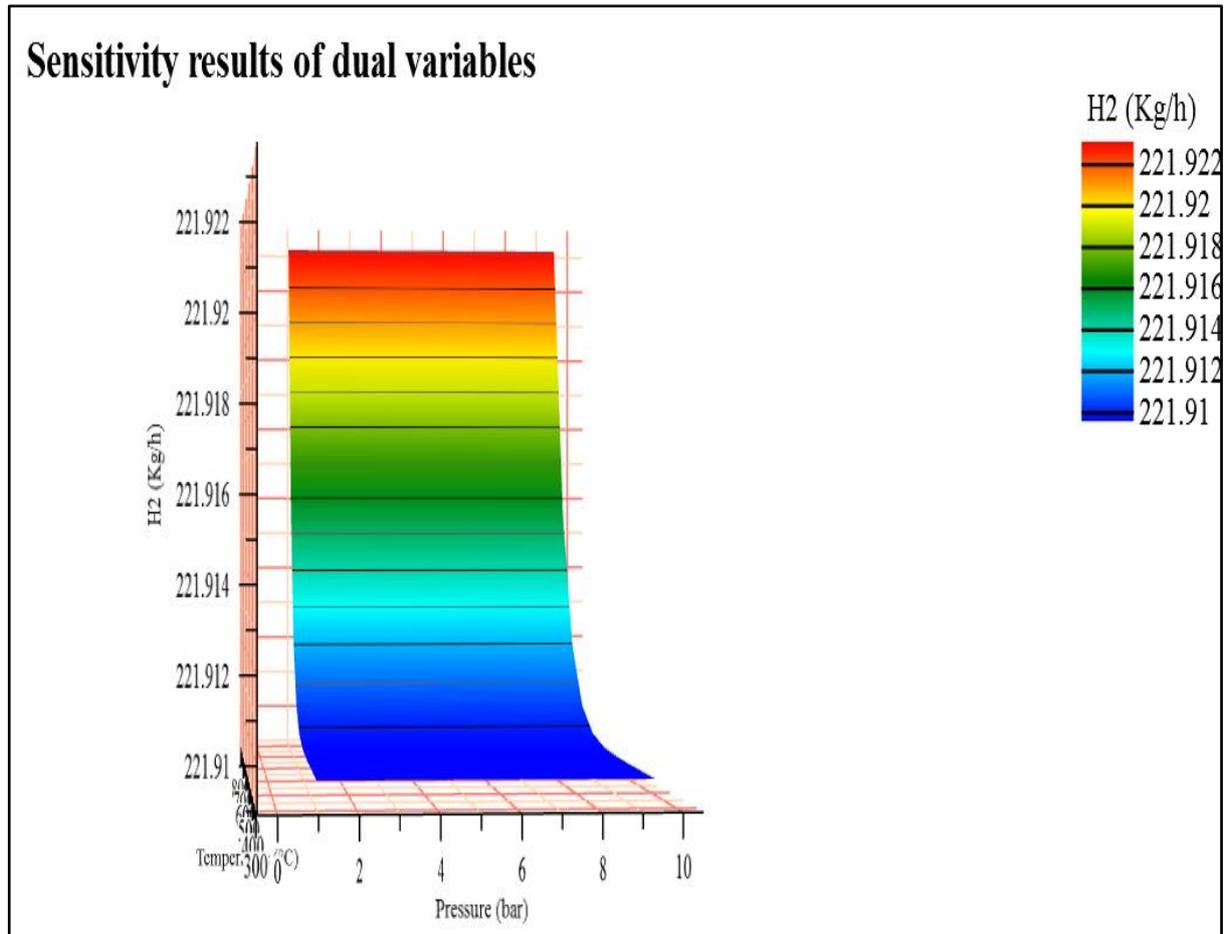


Figure 15: The influence of dual variables, which include pressure and temperature, on hydrogen production using CNS via gasification.

3.5. Optimization process of H_2 production

The optimisation involves selecting the best design, parameters, and catalyst as discussed in the literature review. The product H_2 is the most important output of the gasification process in this study, based on the objective. Only a few parameters are used for the sensitivity analysis, but to maximise H_2 production, it is crucial to optimise key operating parameters and gasifier agents by adjusting all influential factors, including temperature and pressure, as well as steam and air for the gasifier's agents. As shown in **Figs 11, 12, 13, and 15**, temperature plays a critical role; higher temperatures tend to favour endothermic reactions that boost H_2 production, such as steam reforming and methane cracking, while reducing methane and tar formation. Conducting the sensitivity analysis on H_2 yield during gasification without a catalyst reveals some adverse effects concerning the mass flow of CO compared to the mass of other components.

3.6. The main strategies for effective waste management

Considering the serious issues that cashew nutshell waste can cause to our community and the environmental damage linked to traditional disposal methods, strategies for CNS waste management are crucial for humans' well-being. According to Patade et al.[76], The large quantities of cashew shells are regarded as agricultural waste and as byproducts of cashew nut production. Production and unskilled management of solid waste releases contaminants that affect ecology and public health. The main sources of greenhouse gases emitted by landfills and waste treatment processes include methane, which is produced as organic garbage decomposes. Water resources become contaminated when leachate from landfills seeps through the soil into groundwater and nearby surface waters [77]. This study lists three main points as a strategy for the effective management of cashew nutshell waste: plan management for CNS waste, engagement of stakeholders, and training (Education).

3.6.1. Engagement of stakeholders

Effective management of agricultural residues requires the collaboration of various stakeholders, including rural communities, farmers, cashew processing industries, research institutions, and multiple government ministries. According to Joseph [78], Stakeholders are individuals and organisations with an interest in effective waste management and actively participating in enabling activities. They include businesses, organisations, households, and all others involved in waste management activities. Stakeholders might produce waste, serve as service providers, or participate as government departments, non-governmental organisations, and other entities concerned with specific aspects of waste management. According to G. Zotos *et al.*[79], Efforts to improve waste management services and the wider environmental sustainability policies adopted by local authorities rely on the active involvement of all stakeholders. For these initiatives to be successful, actions must be credible, transparent, socially sustainable, and, where feasible, convenient and practical for participants. Therefore, local authorities' public relations strategies should be customised to specific large-scale environments and offer target groups genuine opportunities to take meaningful action. For the possibility of acceptance of any decision concerning waste management, Vasconcelos et al. [81], Van Den Hove's work highlights that the participation of a wide range of concerned stakeholders is an important aspect, because it confers greater legitimacy to the content of the decisions, taking into account different values and knowledge, and allowing the design of more preventive and proactive approaches.

3.6.2. Training (Education)

To enlighten most farmers and companies that processing cashew nuts in Guinea-Bissau about proper methods to manage cashew nutshell waste, there is a need for education and training programmes focused on handling, collecting, and managing crop waste, particularly cashew nutshells properly. According to Stegmann.[82], a good waste management system depends not only on technology and economics but also on public education and civic participation. Raising public awareness and educating community members about waste minimisation are essential. Ecological awareness is fostered through environmental education, encouraging behavioural changes among community members to establish a responsible culture environmentally. Kanji [83], reported that waste prevention requires collaboration among various campus units. Therefore, in addition to implementing diverse informational campaigns to promote waste reduction, targeting different groups within the campus is essential. Universities are suggested to make environmentally friendly waste management practices mandatory. Specifically, the infrastructure employed to collect and transport waste needs to be organized to be energy efficient with a view to reducing environmental impacts to the maximum extent practical. According to Budihardjo et al.[84], understanding and being aware of environmental issues, which include involving people in the programme and encouraging them to be environmentally responsible, are key factors for the effective implementation of SWM in higher education institutions. The level of education is considered a significant influence in this area because highly educated individuals are believed to have greater environmental awareness, leading to a more positive attitude towards solid waste reduction.

3.6.3. Plan management for CNS waste

Guinea-Bissau faces a deficient waste management system, particularly concerning agricultural byproducts like cashew nutshell waste. As one of the world's largest producers of cashew nuts, the country generates substantial quantities of cashew nutshells, as noted in existing literature. However, there is no organised and efficient plan for biomass vapourisation, despite the clear potential for sustainable reuse of this biomass. Implementing a comprehensive treatment and conversion process for cashew nutshell waste could offer economic benefits, reduce environmental harm, and provide regional advantages by creating new value-added activities such as bioenergy, fertiliser production, or the development of raw materials. materials to make traditional products. For the plan of waste management, Ismaeel & Kassim [81], recommended that construction waste management comply with national environmental laws, such as the EU's 99/31/EC directive, and green building standards like LEED, which set criteria for managing construction waste. Despite these regulations, the

amount of construction and demolition waste continues to grow globally without effective disposal methods. This waste puts pressure on landfills and harms the environment, affecting air, water, soil, and natural resources. To mitigate these impacts, a life cycle thinking approach is suggested to promote waste reduction, reuse, and recycling throughout all project phases, as each stage influences SWM effectiveness. After recognising the critical need for proper waste management due to the absence of an effective system in their workplace. Mostafa et al [85], recommended the formulation of a protocol for waste management that would be guided by a comprehensive assessment of the need, enhancing the current provision, and controlling the related risks.

3.7. Theoretical energy potential from H_2

In general, hydrogen is regarded as a high-energy and clean fuel, possessing a high specific energy content. Its energy potential can be theoretically estimated from its chemical properties and combustion nature. As mentioned in the methodology and observed in the literature, fuel cells play an essential role in facilitating the hydrogen economy, as they can transform national energy infrastructures. Hydrogen, with a high energy content of approximately 120 MJ/kg to 142 MJ/kg, has a comparatively low energy density. For energy generation, theoretically, considering the 1000kg of CNS used to produce hydrogen, the mass flow rate of hydrogen was estimated to be approximately 221.922kg/h. Based on this hydrogen mass flow rate and the energy content of hydrogen, particularly the LHV, the theoretical energy output would be approximately 26,630.6 MJ/h, based on the formula applied in the methodology. On the gasification performance aspect, the mass fraction of respective gases was 38.3%, 17.3%, and 0.96%, for CO , H_2 and CH_4 respectively, the rate of gas production was 1.27, calculated based on the formula employed in the methodology. Carbon conversion efficiency (CCE) and cold gas efficiency (CGE) of 93.6% and 84%, respectively, were observed during the study.

Conclusion

Cashew nutshell has been validated as a viable, after knowing the values of cold gas efficiency and carbon conversion efficiency, which were respectively 84% and 93.6%, sustainable feedstock for hydrogen production through gasification. The study found that higher temperatures improve hydrogen yields and can enable catalyst-free operation, which reduces reactor complexity and costs. Temperature is the main factor influencing hydrogen production; pressure has no effect within the examined range. Theoretical energy output from CNS-derived hydrogen is significant, supporting energy diversification and resilience in cashew-producing countries. A comprehensive waste-management strategy for cashew nutshells can reduce environmental impact, generate local employment, and add value to the cashew industry.

Conclusion

This study, after calculating the cold gas efficiency and carbon conversion efficiency, which were respectively 84% and 93.6%, concludes that cashew nutshells are a promising and sustainable biomass feedstock for hydrogen production through gasification. Characterisation of the feedstock, as shown in **Table 9**, confirms CNS's favourable physical and chemical properties, including low ash and moisture content, high volatile matter, and elevated levels of hydrogen and carbon, making it energy efficient and environmentally friendly. The three main strategies proposed by the stakeholder engagement, education, and planned waste management form the socio-environmental model, offering a solution to environmental damage caused by unmanaged CNS waste. Sensitivity analysis identifies temperature as the most influential parameter on hydrogen yield, which increased to 221.922 kg/h when temperatures ranged from 650°C to 800°C, as well as decreasing the CO_2 and CH_4 from 165.407 kg/h to 165.40655 kg/h, and 12.34227 to 12.342 kg/h, respectively, while the impact of pressure appears to be negligible. The theoretical energy yield, calculated from hydrogen mass flow, was estimated at 26,630.6 MJ/h, demonstrating its substantial potential to contribute to Guinea-Bissau's energy mix and address issues related to electricity shortages. Simulation results indicate that effective hydrogen production is achievable without catalysts, especially at higher temperatures.

Study limitation

Several limitations were observed during this study, although it offers a promising simulation for assessing the hydrogen production potential using cashew nutshells via gasification in Guinea-Bissau. Some of the limitations observed are listed in the following points.

- Primarily, the lack of proper tests under local operational conditions means that actual gasification performance, hydrogen yield, and system stability remain unverified.
- Concerns regarding the climate conditions and regional differences between Togo and Guinea-Bissau may impact the accuracy of the gasification performance predictions. This geographical mismatch increases uncertainty in feedstock representation.
- Since the simulation assumes steady-state conditions, it omits crucial factors such as transient reaction dynamics, ash behaviour, heat loss, and tar formation, which may lead to an overestimation of hydrogen yield and energy efficiency, particularly for heterogeneous feedstock like CNS.
- The study also does not incorporate a catalytic effect in the gasification process, limiting the scope of process optimisation. The parameters used during the sensitivity analysis may have constrained the identification of more optimal or efficient gasification conditions.
- The recovery factor of 60% does not fully reflect absolute values due to inefficiencies in cashew nutshells collection, transportation, and handling. Additionally, the omission of all aspects related to economic and political analysis presents a significant barrier to translating technical feasibility into practical application deployment.

Future works and recommendations

For future work, it will not be long before relying on the economical aspect, catalysts and investigations related to other parameters, such as residence time, steam-to-biomass ratio, and equivalence ratio, to determine which of these parameters can positively influence more hydrogen yields. Initially, the focus will be on these proposed catalysts. As mentioned in the literature, a heterogeneous catalyst comprising K_2CO_3 and CaO is proposed for future application in this study. Heterogeneous catalysts play a vital role in promoting and increasing the yield of products in the gasification process. Both catalysts, K_2CO_3 and CaO , when introduced into two different reactors, they influence the efficiency and selectivity of the gasification reaction. These catalysts are effective for tar removal and assist in cracking and reforming tar into simpler, more valuable gases, thereby reducing the tar content in the syngas. Since the target products for transformation into hydrogen are synthetic gas (syngas), both catalysts can reform methane and establish a suitable ratio for the gasification process. These catalysts, K_2CO_3 and CaO , are also easy to separate from the reaction mixture and to regenerate.

- Experimental work will be necessary to establish economic safety to prevent losses while it is in progress. As well as environmental and techno-economic analyses, they should be conducted appropriately.
- As Guinea-Bissau has over 80 islands, the viability of local installations has to be investigated in relation to real needs. From the same perspective, a thorough survey of the areas should be conducted, since CNS potential data are absent to establish cashew nutshell potential mapping in the entire Guinea-Bissau.
- Since there exist contradictory results on pressure and its impact on syngas production, the pressure effect should be investigated carefully.

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