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A Multi-Country Assessment of the Biohydrogen-Derived Urea Potential Across West Africa from Cereal Crop Residues.

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Dedication

I dedicate this Thesis to my family, most especially my mom, Marie Davies Ann, for her continuous support, guidance, and encouragement throughout my academic journey.

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Abstract

The importation of urea fertilizer into West Africa has shown an increase over the years due population growth, which puts a threat to food security. The importation urea fertilizer is disrupted by volatile global markets which put pressure on national economies, and on fertilizer to smallholder farmers. The region possesses vast agricultural residue resources that are underutilized, despite their potential as feedstock for bio-urea production. There is a critical gap in the integration of agricultural residue-to-hydrogen and subsequently fertilizer across West Africa.

The study aims to investigate the viability of substituting the urea demand in West Africa with sustainable, locally viable resources to create a circular economy to improve agricultural production. To achieve this, the urea production potential was estimated through the conversion of residues of high-yielding cereals into biohydrogen through the process of biomass gasification, followed by ammonia and urea synthesis using a stoichiometric model. The outcome was geospatially represented using Quantum Geographic Information System (QGIS) software version 3.30.0. System and conversion efficiencies benchmarks, idealized biomass gasification and water-gas shift, the Haber-Bosch process, and urea synthesis via the Haber- Meiser reaction were utilized. An economic analysis capturing surplus and gap matrix with a novel Tiered Benchmark Scoring System aligned with Economic Community of West African States (ECOWAS) self-sufficiency goals was used to assess the urea coverage across the nations. Results show a sharp difference across the 16 West African states for both technical biomass availability and biohydrogen potentials. Nigeria shows a lead with 36.61Mt/year in technical potential. Similar recordings of technical biohydrogen output were observed: Nigeria yields up to 14.8 Kt/year, with Niger, Mali, and Burkina Faso showing substantial technical potential. The corresponding ammonia yields indicate Nigeria could produce 303.8 Kt/year, while Niger reaches 192.5 Kt/year. Urea synthesis estimates place Nigeria at 466 Kt/year, far ahead of other countries like Ghana (75.9 Kt/year) and Mali (235.4 Kt/year). An economic gap analysis highlights countries exceeding national fertilizer needs, such as Niger, Burkina Faso, and Guinea, where substitution percentages reach over 2,000%. Conversely, Côte d'Ivoire and Nigeria face sizable gaps, covering only 54% and 76% of national urea demand, respectively. The results obtained from the Tier Benchmark Scoring Analyses reveal that some countries, like Niger, far exceed their fertilizer needs and could become exporters and regional hubs, while others face supply shortfalls. These findings emphasize the importance of tailored infrastructure, residue mobilization strategies, and scalable technologies, ranging from modular biorefineries to decentralized urea systems. By bridging agricultural waste with green fertilizer synthesis, this study offers a roadmap for a circular economy for agricultural residue and agricultural resilience in West Africa.

Key words: agricultural residues, gasification, biohydrogen, green fertilizer, circular economy.

Résumé

Les importations d'engrais à base d'urée en Afrique de l'Ouest ont augmenté au fil des ans en raison de la croissance démographique, qui constitue également une menace pour la sécurité alimentaire. La volatilité du marché mondial des importations exerce une pression sur les économies nationales et sur les petits exploitants agricoles. La région dispose de vastes ressources en résidus agricoles qui sont sous-utilisées, malgré leur potentiel en tant que matière première pour la production de bio-urée. Il existe un écart critique dans l'intégration des résidus agricoles en hydrogène, puis en engrais, en Afrique de l'Ouest.

L'étude vise à examiner la viabilité du remplacement de la demande en urée en Afrique de l'Ouest par des ressources locales durables afin de créer une économie circulaire pour améliorer la production agricole. Pour ce faire, le potentiel de production d'urée a été estimé grâce à la conversion de résidus de céréales à haut rendement en bio-hydrogène par le biais d'un processus de gazéification de la biomasse, suivi d'une synthèse d'ammoniac et d'urée à l'aide d'une modélisation stœchiométrique. Les résultats ont été représentés géo-spatialement à l'aide du logiciel QGIS version 3.30.0. Des références en matière d'efficacité des systèmes et de conversion, une gazéification idéalisée de la biomasse et une conversion eau-gaz, le procédé Haber-Bosch et la synthèse de l'urée via la réaction Haber-Meiser ont été utilisés. Une analyse économique tenant compte de la matrice des excédents et des déficits, avec un nouveau système de notation par niveaux aligné sur les objectifs d'autosuffisance de la Communauté économique des États de l'Afrique de l'Ouest (CEDEAO), a été utilisée pour évaluer la couverture en urée dans les différents pays. Les résultats montrent des différences marquées entre les 16 États d'Afrique de l'Ouest en termes de disponibilité technique de la biomasse et de potentiel de bio-hydrogène. Le Nigeria arrive en tête avec un potentiel technique de 36,61 Mt/an. Des résultats similaires ont été observés pour la production technique de bio-hydrogène : le Nigeria produit jusqu'à 14,8 Kt/an, tandis que le Niger, le Mali et le Burkina Faso présentent un potentiel technique important. Les rendements correspondants en ammoniac indiquent que le Nigeria pourrait produire 303,8 Kt/an, tandis que le Niger atteindrait 192,5 Kt/an. Les estimations de la synthèse d'urée placent le Nigeria à 466 kt/an, loin devant d'autres pays comme le Ghana (75,9 kt/an) et le Mali (235,4 kt/an). Une analyse des écarts économiques met en évidence les pays qui dépassent leurs besoins nationaux en engrais, tels que le Niger, le Burkina Faso et la Guinée, où les pourcentages de substitution atteignent plus de 2 000 %. À l'inverse, la Côte d'Ivoire et le Nigeria sont confrontés à des écarts importants, ne couvrant respectivement que 54 % et 76 % de la demande nationale en urée. Les résultats obtenus à partir des analyses de notation comparative révèlent que certains pays comme le Niger dépassent largement leurs besoins en engrais et pourraient devenir des exportateurs et des pôles régionaux, tandis que d'autres sont confrontés à des pénuries d'approvisionnement. Ces conclusions soulignent l'importance de mettre en place des infrastructures adaptées, des stratégies de mobilisation des résidus et des technologies évolutives, allant des bioraffineries modulaires aux systèmes décentralisés d'urée. En établissant un lien entre les déchets agricoles et la synthèse d'engrais verts, cette étude propose une feuille de route pour une économie circulaire des résidus agricoles et la résilience agricole en Afrique de l'Ouest.

Mots clés : résidus agricoles, gazéification, bio-hydrogène, engrais verts, économie circulaire.

Acronyms and Abbreviations

AVCRs:	**Average Value Cost Ratios**
CRFs:	Controlled-Release Fertilizer
FAOSTAT:	Food and Agricultural Organization Statistic Tool
GDP:	Gross Domestic Product
GFT:	Green Fertilizer Technologies
GHG:	Greenhouse gas
GWP:	Global Warming Potentials
HRES:	Hybrid Renewable Systems
IEA:	International Energy Agency
IFA:	International Fertilizer Association
IFDC	International Fertil
LHV:	Lower Heating Value
MOP:	Muriate of Potash
NPK:	Nitrogen, Phosphorus, and Potassium
PAW:	Plasma-Activated Water
PV:	Photovoltaic
RE:	Renewable Energy
RPR:	Residue to Product Ratio
SAF:	Surplus Availability Factor
SDGs:	Sustainable Development Goals
SNF:	Synthetic Nitrogen Fertilizers
SSA:	Sub-Saharan Africa
TRL:	Technology Readiness Level
UAN:	Urea blended with Ammonium Nitrate Solution
WASCAL:	West African Science Service Centre on Climate Change and Adapted Land Use

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

Table of Contents

INTRODUCTION

Background

West Africa is well known for its agricultural economy, which harbors vast employment for its people and significantly contributes to its gross domestic product (GDP). The population growth of the region is currently recorded at 466,527,806 with an annual growth of 2.3% [1], which adds a burden to its agricultural sector. The region stands at a crossroad in its agriculture and climatic impact strategies, due to taking the toll of the plunging cost of imported fertilizers and the environmental impacts of anthropogenic practices. Based on the International Fertilizer Association (IFA), about 60% of the global nitrogen-based fertilizer consumed is Urea [2]. However, conventional urea production relies on ammonia produced from fossil sources via the Haber- Bosch process. It is estimated that approximately 1.6tons of carbon dioxide (CO_2) are emitted per ton of urea produced [3]. Based on the reference, there is a strong need to decarbonize the agricultural sector. To create a climate-neutral zone, researchers and industrial stakeholders are looking into low-carbon hydrogen and an integrated renewable energy system. An alternative to the conventional pathway is from water electrolysis powered by a solar photovoltaic (PV) system and hydrogen from biomass gasification shows a promising approach.

Urea fertilizer is the most widely utilized nitrogen-based fertilizer in the region. However, the importation of this fertilizer exposes the region to volatile global markets, logistical disruptions, and currency fluctuations. Nigeria is the only country in the region with an industrial-scale urea production-Dangote Fertilizer and Notore Chemical [4]. This shows a high dependency on the importation of fertilizer across the region. Nigeria's urea production uses natural gas as feedstock for hydrogen production. The major importing country of Nigeria's urea manufacture is Brazil, with 79% of its urea import in 2020 and 83% in 2021 [5]. This shows an increase in production capacity and volume, increasing the exports to 202% in 2021 [5].

The synthesis of Urea Fertilizer is from ammonia (NH_3), which itself is produced through the Haber-Bosch Process, which combines hydrogen with nitrogen from the air under high temperature and pressure.

Current NH_3 production depends on hydrogen driven from Natural gas, a carbon-intensive pathway that contributes significantly to greenhouse gas (GHG) emissions. The limitation of West Africa's domestic refining and petrochemical capacities, and skilled workforce, puts it in need to import large-scale both hydrogen-derived ammonia and final urea products.

Recent advances made in the field of green hydrogen production, particularly in the use of the thermochemical gasification process on agricultural crop residues, offer an opportunity for West Africa to readjust its energy and agricultural sectors to be more reliable.

The region has extensive biomass reserves, which include agricultural residues, wood biomass, and forest biomass. As reported by [6], Niger's Agadez region recorded a biomass anomaly of +268%**,** while Tahoua reached +163% in the year of 2024, indicating feedstock availability during seasonal peaks. Biomass remains the primary energy source for 81% of West Africans, and demand is expected to rise to 720 million Africans dependent on biomass by 2030 [7].

Transitioning to a domestic-based fertilizer manufacturing using biohydrogen in the synthesis of NH_3 from cereal-based crop residues such as maize stalk and cob, rice husks, and millet stalk, offers an environmentally friendly and economically viable alternative to fossil-based hydrogen and imported ammonia.

West Africa lacks skilled experts in hydrogen-related fields. Besides the introduction of the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) in 2021, most West African countries' universities have no hydrogen track in their curriculum, which shows a lack of research and development in the field. The WASCAL program is a timely intervention that will foster the right labour force for the region to advance to cleaner and more sustainable ways of development.

The use of renewable energy to enhance sustainability through a circular economy and mitigate climate change, the region could be self-sufficient, and its agricultural sector will flourish with hydrogen being the base feedstock for urea fertilizer manufacturing.

Moreover, with an adequate workforce, building these local manufacturing fertilizer industries in West African countries will reduce importation dependency and stabilize the supply chain of their products. This approach not only aligns with the region's climate goals under the Sustainable Development Goals- SDG 13- taking urgent action is combat climate change- but also supports SDG 7 by promoting sustainable energy use.

Problem Statement

The increasing population growth in West Africa demands the need for food security. The region is largely dependent on imported urea fertilizer to sustain agricultural productivity. Fertilizer importation represents a substantial share of agricultural expenditure. This dependency takes a toll on national economies, volatile global markets, and limited access to fertilizers for smallholder farmers. Currently, a large share of hydrogen produced globally is from a non-renewable, petroleum-based raw material, which results in a high cost of fertilizer and a significant emission of greenhouse gases. About a small percentage of hydrogen is produced from renewable energy sources through the process of electrolysis, while there are only pilot project and laboratory-based experiment on biomass to hydrogen production. Moreover, fossil-derived ammonia is used to produce conventional urea, which contributes significantly to greenhouse emissions. The region shows vast agricultural residues that are underutilized, despite their potential as feedstock for biohydrogen production. There is a critical gap in the integration of renewable energy solutions, particularly biomass-to-hydrogen conversion with fertilizer manufacturing infrastructure across West Africa.

Significance of Study

There exists neither an industrial scale nor a pilot program in which biohydrogen from biomass gasification has been subjected to urea synthesis for fertilizer production in West Africa. This research holds vital importance in the advancement of sustainable agriculture and economic flexibility across West Africa. The study examines how local resources, such as cereal residues, can be utilized to reduce reliance and cost on imported fertilizer, but most importantly, how the production process can be made green through the usage of renewables. The study supports the transition towards green urea production by using environmentally friendly feedstock like biomass and the process of gasification to attain hydrogen, which is the main feedstock in the production process. The study delved into the net economic impact for the usage of green urea for potential regional hubs for export and domestic coverage supplies.

The findings of this study provide insight into strategic renewable energy integration, agricultural productivity yield, and the attainment of the SDGs. By highlighting top-performing countries, the study helps reveal national potential and helps target capacity-building efforts. Therefore, promoting fertilizer independence and empowering local economies, West Africa stands as the beacon of green innovation for its agricultural sectors.

Research Questions

1. What are the technical potentials of biomass-based urea production using cereal crops in West Africa?
2. Which West African countries demonstrate the highest strategic suitability for decentralized biomass-based urea production based on mapping the surplus or Gap?
3. What is the net economic impact of surplus-based biohydrogen-urea production in the five leading West African countries, and how does it influence national fertilizer self-sufficiency?
4. Which West African countries stand out as potential regional and domestic hubs for Biohydrogen-based Urea production?

Research Objectives

Main objectives

To evaluate the potential, strategic suitability, of decentralized biomass-based urea production from cereal crop residues using biomass gasification in West Africa.

Specific Objectives

1. Assess the technical potentials of biomass-based urea production using cereal crops in West Africa.
2. Assess West African countries who demonstrate the highest strategic suitability for decentralized biomass-based urea production based on mapping the surplus or gap produced from their technical urea production.
3. To evaluate the net economic impact of the five top countries with surplus-based biohydrogen-urea production.
4. To categorize West African countries based on domestic coverage of urea supply percentages.

Structure of the Study

The study is organized into four main chapters. The first part of the work is dedicated to the introduction, where the state of the current fertilizer importation and consumption is highlighted. The growing demand for food security due to population growth and its consequences is shown. Moreover, alternative solutions are presented. This part encompasses the problem, the objectives of the study, and the research questions. Chapter one deals with the state of knowledge, where all global fertilizer overview is stated, with production and consumption demands. This section has been streamlined to fit the area of interest, which is West Africa. An overview of hydrogen production through the gasification method is also discussed. In Chapter Two, the methodology used to conduct this study is presented. Moreover, chapter three highlights the results found according to the different objectives followed by important discussions. Finally, the conclusion and research Perspectives are drawn in the last part of the work.

1. CHAPTER 1: STATE OF KNOWLEDGE

1.1 Global and Strategic Context

Global Fertilizer Demand and Sustainability Concerns

Global fertilizer demand has a direct correlation to global population growth. Therefore, fertilizer price shocks and sustainable alternatives need to be assessed to combat food insecurity. A study conducted by [8] assessed the impact of the global fertilizer price spike in the year 2021-2022. The objectives carried out were to examine structural vulnerabilities in the global fertilizer market, evaluate fertilizer price shocks and their impact on global demand and food security. A proxy indicator, comparative analysis on regional impact, market structure, and the integration of sustainable literature were used to carry out the study. The study concluded with the findings that there was a slight drop in fertilizer demand despite the price increase, and nitrogen production was widespread but constrained by natural gas prices. The study went further to state that an increase in the production of green fertilizer could diversify producers and hence reduce emissions. [9] looked into the sustainability concerns of Synthetic Nitrogen Fertilizers (SNF).

A comprehensive literature review on SNF was carried out, global emission data, and finally, an evaluation of mitigation strategies were carried out. The finding showed that SNF adds approximately 0.41GtCO_2e, which accounts for 0.7% of global GHG emissions. It further went on to state that promoting biofertilizers and the implementation of site-specific nutrients and a regulatory framework can serve as a mitigation strategy. [10] looked into how global and domestic price surges affect fertilizer demand and profitability. The objectives laid out in the study were to carry out a comparative study on price response and evaluate Average Value Cost Ratios (AVCRs). The methodology used was a household survey from three time periods: 2016, 2019 (pre-crisis), and 2023 (post-crisis). The feedstock of interest where maize, teff, and wheat, which constitute the country's major fertilizer crop consumption. The results obtained illustrated that fertilizer demand and yield were on the increase until the crisis but have since been stalled. Fertilizer demand price elasticity ranged from -0.40 to -1.12, higher than previous estimates, and the AVCRs remained profitable. An assessment of fertilizer demand and supply was carried out by [11] from 2007 through 2024 in Africa. The study identified gaps and suggested broader agenda for sustainable fertilizer use and agricultural productivity. The result highlighted the underexplored supply-side issues like high cost, logistics, and distribution inefficiencies. The food demand projections showed a 70% increment in global food production to meet the food demand of 2050 [12]. This increment is due to a projected population increase of 2.3 billion from 2009. The report showed that the magnitude of this growth was logged from developing countries with a fast growth rate of +114% from sub-Saharan Africa and +13% from East and Southeast Asia. An acceleration in urbanization was projected to be 70% in 2050, with a deceleration in the rural population after the peak of the 2020s. [13] investigated the projection of nitrogen demand by end use and scenario, 2020-2050. Three different scenarios were assessed, and Figure 1.1 below shows the result

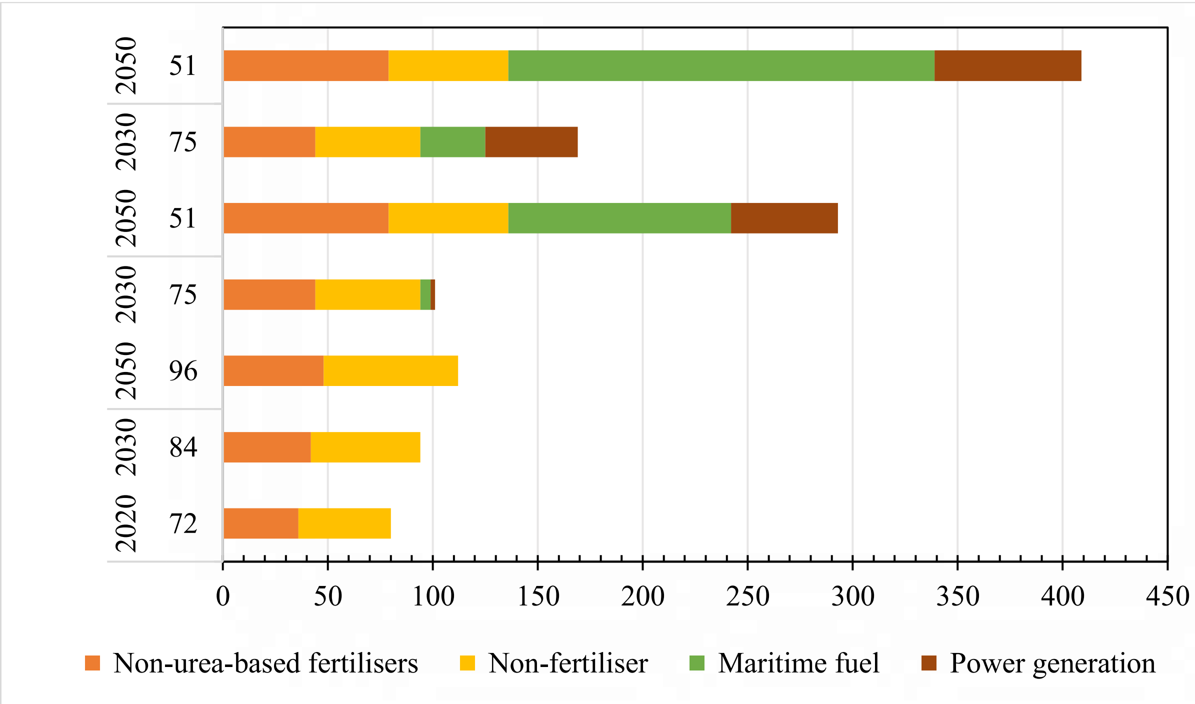

Figure 1.1: Nitrogen demand by end use and scenario, 2020-2050. Source: data source from IEA. Graph created by the Author

Importance of Nitrogen Fertilizers in Agriculture

Nitrogen is the most abundant element on planet Earth, but it is impossible for plants to use directly in its unreactive or inert gaseous form. As stated by [14] [15], plants undergo a symbiotic relationship with microorganisms in the soil to absorb the nitrogen in the form of ammonium ion (NH_4^+) and nitrate ion (NO_3^-) through their cells directly. Therefore, one of the most essential micronutrients for plant growth and production is Nitrogen (N). [16] stated that nitrogen is the building block in chlorophyll, amino acids, and nucleic acids. Therefore, nitrogen facilitates photosynthesis, cellular metabolism, and biomass accumulation. The inadequate supply of nitrogen can lead to poor root development and delay crop maturity, which directly affects the crop yield.

The importance of nitrogen as a fertilizer base became evident with the development of the Haber-Bosch process in the early 20[th] century. The Haber- Bosch process facilitates industrial-scale ammonia production from atmospheric nitrogen. The advancement of the process brought forth the Green Revolution, where synthetic nitrogen swiftly improved food production [17]. In the study of [18], the need for fertilizer in the year 2019 accounted for about 190 million tons, and out of the consumables, 57% were nitrogen-based. Furthermore, [15] stated that mineral fertilizers are the most sourced fertilizers in developing nations for crop production. [19] Ranged urea-based fertilizer amongst the most widely used in the years 2002-2019, pre-COVID-19 as shown in Figure 1.2. The types of mineral fertilizers are ammonium nitrate (AN), calcium ammonium nitrate (CAN), ammonium sulphate, NPK fertilizers, urea, and urea blend with ammonium nitrate solution (UAN). These fertilizers can be easily assimilated by crops. In 2019, just before COVID-19 took its toll in most nations, a recorded figure of 190 million tons of fertilizer was us, and 57% of it was nitrogen-based [18].

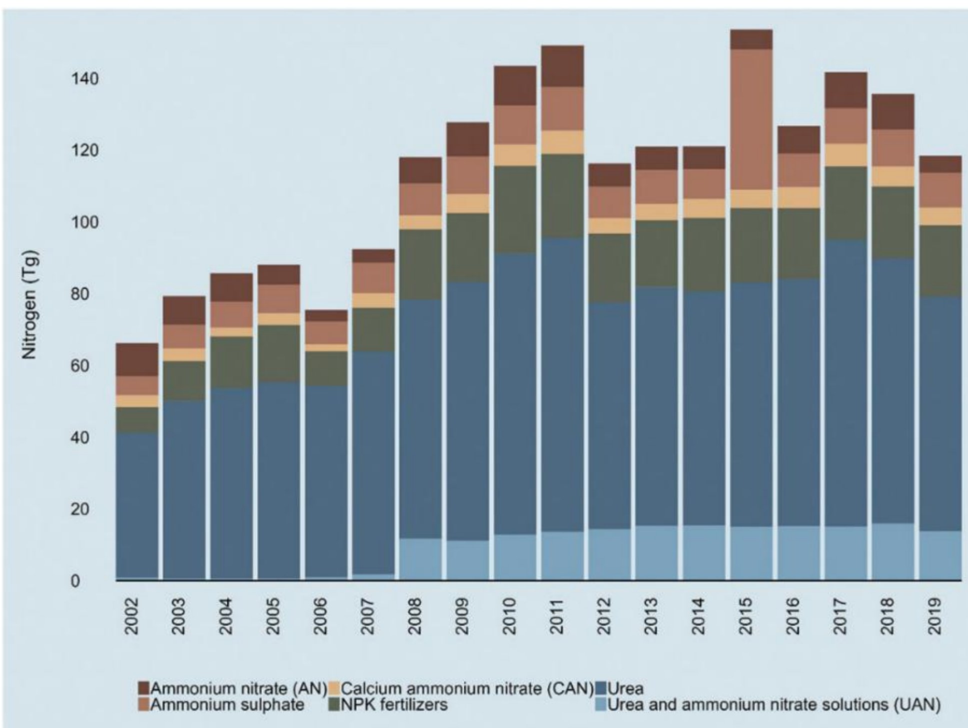

Figure 1.2: Rate of fertilizer usage from 2002-2019. Adapted from [15]

Overview of Global Fertilizer Challenges and Food Security Risks

Challenges faced by global fertilization can be associated with increased global demand due to a rise in population growth, rising cost of inputs for fertilizers, shortage of supply in the international market, domestic policies, and geopolitical risk. [20] reported that the geopolitical war between Russia and Ukraine did impact the price of fertilizer and its availability [21]. It was further stated that due to the circumstances, landlocked African countries faced severe affordability and access issues, which end up causing currency depreciation with macroeconomic imbalances. A latest report from the [22] highlighted a price surge in early 2025, recording a 15% increase in the fertilizer market, which was led by di-ammonia phosphate (+23%) and tri-ammonium phosphate (+43%). The report also emphasized the geopolitical tensions with export restrictions in China, sanctions in Belarus, and tariffs, and rounded up by stressing the cost risk due to natural gas volatility. [23] A study focused on geopolitical, environmental, and supply chain disruptions, and the findings showed that due to war, climate shocks, and trade restrictions, fertilizer supply chains tend to experience vulnerabilities. Vulnerabilities come with volatile global market prices, and as such, importers of fertilizers from producers are faced with an inadequate amount of fertilizer for their agricultural crop production. This volatility has been recorded in the study of [24], which examined the historical role of chemical fertilizer in agricultural productivity and how the global fertilizer market influences it. The study focused on developing countries. The study focused on fertilizers like urea, Di-ammonia Phosphate (DAP), and Muriate of Potash (MOP). Global price data from 2020 to 2022 were utilized in the study to illustrate the volatility. The findings showed price surges from $231 to $990, $314 to $924, and $230 to $590 per metric ton of urea, DAP, and MOP, respectively.

The impact of food insecurity in most developing countries is directly linked to the insufficient fertilizer used for maximum crop yield. As stated by [25], agricultural output is based on the use of fertilizer, and the imbalance of nutrients, and persistent food insecurity is based on the uneven distribution and the inefficient application of it. [26] investigated how fertilizer limitation in Sub-Saharan Africa (SSA) has an impact on its food insecurity. The types used were mineral fertilizers. A comprehensive literature review, evaluation mechanism, and analysis were used to examine the historical and economic factors causing the low fertilizer application in SSA. The results showed that about 70% of nitrogen is lost due to the inefficient transformation. The decarbonization of the fertilizer industries cannot be overemphasized. A study by [27] investigated the assessment of current fertilizer state industries. The study delved into novel technologies like biomass gasification, electrolysis, and mechanisms for the decarbonization of their lifecycle.

A comparative assessment was done based on conventional and low-carbon fertilizer technologies, and a discussion on the policy framework was carried out. The results of the work revealed that the production of ammonia is the most energy-intensive and the largest emitter of carbon during its manufacturing, compared to biomass gasification. The study went on to reveal that about 80% of industrial greenhouse gas (GHGs) is reduced through the production of low-carbon fertilizers. A nexus-based approach is needed to link fertilizer to energy to food security, as conventional fertilizer production adds to the emission of GHGs.

Sustainable Production Systems

Sustainable mechanisms to produce nitrogen-based fertilizer are desirable since its present production method is both energy-intensive and a high emitter of GHGs. Brown ammonia (also known as grey ammonia) is produced from a fossil feedstock through the Haber Bosch process. Blue ammonia is produced by incorporating carbon capture and storage into the production of brown ammonia. Green ammonia is supposed to be the most sustainable form, where renewables are the base feedstock used to produce hydrogen. There have been several studies carried out on the adaptation of Green Fertilizer Technologies (GFT). Research conducted by [28] used a multi-theoretical framework approach to assess the adoption of GFT in Malaysian Paddy Farmers. The paper focuses on Controlled Release Fertilizer (CRFs), biochar-enhanced urea, and nitrification inhibitors. The research findings showed that integrated model adoption is multi-faceted, and the actual adoption rate remains low, thereby highlighting a gap between intention and implementation. [29] looked into the integration of green fertilizer and renewable energy for climate climate-resilient agricultural system. The study assessed the environmental limitations of conventional fertilizer usage and synergistic benefits of converging biofertilizers and renewable energy. The methods utilized were interdisciplinary literature reviews, system-level analysis, and policy mapping. The findings of the research denote that a significant reduction in GHG emissions occurs when green fertilizers are powered by renewable energy compared to conventional fertilizers. Another key result obtained was that green ammonia produced through biomass gasification or electrolysis gives a scalable, low-carbon nitrogen output.

An innovative wind and solar integration into nitrogen fertilizer is becoming an attractive research focus. [30] investigated the influence of integrating wind and solar energy for nitrogen fertilizer production on its carbon sink. The study showed similar objectives to those of [31], but did an economic and environmental benefit assessment of renewable-powered fertilizer systems. The methodology assessed was reviewing the literature, evaluating the electrochemical hydrogen produced from the two renewable sources, comparative analysis of the carbon footprint, and lastly, energy efficiency and pollution reduction assessment, capturing the supply chain resilience. The findings of the study showed that transitioning to renewable-based fertilizer production methods and improvement will be noticed in the energy efficiency, pollution control, and resilience of the food supply chain. The Plasma-Activated Water (PAW) for a sustainable nitrogen source [32] can serve as a decentralized alternative for renewable-energy power to conventional fertilizers. The study on PAW showed that an on-site production using renewable electricity will reduce transportation costs and fossil dependency. Same as wind and solar energy, PAW also exhibits the trend of reducing the carbon footprint, air pollution, and GHG emissions compared to conventional fertilizers.

1.2 Technical Foundation

Definition and properties of hydrogen.

Hydrogen is the first element in the Periodic table with the symbol H. It contains only one electron and a proton and is known to be the most abundant element in the universe. Hydrogen exhibits a physical characteristic of being colorless, odorless, tasteless, and nontoxic. It is a diatomic gas with the ability to be an energy carrier. Hydrogen does not exist as a rare element; it is often combined with other elements to form a chemical compound. The extraction of hydrogen requires various technics. Table 1.1below gives the properties of hydrogen in detail.

Table 1.1: Physical properties of hydrogen.

Property	Hydrogen
Density (gaseous)	0.089 kg/m^3 (0°C,1bar)
Density (liquid)	70.79 kg/m^3 (-253°C, 1
bar) Boiling point	-252.76°C (1 bar)
Energy per unit of mass (LHV)	120 MJ/kg
Energy density (ambient cond., LHV)	0.01 MJ/L
Specific energy (liquefied, LHV)	8.5 MJ/L
Flame velocity	346 cm/s
Ignition range	4-77% in air by volume
Auto ignition temperature	585°C
Ignition energy	0.02J

Source: Adapted from IEA, 2019

Hydrogen production pathways

According to the energy source used, hydrogen requires different methods of production. Global hydrogen production is dominated by using fossil fuels, which accounts for 95% [33]. As stated, almost 47% is from natural gas, 21% from oil, and 27% from coal. Consequently, only 5% comes from water electrolysis, and none from biomass sources; only pilot projects are recorded. Figure 1.3 summarizes different pathways for hydrogen production

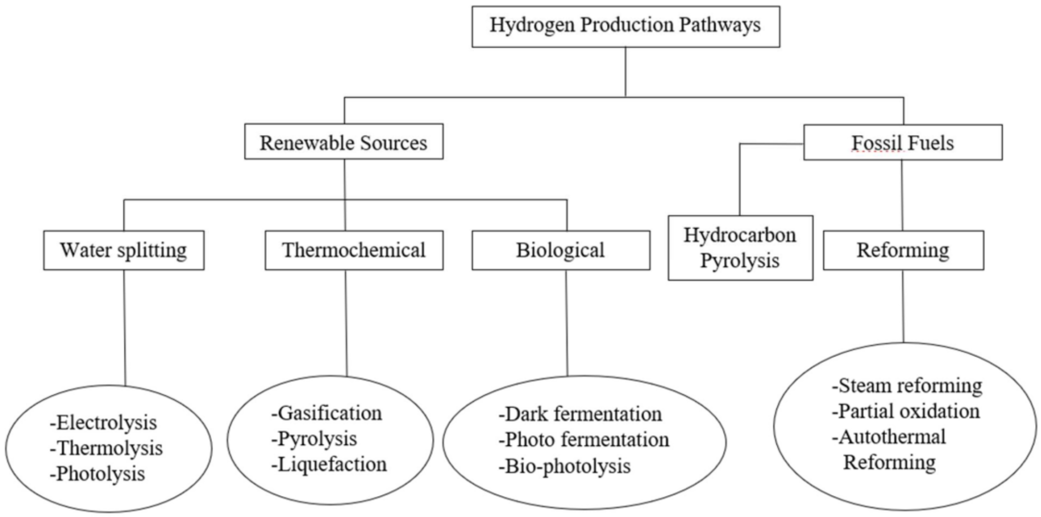

Figure 1.3: Hydrogen production pathways Adapted from (Strømholm & Rolfsen, 2021)

Hydrogen Production Using the Gasification Method

To effectively harness the potential of biomass gasification, proper feedstock pretreatment is essential. Cereal crop residues are rich in chemical energy, primarily stored as carbohydrates through photosynthesis. However, these residues can exhibit variable moisture content and chemical compositions, necessitating the evaluation of various pretreatment methods to fully capitalize on their chemical properties. By addressing these pretreatment considerations, we can unlock the potential of biomass gasification in sustainable urea production.

Pretreatment Methods

The pretreatment of biomass can be categorized into four main processes namely, Mechanical pretreatment, Thermal Pretreatment, Biological Pretreatment and Chemical Pretreatment. All these pretreatment methods are suitable for lignocellulosic biomass. For the process of Gasification, only two of the pretreatment methods will be addressed in this study.

Mechanical Pretreatment

This method is used for all biomass types [34]. Cereal crops are categorized under lignocellulosic biomass and hence are solid feedstock comprising of shape, and sizes. Mechanical pretreatments used to break down the heterogeneous mixture of different sizes into a homogeneous entity. The process involves crushing, grinding, drying and densification [35], [36]. The first step for biomass gasification pretreatment process is crushing and grinding, larger particle size has a great impact in the gasification process. This can contribute to higher amount of energy required for the breaking down of the hemicellulose and lignin component. As elaborated by [37] that decrease in particle size is directly proportional to the carbon conversion efficiency and in turn the hydrogen yield.

Thermal Pretreatment

This process involves the use of heat to reduce the moisture content in the biomass feedstock before it is subjected to the gasification process. Thermal pretreatment includes torrefaction, hydrothermal carbonization (HTC), and carbonization [38]. Torrefaction has been the most favored technique with a temperature range of 180-300 °C enhancing the upgrading effectivity of the biomass [39]. The process of torrefaction can decrease the formation of tar formation in the syngas production in the gasification process [40]. HTC techniques have the same temperature range as torrefaction but in pressure water [41]. The main production of the HTC is the hydro-char which has strong dehydration and grindability characteristics which are ideal for the gasification process [42].

As in Figure 1.3, gasification is a thermochemical process. This process converts materials that are rich in carbon, such as biomass, into a combustible gas mixture called syngas. Unlike combustion, in which feedstock undergo complete combustion to produce energy and heat, gasification operates under limited oxygen to partially oxidize the feedstock. The temperature range for a gasification process is between 700ºC to 1,200ºC, in the presence of a gasifying agent such as air, oxygen, steam, or a combination [43]. The gasification process consists of three steps, which are Pyrolysis, oxidation, and reduction. During pyrolysis, the main products formed are volatile gases, tar, and char. In the oxidation stage, products produced from the pyrolysis stage react with oxygen to generate more gases and release heat for the reduction process [44] .

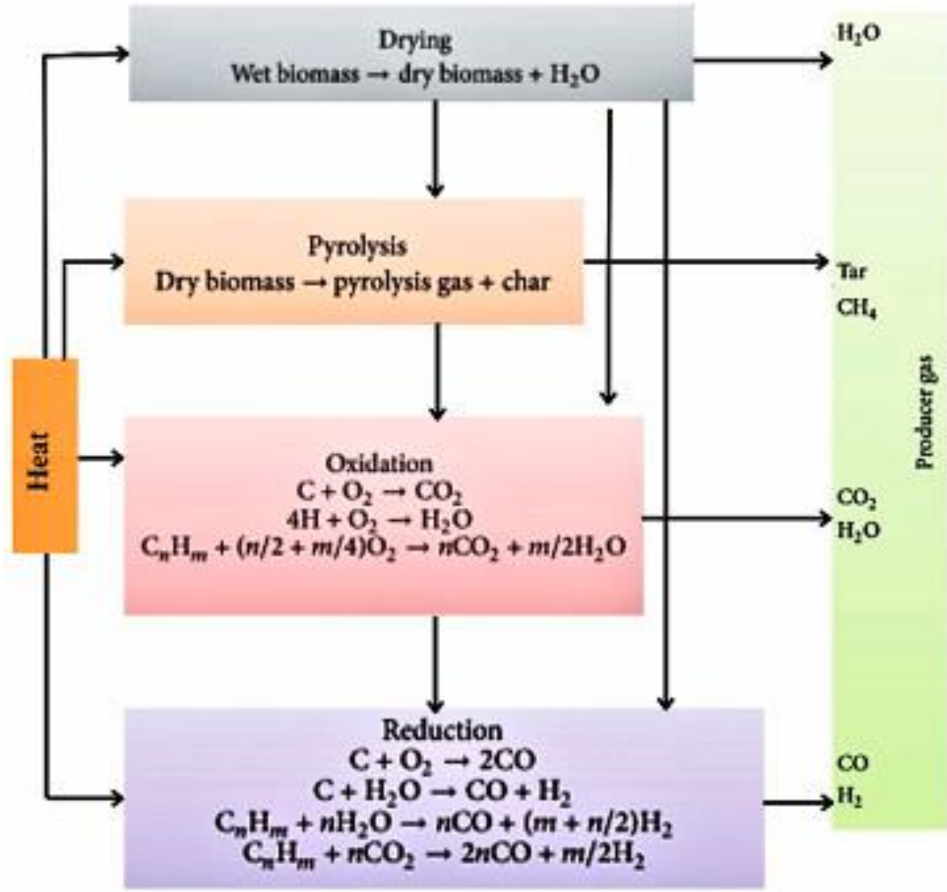

Figure 1.4: Different stages and reactions through a gasification process. Adapted from [45]

[46] Conducted a study in Brazil to carry out a comparative analysis on the techno-economic performance of using steam gasification to evaluate potential agro-residues and municipal wastes for hydrogen production. The results showed promising hydrogen production through steam gasification and stressed the need for further assessment in the optimization of the cost involved in hydrogen production. [47] focused on the economic viability of producing low-emission hydrogen through biomass gasification. This study was conducted in the United States of America with selected states, namely: Colorado (Park County), Oregon (Klamath County), and Massachusetts (Middlesex County). The study used a novel simulation model to determine the influence of biomass composition on hydrogen yield, a life cycle analysis using Argonne's GREET tool, economic analysis of the cost of hydrogen production, and sensitivity analysis. The results obtained showed a hydrogen production cost of $3.47/kg in Klamath County, Oregon, $4.11/kg in Park County, and $3.63/kg in Middlesex County.

[48] In their study did a comparative analysis on different types of gasification processes on hydrogen yield and evaluated the economic viability of gasification plants for hydrogen production. The methods used were Aspen Plus® for the estimation of hydrogen yield, the economic analysis, and the sensitivity analysis. The results obtained showed that Supercritical water gasification recorded the highest hydrogen yield, followed by conventional and then plasma gasification with a hydrogen selling price of 10 €/kg, 7 €/kg and 13 €/kg respectively. [49] Conducted a study in blending five different types of biomass residues through steam gasification to optimize the production and yield of hydrogen while minimizing unwanted by-products. Aspen Plus V.11 was used to simulate the findings, and parameters were optimized for a higher bio-hydrogen yield. The variables that were investigated in this study were: the composition of the feedstock material and to biomass ratio. The results showed that the composition of the biomass has an influence on the gasification process, and case V showed the best performance amongst the rest.

Biomass Gasification to Urea Production

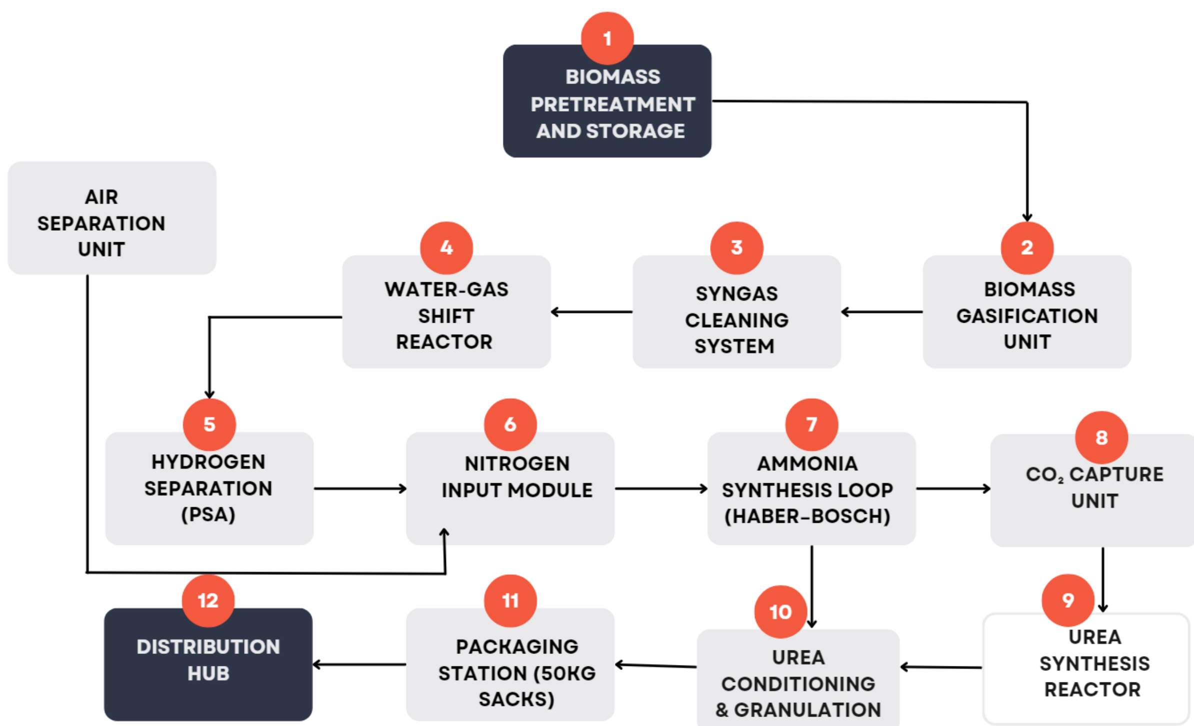

Figure 1.5: Urea Production Pathway through Gasification Process. Created by Author

The literature on biomass gasification of cereal crop-based residues is somewhat limited, particularly in its application for green urea production. Most existing studies focus on hybrid systems, highlighting a significant opportunity to explore biomass gasification as a primary method for synthesizing urea. [50] looked into Hybrid Renewable Systems (HRES) for the decarbonization of the fertilizer industry. The study assessed energy intensity and carbon footprint, as other studies stated earlier. The study concluded by stating that HRES improves energy efficiency and reliability. It further stated that a decentralized approach to HRES will enhance rural access and economic resilience. Biomass and wind integration in fertilizer production for decarbonization [51] can be a decarbonization mechanism for the agricultural sector. The study assessed the energy demand and carbon footprint of synthetic fertilizer manufacturing and evaluated the nexus of wind-powered electrolysis and biomass gasification for green hydrogen production. Technical reviews of ammonia synthesis, comparative analysis of fossil-based versus renewable-powered-based systems, case study evaluations, and environmental and economic assessment were methods used in the study. The findings showed that wind-powered electrolysis reduces ammonia-related emissions up to 90%, while biomass gasification, on the other hand, provides carbon-neutral thermal energy and hydrogen, hence promoting a circular economy. The study went on to show that HRES offers a stable energy supply. The economic viability aspect of the study was illustrated and enhanced by carbon pricing and subsidies.

Regional Biomass Potential from Cereal Crops in West Africa

Cereal crops belong to the family name Gramineae (grass family), they are mainly cultivated for their edible seeds. Cereal crops serve as the major source of carbohydrate, dietary fiber, vitamins and minerals in most West Africa stable food. Globally, it has been recorded in 2019 that about 6,006 million acres of land were utilized for the cultivation of these crops and an amount of about 2.719 million tons of grains were harvested [52]. [52], further gave out the statistics stating that the total cropland for cultivation corresponded to 60% and 50% of the world's food output and Africa records 27% of the cereal crop production.

West Africa contains vast biomass potential from cereal crops, especially from millet, rice, maize and sorghum. The residues from these crops generate large number of biomasses that could be utilized for biohydrogen production. In their study, they evaluated a multi-country using secondary data from FAO data sources. [53] gave an estimate of biomass residues across ECOWAS countries. The results suggested that maize stalk, rice husks and sorghum straw are feedstocks that are abundant. The study went further to align with the notion that these crop residues are viable for biohydrogen production. evaluated the energy potentials from agricultural residues particularly from maize stalk and cob, sorghum straw, and rice husks. This study was conducted in Benin.

They use a decade long crop production data and performed a statistical analysis, physiochemical characterization and an estimation of energy potential. The results concluded by suggesting that maize residue has the highest energy potential and allocated the northern part of Benin to be residue concentrated.

1.3 Regional Relevance and Application

Fertilizer Demand in West Africa

The region's agricultural sectors thrived based on nitrogen-based fertilizers for high crop yield. Nigeria, the most populous nation in West Africa, consumes about 1.8 million tons annually, attributing to both imported and locally produced fertilizer in the country, while Côte d'Ivoire recorded an import of 600,000 metric tons (Mt) in 2024, which shows an increase in its estimated requirement of 350,000MT [54]**.** The region's different subsidy programs and import route of fertilizer give rise to a varying fertilizer price of $25-78/50Kg bag [55]. As shown in Figure 1.6, West Africa consumes both Nitrogen and phosphate-based fertilizers.

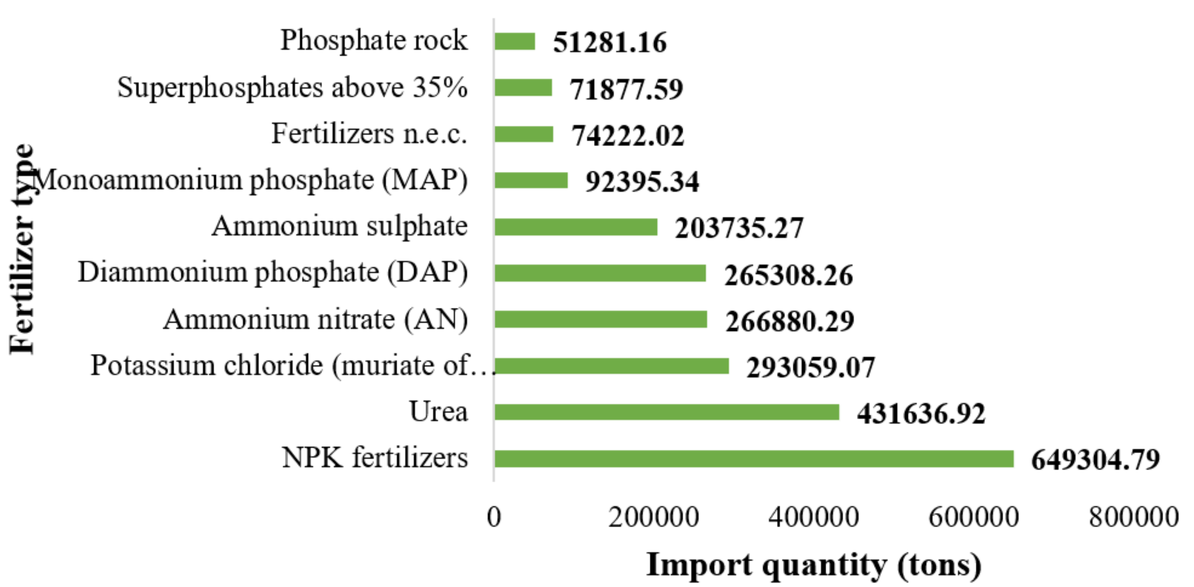

Figure 1.6: Fertilizer types and import quantities in West Africa. Source: FAOSTAT,2025.

Fertilizer Market in West Africa

Report from [56] gave the fertilizer market comparison of some West African countries. As stated, Côte d'Ivoire has a low post-harvest demand and an off-season crop stability demand dynamic with a surplus supply of more than 600,000 MT of imports. Its price overview showed CFA 21,000, which was equivalent to $35 per 50Kg urea bag and was seen as a potential regional supplier.

The report also showed that for The Gambia, its demand dynamic is based on rice cultivation and horticulture, with a supply status of liquid fertilizer that was adequate. The price overview that was recorded for The Gambia ranges from $17-18/50Kg urea bag.

Ghana, on the other hand, had a consistent supply because of retail availability nationwide, with a price of $28.76. Liberia experienced an urban shock on fertilizer supply with a price of $43.65-448.50. This steep increase in price was attributed to monetary depreciation and the impact of the Russian-Ukraine war, which caused disruption in the fertilizer market and hence spiked the cost. Nigeria has been the only country in West Africa that produces urea on an industrial scale, has a stable overall supply, and Minimal disruption with a urea price drop of about 0.5%

State of Urea Production in West Africa

The region shows high consumption of urea-based fertilizers compared to other nitrogen-based fertilizers [19]. All but Nigeria is the only country in the region with an industrial-scale urea production-Dangote Fertilizer and Notore Chemical [57]. This shows a high dependency on the importation of fertilizer across the region. Nigeria's urea production uses natural gas as feedstock for hydrogen production. [58] shows the figures in metric tons of urea produced by Notore Chemical Industries PLC, Indorama Fertilizers & Chemicals, and Dangote Fertilizer Limited. The increment seen in the urea production is attributed to the different start dates of the industries and hence is shown in the records. The major export country of Nigeria's urea manufacture is Brazil, with 79% of its urea exported in 2020 and 83% in 2021 [21]. This shows an increase in production capacity and volume, increasing the exports to 202% in 2021.

Table 1.2: Urea Product in Nigeria (2017-2021) in Metric Tons

HS Code	**product**	**2017**	**2018**	**2019**	**2020**	**2021**
3102100000	Urea	1,420,325	1,595,935	1,473,858	1,435,193	2,701,279

Source: AfricaFertilizer.org, 2022 edition

State of Urea Consumption in West Africa

Data from [19] showed that all 16 West African countries import Urea fertilizer. The importation of these fertilizers varies from year to year, and this can be attributed to supply chain disruptions, economic downturns, or global fertilizer market shocks. The regions import its fertilizer from North Africa, Europe, and Asia [56], which brings along vulnerabilities in pricing and supply.

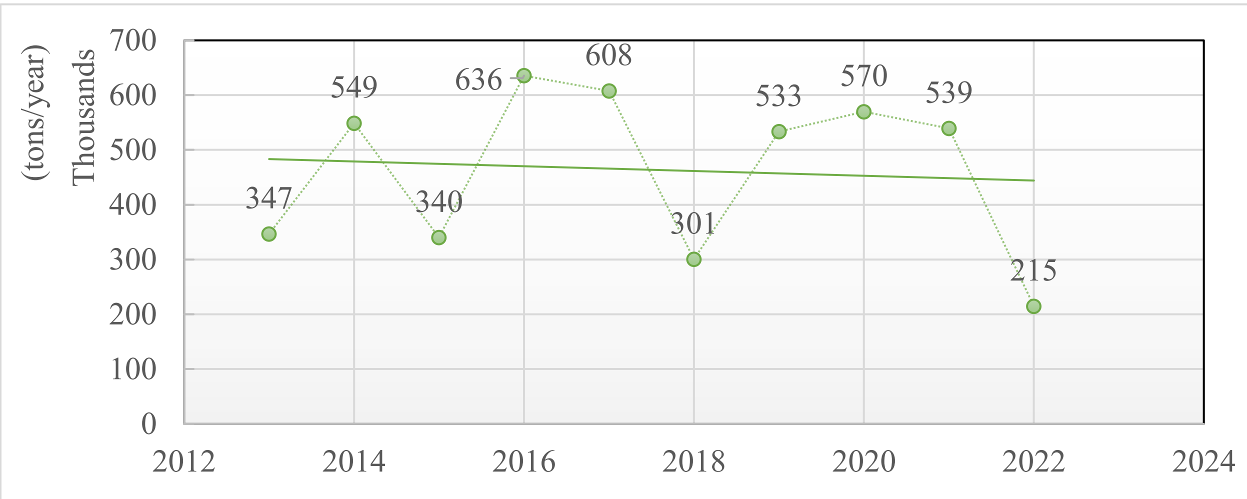

Figure 1.7: Urea consumption in West Africa (2012-2022), data source [19]. Created by Author.

A strategic industrial analysis done by [55] investigated pathways in which urea granular has been used in West Africa. The county of interest in their study where Nigeria, Ghana, Benin, and Côte d'Ivoire. The results concluded that urea granular does well in cereal crops like maize, millet rice and sorghum which are cultivated in areas of high rainfall, attributing it to good nitrogen retention. The study went on to state that about 35% of fertilizer demand is from SSA.

2. CHAPTER 2: MATERIAL AND METHODS

This research investigates a multi-phase approach for the assessment of the viability of a biomass-based urea decentralized production system in West Africa. Key parameters will be employed, such as resource quantification, process pathways, and country-level economic impact.

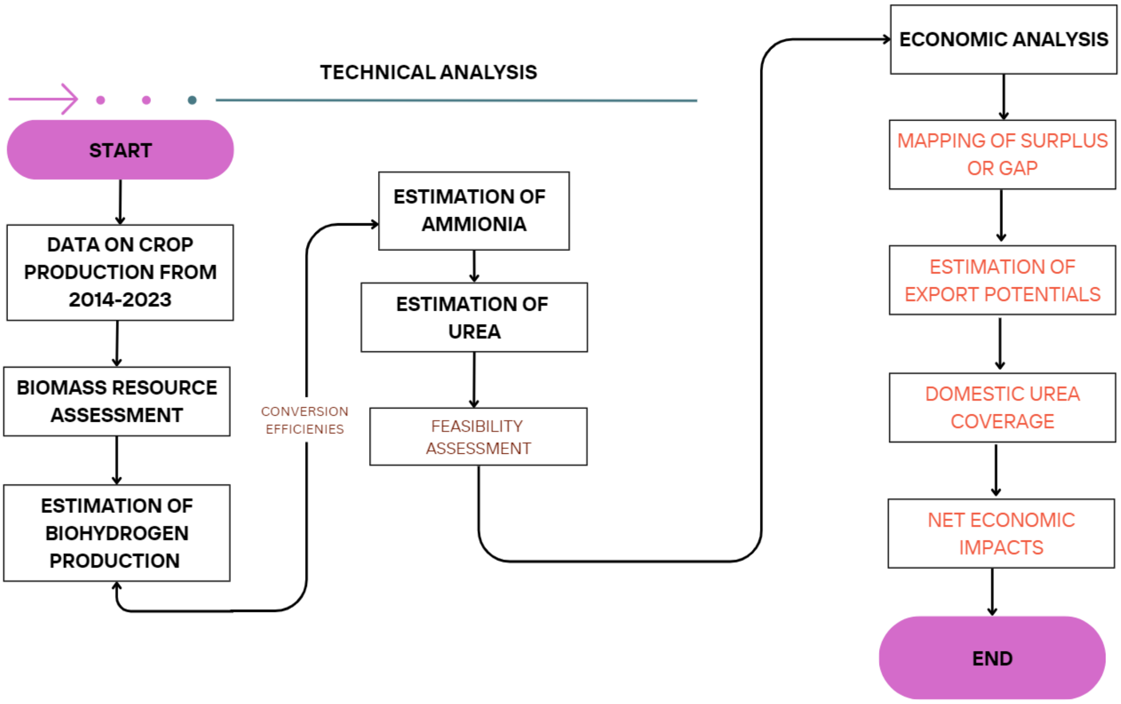

Figure 2.1: Methodological Framework

2.1 Study Area

West Africa lies between longitude 15°E and 18° W of the meridian and latitude 4ºN and 20ºN of the equator. The region extends to approximately six million square kilometers (6million km^2) and records a population of 418 million in 2021. West Africa is surrounded in the North by the Sahara Desert, in the East by the Republic of Cameroon, Adamawa, Mandara Mountains, and Lake Chad, and in the West and South by the Atlantic Ocean. It comprises four relief features, namely: The Highlands, the West African Coast, the Plateau, and the Coastal Plain. The Region is composed of 16 countries, namely: Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. The region has abundant natural and agricultural resources; its vegetation is grouped into five categories: Forest, Savanna, Desert, Montane, and

Mangrove Swamp. West Africa is challenged with food insecurity, limitations in infrastructural development, and limited access to agricultural inputs such as fertilizer [59]. The region's unemployment rate has hit a fall since the COVID-19 pandemic. As recorded by the [59], Cabo Verde showed the highest unemployment rate in the region at 15.4%, while Niger has the lowest rate at 0.8%. Nigeria, the most populous country in the region, has an unemployment rate of 9.8%, which is higher than the regional average. Other countries with relatively high unemployment rates include Mauritania at 11.5%, Gambia at 11.2%, Mali at 7.7%, and Guinea-Bissau at 6.8%.

The shift toward sustainable energy has the potential to generate a substantial number of new employment opportunities in the renewable energy (RE) sector. By 2030, it is estimated that the sector could support 38 million jobs, a figure that could rise to 43 million by 2050 [60].

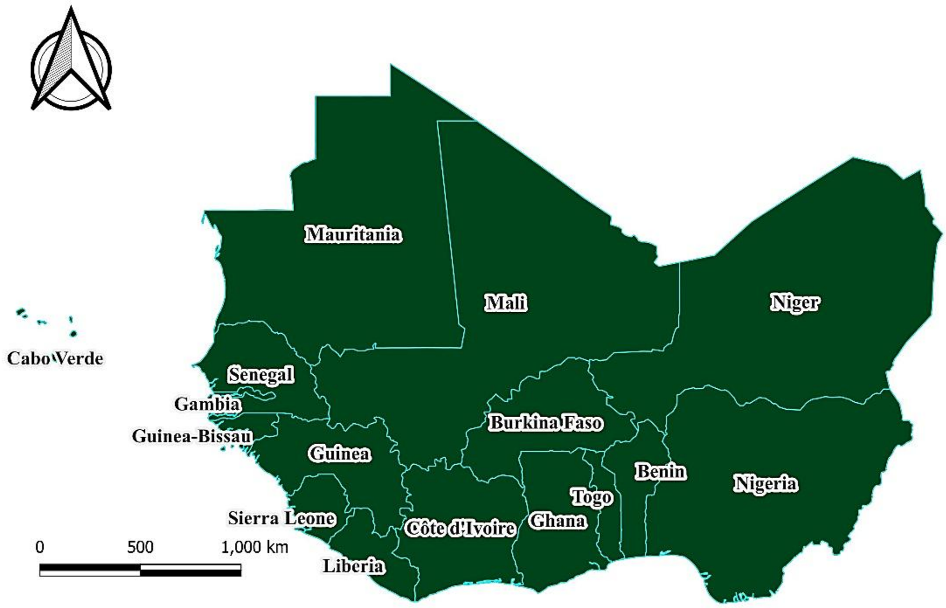

Figure 2.2: Map of West Africa showing all 16 countries.

2.2 Biomass Resource Assessment

A secondary data was obtained from Statistics Division of Food and Agriculture Organization of the United Nation [19] to compute the annual ranking of crop production using and average from a Ten (10) years interval (2014-2023) of all West African countries. The annual crop production of the four most grown cereal crops was selected from each country. The four crops were maize, millet, sorghum, and rice. The average production of these crops was computed using Microsoft Excel for each country.

Secondary data from literature reviews will be assessed to obtain proximate and ultimate analysis, that is, the moisture content, volatile matter, ash, fixed carbon, hydrogen, carbon, nitrogen, Sulphur, and oxygen of the major crop residue.

The dry mass of the biomass is computed as a pretreatment method for the gasification process using Equation 1.

Equation 1: Biomass dry mass

$$\boldsymbol{D_B = M_C \times \frac{100 - W_B}{100}}$$

Where:

D_B: *dry biomass*

M_C: *moisture content*

W_B: *wet biomass*

Equation 2: Evaluate the theoretical biomass availability

$$Q_{thc} = Cpi * RPRi \qquad [61]$$

Equation 2 is used to evaluate theoretical biomass potential.

Where Q_{thc} is the residue potential of crop i, Cpi annual production of crop i, n is the total number of residue categories, and RPRi is the residue-to-product-ration of crop i.

To attain technical biomass availability, the surplus availability factor should be considered, and this will account for all the useful biomass used either for soil aeration, animal feeds, or for environmental balance. Equation 3 is used to evaluate the technical potential that could be attained from the theoretical biomass availability [61].

Equation 3: Technical biomass potential

$$Q_{tc} = \sum_{i=1}^{n} (AFi * Q_{thc})$$

Where: AFi is the availability factor expressed in %, and Q_{thc}Crop is the technical energy potential.

Table 2.1: Table of Residue to Product Ratio (RPR) and Surplus Availability Factor (SAF)

Crop	Type of residue	RPR	SAF	Reference
Maize(corn)	stalk	1.57	0.8	[62]
	husk	0.3	0.8	
	cob	0.57	1	[63] [64]
Millet	stalk	5.53	0.8	[62]
	cob	0.29	0.6	[62]
Rice	husk	0.26	0.4	[61] [65]
	straws	1.54	0.4	[61] [65]
Sorghum	straws	1.9	0.3	[61] [65]

Table 2.2: Proximate and Ultimate Analysis Reference Table

Ultimate Analysis					Proximate Analysis				Reference
Nitrogen (%)	Carbon (%)	Sulphur (%)	Hydrogen (%)	Oxygen (%)	Moisture	Volatile Matter	Fixed Carbon	Ash Content	
0.52	45.33	0.98	6.18	46.99	3.75	55	44.3	0.7	[66]
0.26	44.61	1.02	6.23	47.88	3.05	75	22.3	2.7	[66]
0.3	44.4	0.15	6	43.8	4.9				

0.77	45	-	6.39	47.84	10	72.5	4.4	13.1	[67]
2.17	38.9	0.12	5.1	37.9	7.5	58.03	16.65	17.82	[68]
4.43	39.98	0.53	2.45	52.61	10.8	66.89	14.57	7.56	[69]
0.57	43.19	0.3	5.74	50.2	9.7	70.36	15.02	4.62	[70]

2.3 Estimation of Biohydrogen Production

2.3.1 Biohydrogen Production Through Gasification

The biomass steam gasification reaction can be expressed as follows in Equation 4.

Equation 4: Biomass gasification reaction

$$nC_xH_yO_z + mH_2O \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4CH_4 + x_5H_2O + x_6O_2 + Char + Tar$$

Theoretical Production of Biohydrogen

Assuming that the fractions of CO_2, O_2 and H_2O involved in the process are combustion products, $Char$ and Tar are residues of the process, and CH_4 In the syngas is negligible [71] Equation 4 changes to Equation 5.

Equation 5: Ideal biomass gasification

$$nC_xH_yO_z + mH_2O \rightarrow x_1CO + x_2H_2$$

To enhance the hydrogen potential in practice, a water-gas shift step is conducted after the gasification. The equation of the reaction involved is:

Equation 6: Water-gas shift reaction

$$x_1CO + x_3H_2O \rightarrow x_4CO_2 + x_5H_2$$

Equation 5 and Equation 6 are used to calculate the theoretical biohydrogen potentials. This gives rise to Equation 7

Theoretical calculations

To calculate the biohydrogen yield, Equation 5 and Equation 6 will be used

From Equation 5

$$\frac{m(C_xH_yO_z)}{n * M(C_xH_yO_z)} = \frac{m(H_2)}{x_2 * M(H_2)}$$

Then

$$\boldsymbol{m(H_2) = \frac{m(C_xH_yO_z) * x_2 * M(H_2)}{n * M(C_xH_yO_z)}} \quad \textbf{(a)}$$

Also,

$$\frac{m(C_xH_yO_z)}{n * M(C_xH_yO_z)} = \frac{m(CO)}{x_1 * M(CO)}$$

From Equation 6,

$$\frac{m(CO)}{x_1 * M(CO)} = \frac{m(H_2)}{x_5 * M(H_2)}$$

Therefore;

$$\frac{m(C_xH_yO_z)}{n * M(C_xH_yO_z)} = \frac{m(H_2)}{x_5 * M(H_2)}$$

Then

$$\boldsymbol{m(H_2) = \frac{m(C_xH_yO_z) * x_5 * M(H_2)}{n * M(C_xH_yO_z)}} \quad (\boldsymbol{b})$$

The total theoretical yield of biohydrogen from Gasification followed by Water-Gas-Shift ($\boldsymbol{m_{TTheoG_{H_2}}}$) is there for the sum of (a) and (b) to give Equation 7.

$$m_{TTheoG_{H_2}} = \frac{m(C_xH_yO_z) * x_2 * M(H_2)}{n * M(C_xH_yO_z)} + \frac{m(C_xH_yO_z) * x_5 * M(H_2)}{n * M(C_xH_yO_z)}$$

Equation 7: Theoretical biohydrogen formula

$$\boldsymbol{m_{TTheoG_{H_2}} = (x_2 + x_5) \frac{m(C_xH_yO_z) * M(H_2)}{n * M(C_xH_yO_z)}}$$

Technical Biohydrogen Production

To assess the technical potential for biohydrogen, the same procedures are examined as those of the theoretical. The only difference is the inclusion of the process efficiencies for both the gasification and water-gas shift. To carry out this step, efficiencies of the process are added to Equation 5 and Equation 6 to account for losses.

Equation 8: Technical biohydrogen gasification reaction

$$\boldsymbol{nC_xH_yO_z + mH_2O \xrightarrow{\eta_1} x_1CO + x_2H_2}$$

Biomass gasification process is shown to have an efficiency of 67% IEA, 2024a and assumption of $\eta_1 = \mathbf{67}\%$ for our work.

For the water-gas shift step, the reaction is:

Equation 9: Water-gas shift reaction

$$\boldsymbol{x_1CO + x_3H_2O \xrightarrow{\eta_2} x_4CO_2 + x_5H_2}$$

For this work, an assumption of the water-gas shift to be $\eta_2 = \mathbf{60}\%$ efficient.

To calculate the technical biohydrogen potential, Equation 8 and Equation 9 is used to generate Equation 10.

From Equation 8

$$\eta_1 * \frac{m(C_xH_yO_z)}{n * M(C_xH_yO_z)} = \frac{m(H_2)}{x_2 * M(H_2)}$$

Then

$$\boldsymbol{m(H_2) = \frac{\eta_1 * m(C_xH_yO_z) * x_2 * M(H_2)}{n * M(C_xH_yO_z)}} \quad (\boldsymbol{c})$$

Also,

$$\eta_1 * \frac{m(C_xH_yO_z)}{n * M(C_xH_yO_z)} = \frac{m(CO)}{x_1 * M(CO)}$$

From Equation 9

$$\eta_2 * \frac{m(CO)}{x_1 * M(CO)} = \frac{m(H_2)}{x_5 * M(H_2)}$$

So

$$\eta_1 * \frac{m(C_xH_yO_z)}{n * M(C_xH_yO_z)} = \frac{m(H_2)}{\eta_2 * x_5 * M(H_2)}$$

then

$$\boldsymbol{m(H_2) = \frac{\eta_1 * \eta_2 * m(C_xH_yO_z) * x_5 * M(H_2)}{n * M(C_xH_yO_z)} (d)}$$

The total technical yield of biohydrogen from gasification followed by Water-Gas-Shift ($\boldsymbol{m_{TTechG_{H_2}}}$) is given by the summation of (c) and (d) to give Equation 10

$$m_{TTechG_{H_2}} = \frac{\eta_1 * m(C_xH_yO_z) * x_2 * M(H_2)}{n * M(C_xH_yO_z)} + \frac{\eta_1 * \eta_2 * m(C_xH_yO_z) * x_5 * M(H_2)}{n * M(C_xH_yO_z)}$$

Equation 10: Technical Biohydrogen potential

$$\boldsymbol{m_{TTechG_{H_2}}} = [x_2 + (\eta_2 * x_5)] \boldsymbol{\frac{\eta_1 * m(C_xH_yO_z) * M(H_2)}{n * M(C_xH_yO_z)}}$$

Equation 6, and the ultimate analysis of the carbon, hydrogen, and oxygen of the biomasses given in Table 2.3, is used to generate the chemical formula on a molar basis for each biomass. This approach was used by [72] [73] in their study. Below are the various equations of the biomass considered in this work.

Table 2.3: Stoichiometric equation for biohydrogen production from cereal crop residues

RESIDUES	EQUATIONS
Maize Stalk	$\boldsymbol{2C_9H_{15}O_7 + 4H_2O \rightarrow 18CO + 19H_2}$
Maize Cob	$\boldsymbol{4C_{31}H_{52}O_{25} + 24H_2O \rightarrow 124CO + 128H_2}$
Millet Stalk	$\boldsymbol{C_{135}H_{217}O_{100} + 17.5H_2O \rightarrow 135CO + 108.5H_2}$
Millet Cob	$\boldsymbol{C_{125}H_{212}O_{100} + 25H_2O \rightarrow 125CO + 131H_2}$
Rice Husk	$\boldsymbol{C_{137}H_{214}O_{100} + 37H_2O \rightarrow 137CO + 125H_2}$
Rice Straw	$\boldsymbol{C_{137}H_{100}O_{135} + 2H_2O \rightarrow 137CO + 52H_2}$
Sorghum Straw	$\boldsymbol{C_{115}H_{181}O_{100} + 15H_2O \rightarrow 115CO + 98H_2}$

2.4 Reaction Stoichiometry for Ammonia and Urea Production

2.4.1 Reaction Stoichiometry for Ammonia

Ammonia (NH_3) is synthesized industrially through the Haber-Bosch process, a cornerstone to produce fertilizer. The balanced chemical reaction to produce Ammonia can be stated as:

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad (1)$$

The stoichiometry implies that 1 mole of Nitrogen (N_2) reacts with 3moles of hydrogen (H_2) to produce 2moles of NH_3. From this ratio, the basis for the estimation of the theoretical ammonia yield and deducing the technical ammonia yield through the conversion efficiency for decentralized fertilizer production is established.

The Molar mass of H_2 =2.016g/mole

The molar mass of NH_3 =17.031g/mole

The technical biohydrogen produced from each of the 16 West African countries will be used for the calculation of their ammonia potential through the stoichiometry pathway.

The steps to be carried out in this research work are stated as follows:

Step 1:

Converting the technical biohydrogen produced from the 16 countries from **mass to moles**. This is done by using the conversion factor of

$$\mathbf{1ton = 1 \times 10^6 grams}$$

Then using the formula:

$$n = \frac{m}{M} \qquad (2)$$

where n: moles

m: mass of compound

M: molecular mass of the compound

Step 2:

Calculating the technical moles of Ammonia.

Knowing that 3moles of H_2 produces 2moles of NH_3, then to evaluate the number of moles of NH_3 produced from the technical biohydrogen, this formula would be used.

$$Xmoles\ of NH_3 = \frac{Ymoles\ of\ H_2\ \times 2moles\ of\ NH_3}{3moles\ of\ H_2} \qquad (3)$$

Step 3:

To get the mass of Ammonia produced, equation 3 will be used, and the mass will be made the subject of the relation.

$$m = n \times M \qquad (3)$$

For simpler and error-free methods, these steps will be subjected to Microsoft Excel for the calculations.

Now, to evaluate the technical Ammonia produced, conversion efficiency will be considered.

$$Technical\ NH_3\ Produced = Conversion\ Effeciency\ \times mass\ of\ NH_3 \qquad (4)$$

Table 2.4: Benchmark Conversion Efficiencies

Conversion Efficiencies	Efficiency (%)	Reference
Biomass → H2	67	[74]
H2 Purification WGS. PSA	WGS- 60, PSA-70-72	[75]
NH3 Synthesis (Haber – Bosch)	55-71	[76]
Urea Synthesis & Recovery	70-87	[77]

2.4.2 Reaction Stoichiometry for Urea Production

The **Bosch–Meiser process** is an industrial process for the large-scale manufacturing of Urea, a valuable nitrogenous chemical. Using the Bazarov reaction in which carbon dioxide (CO_2)

and ammonia ($\boldsymbol{NH_3}$) are converted to ammonium carbamate $NH_2\,COONH_4$ (reaction 5) which then passes through a dehydration process to urea (reaction 6) [78]

$$\boldsymbol{2NH_3 + CO_2 \rightarrow NH_2\,COONH_4\,(carbonate)}\ \ (\mathbf{5})$$

$$\boldsymbol{\Delta H^O = -136.2\,\frac{kJ}{mol}}$$

$$\boldsymbol{NH_2\,COONH_4 \rightarrow NH_2\,CONH_4 + H_2\,O}\quad (\mathbf{6})$$

$$\boldsymbol{\Delta H^O = -17.6\,\frac{kJ}{mol}}$$

This means:

2moles of NH_3 will produce 1mole of Urea

The Molar mass of NH_3=17.031g/mole

The molar mass of Urea = 60.06g/mole

As done in the earlier calculation for the Ammonia synthesis, the same steps will be used to evaluate the urea synthesis. This will give rise to

Equation 11

Equation 11: moles of Urea

$$\boldsymbol{Xmoles\ of Urea = \frac{Ymoles\ of\ NH_3 \times 1moles\ of\ Urea}{2moles\ of\ NH_3}}$$

By using equation 3, and the conversion efficiency, the technical mass of Urea output can be evaluated for each of the 16 West African Countries.

2.5 Economic Analysis

2.5.1 Mapping Urea Surplus and Gap

The mapping of the surplus or Gap will give an insight into potential country exporters, importers, or countries that should co-invest in shared bio refinery hubs. To evaluate the surplus or gap chain, a comparison of the urea self-sufficiency to that of the current imported volumes is assessed. The surplus and gap modelling approach is adapted from [79],whose analysis investigated fertilizer surpluses across Chinese provinces. In his work, fertilizer surplus (FS) was defined as the difference between nutrient input (NI) and crop nutrient update (CU).

Equation 12: Fertilizer Surplus

$$FS = NI - CU$$

The study reinterprets NI as potential urea yield from cereal crop residue in West Africa denoted as UY and CU as national fertilizer demand denoted as ND. Thus, the surplus gap equation becomes:

Equation 13: Surplus and Gap

$$FS = UY - ND$$

Noting that when FS denotes a negative value, it is gap and the reverse denoted as surplus.

Assumption: This study interprets the national urea demand of the 16 West African countries as the summation of production and importation quantities of urea recorded from the year 2014 to 2023.

Substitutional Percentage (SP)

The study adapted the surplus based substitution reasoning made in the study of [79]. The metric is in line with the nutrient surplus modelling used in their study which assessed environmental and economic thresholds based on utilizing the input relative to the uptake of nutrients. Therefore, following this approach, the substitutional percentage (SP) acts as a substitute for import displacement potential. The surplus percentage equation is given in

Equation 15 where NI denotes national fertilizer import. Moreover, another study conducted by [80] estimated substitutional behavior of domestic and imported goods by using a logarithmic-linear regression approach. This approach was redesigned to fit the study perspective by evaluating SP as a fixed description of the substitutional potential.

Equation 14: Armington Elasticity approach

$$\log\left(\frac{q_i^1}{q_i^2}\right) = \propto + \varepsilon \cdot \log\left(\frac{p_i^1}{p_i^2}\right) + \mu_i$$

Where: q_i^1: quantity of domestic good *i,*

q_i^2: quantity of imported good *i,*

p_i^1, p_i^2: price of domestic and imported goods

$\log\left(\frac{q_i^1}{q_i^2}\right)$ can be redesigned without a log function to be $\frac{NI}{UY}$.

Therefore, $\frac{q_i^1}{q_i^2} = \frac{NI}{UY}$

Noting that [80] on price-based parameter, this work is mainly concerned on volume-based approach and hence conceptually aligned in focus of quantifying domestic input replacement offering a static but policy relevant measurement for import displacement potentials.

Equation 15: Substitutional Percentage formula

$$SP\ (\%) = \frac{NI}{UY} \times 100$$

2.5.2 Estimation of Export Potentials

The net economic impact of the top five countries recorded in the surplus analysis is evaluated for the export value of each country. With this computation, regional market dominancy can be evaluated. Using the benchmark for urea price of $443/ton [81]. This method aligns with the research done by [82] on global trade values of urea, where they evaluated import volumes and international prices. This study evaluates the monetary value from the excess production (Surplus) and hence Equation 16 assess the importance of knowing whether surplus potential will enable export potentials. This approach is supported by [83] stressing the importances of surplus quantification.

Equation 16: Export Potential Formula

$$Export\ Potential = Surplus\ \times International\ Urea\ Price$$

2.5.3 Domestic Coverage (percentage of local fertilizer demand met)

Utilizing the aim stated by the Economic Community of West African States (ECOWAS) regional fertilizer strategy (2022), for an increase of about 80% in local fertilizer coverage by 2030. The study is in alignment with [84] mapping exercise which evaluated the ratio of production to demand across the region. This stressed the importance of domestic coverage to reduce importation.

Equation 17: Domestic Coverage Percentage

$$\boldsymbol{Domestic\ Coverage\ Percentage = \frac{Production}{demand} \times 100}$$

Table 2.5: Criteria for Domestic Coverage

Score Tier	Coverage % Range	Interpretation
Tier 1	≥80%	Strategic target met or exceeded
Tier 2	60-79%	Progressing well
Tier 3	<60%	High import reliance

Source: Created by Author

3. CHAPTER 3: RESULTS AND DISCUSSION

3.1 RESULTS

3.2 Technical potentials of biomass-based urea production

3.2.1 Average Cereal Crop Production in West Africa (2014-2023)

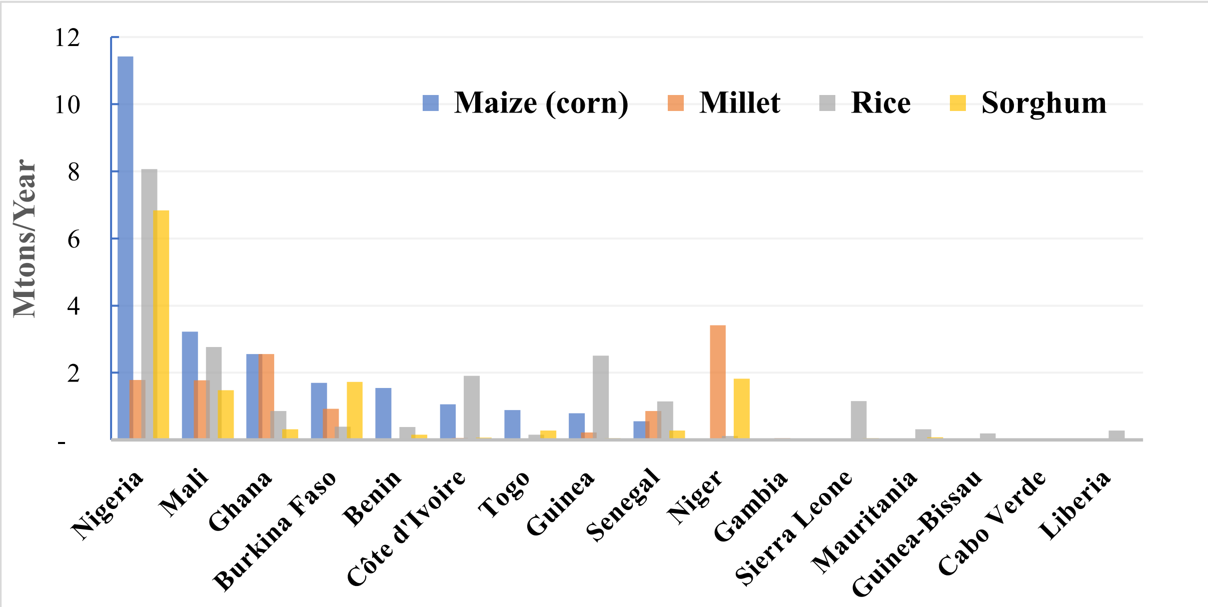

Figure 3.1: Average Cereal Crop Production 2014-2023. Data Source: FAOSTAT, 2025.

Figure 3.1 shows the average cereal crop production from all 16 West African countries. Nigeria dominates in rice and maize cultivation with approximately 11Mtons/year and 8Mtons/year, respectively. Moreover, Mali, Burkina Faso, and Niger show millet and sorghum dominance in their cereal crop production with total averages of approximately 10.5Mtons/year for Mali and 6.5Mtons/year for both Burkina Faso and Niger. Ghana and Guinea show similar crop dominancy of maize and rice, but unlike Nigeria, these countries show a lesser average crop production of approximately 5Mtons/year and 3.5Mtons/year. The Gambia, Mauritania, Guinea-Bissau, Liberia, and Cabo Verde all show fewer cereal production activities.

3.2.2 Biomass Residues from Cereal Crops in West Africa

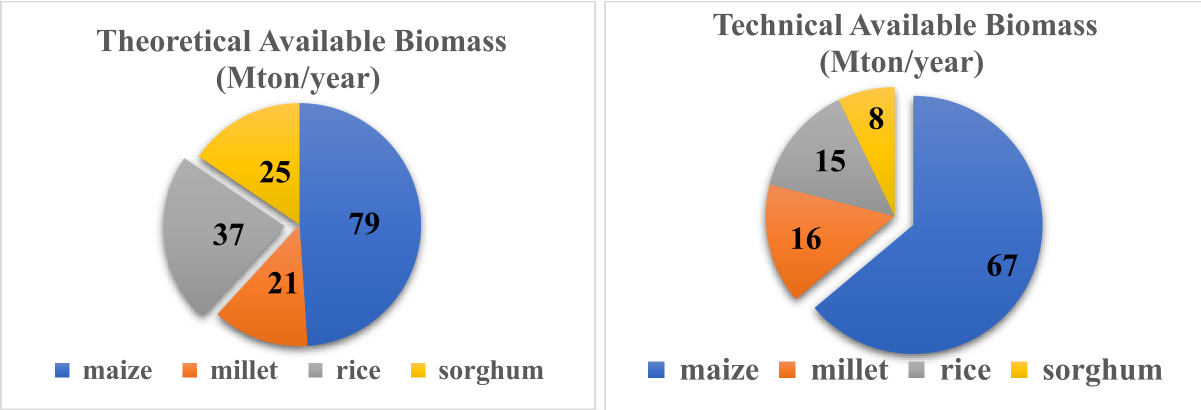

Figure 3.2: Theoretical and Technical Biomass Potential of Cereal Crop in West Africa

Figure 3.2 shows both the theoretical and technical biomass potentials from the major cereal crops in West Africa, including maize, millet, rice, and sorghum. As shown in the figure, maize residues dominate through both theoretical and technical available residue, with a reduction of approximately 12Mton/year for technical biomass availability. The technical available Biomass records the unused biomass available in the region and hence shows the difference in the theoretical and technical biomass recorded. Sorghum, rice, and millet also show a significant drop in technical value due to the RPR and SAF of the crops. However, despite this, the region still shows a significant amount of residue from cereal crops.

3.2.3 Biomass Assessment

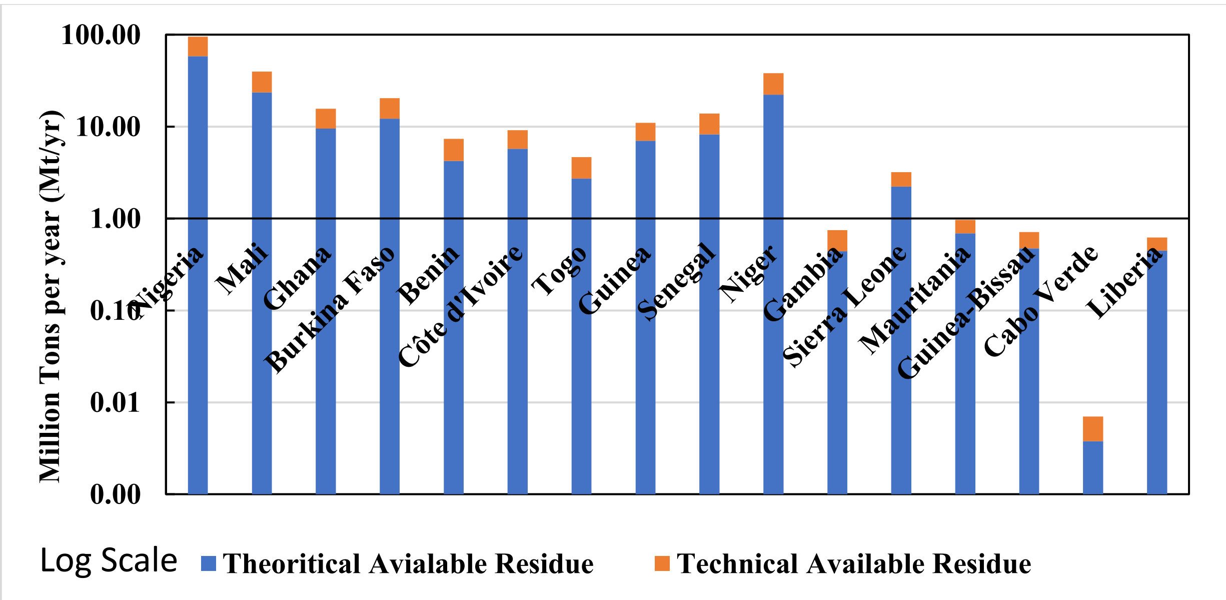

Figure 3.3: Average Annual Theoretical and Technical Biomass Potential in West Africa

Figure 3.3 shows the average annual theoretical and technical biomass potential in the sixteen West African countries. The two crucial estimates are the theoretical biomass potential, representing the gross biomass residue generated annually, while the technical biomass potential represents the realistic factors that are recoverable.

Nigeria has the highest in both the theoretical and technical available residue. Its average annual theoretical residue is estimated at 58.14 Mt/yr. This is largely made from maize, millet, rice, and sorghum. However, the technical biomass potential drops to nearly 36.61 Mt/yr. Ghana indicates a theoretically available biomass potential of about 9.52 Mt/yr, with a technically available residue dropping to 6.05 Mt/yr.

In countries like the Gambia, the theoretical residue value was much lower, with a value of 0.44 MT/YR, with a reduction of technical potential of 0.31 Mt/yr.

Similarly, Guinea-Bissau exhibits a theoretical value of 0.47 Mt/yr with a reduction of 0.24 Mt/yr technically.

This reduction can be attributed to completely shows the complete impact of factors such as field losses, logistics barriers, and the use of crops for animal feeds and soil improvement. The ratio of technical to theoretical potential ranges from 60-70%, which shows that nearly 30-48% of the biomass residue is not practically collectible under the current conditions. This shows that there is an urgent need for rural collection centers, farmer incentives, and a better transport system to capture more available biomass.

The geographical pattern also plays a crucial role in biomass potential. In Nigeria and Ghana, a high potential can be attributed to the intensive cultivation of maize, rice, millet, and sorghum. In contrast, the Gambia and Guinea-Bissau lower figures stem from the smaller agricultural scale and more dispersed production, which complicated residue aggregation

3.2.4 Estimation of Biohydrogen Potential from Biomass Residue in West Africa

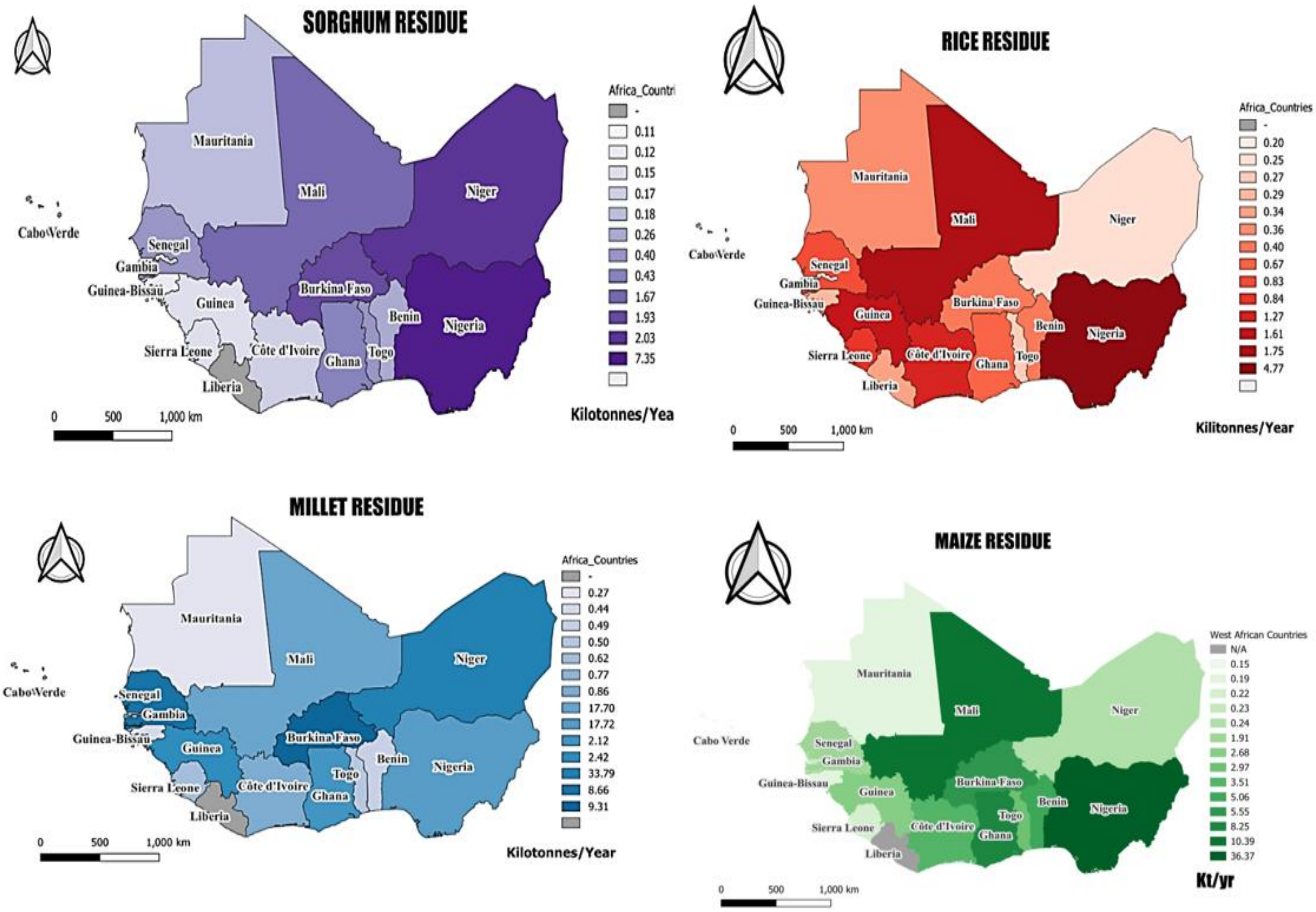

Figure 3.4: Composite map layout showing the technical biohydrogen potentials of four cereal crops across West Africa.

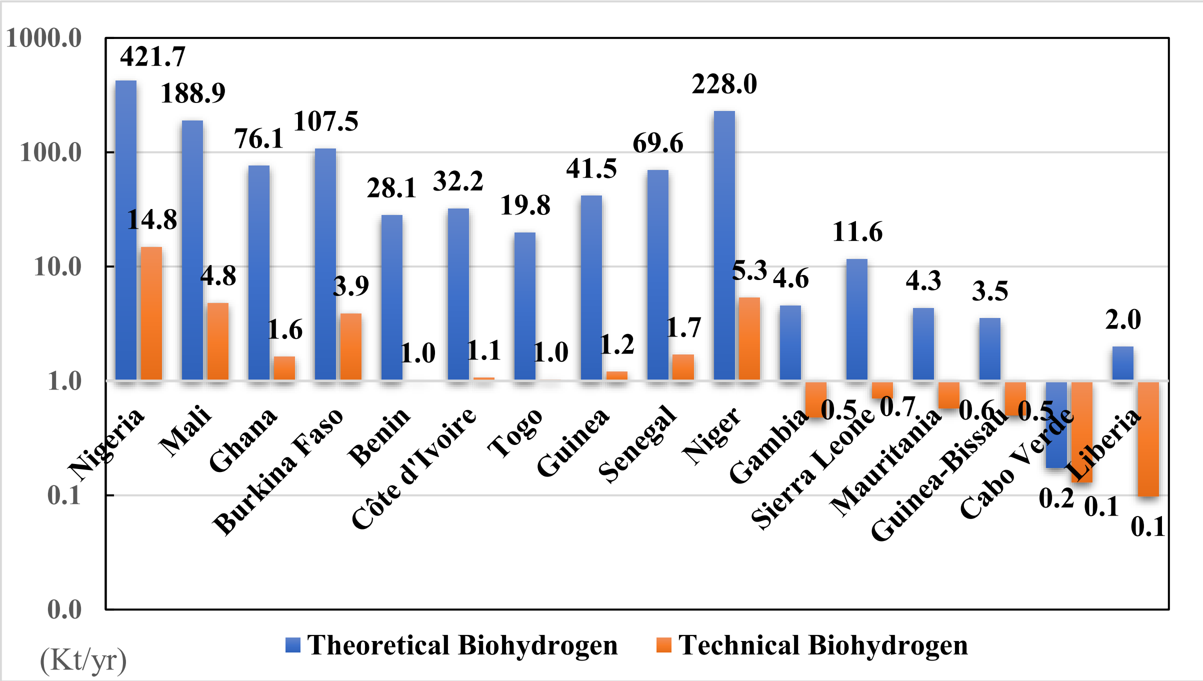

Figure 3.5: Theoretical and Technical Biohydrogen Potentials

Figure 3.5 shows the comparative evaluation of biohydrogen potential derived from cereal crop residues across 16 West African countries measured in kilotons per year (Kt/yr). Theoretical peaks are recorded in Nigeria at 421.7 Kt/yr, followed by Niger (228.0 Kt/yr), Mali (188.9 Kt/yr), Ghana (76.1 Kt/yr), and Burkina Faso (107.5 Kt/yr). In contrast, technical biohydrogen potential is considerably lower, with Nigeria leading at 14.8 Kt/yr, followed by Niger (5.3 Kt/yr), Mali (4.8 Kt/yr), Burkina Faso (3.9 Kt/yr, and Ghana (1.6 Kt/yr).

The large deviation between theoretical and technical values underscores the challenges associated with biomass mobilization. Low technical values in countries such as Liberia (0.1 Kt/yr) and Cabo Verde (0.5 Kt/yr) reflect limited residue availability and possible constraints in agricultural intensity. These findings emphasize the necessity for region-specific biomass valorization strategies, including pre-processing innovations, decentralized gasification units, and targeted infrastructural investments to bridge the gap between theoretical potential and practical biohydrogen output.

3.2.5 Estimation of Ammonia Production

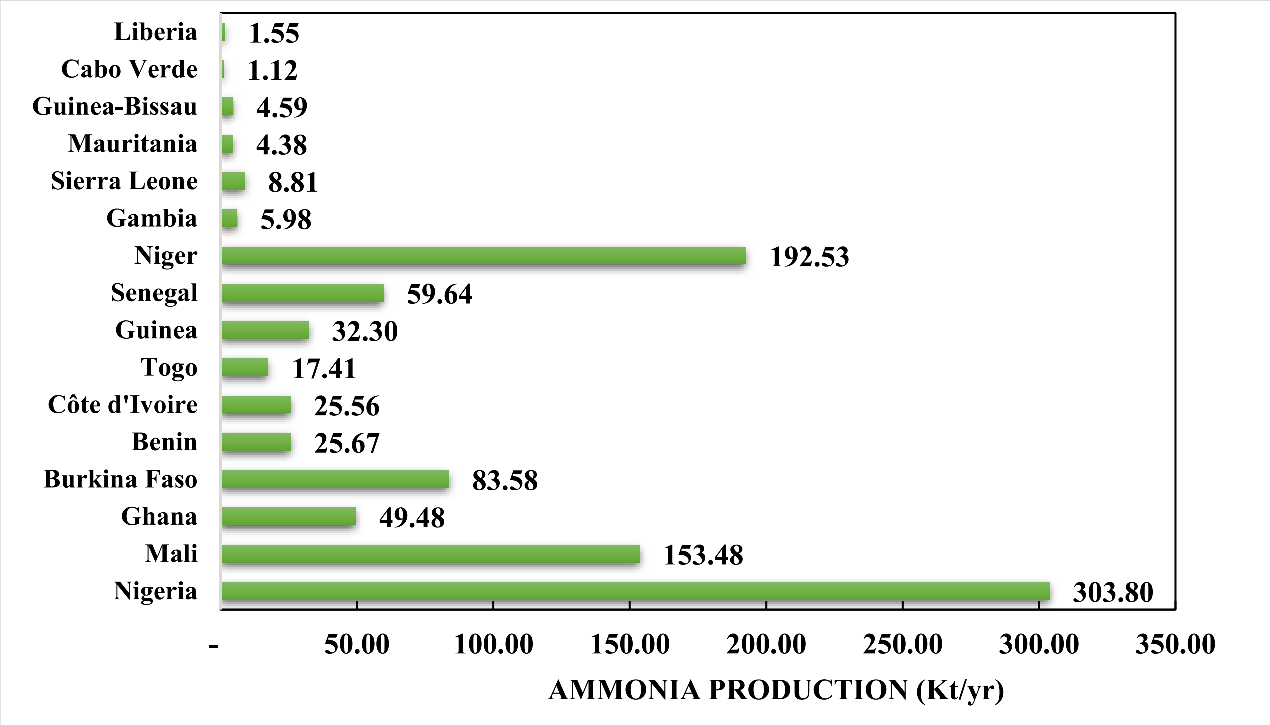

Figure 3.6 Estimates of Technical Ammonia Production

Figure 3.6 shows the estimated technical ammonia production potential in Kilotons per year (**Kt/yr**) for selected West African countries based on the hydrogen derived from agricultural biomass residues. The values reveal substantial differences across the region, largely influenced by the scale and efficiency of biomass collection and conversion.

Nigeria, with a potential of 303.8 Kt/yr, dominates the list due to its extensive agricultural sector and high availability of crop residue such as maize, millet, rice, and sorghum. This production level could significantly offset its ammonia import requirements, supporting local fertilizer industries and reducing foreign exchange expenditure.

Niger (192.5 Kt/yr) and Mali (153.5 Kt/yr) also indicate a strong potential. Niger's figure is particularly notable, reflecting a higher recovery rate or concentrated biomass availability from key crops. These countries have the potential to establish medium to large-scale green ammonia plants using biohydrogen, which can enhance domestic urea production and support food security policies.

Mid-range producers like the Gambia (8.8 Kt/yr), Togo (32.3 Kt/yr), and Benin (83.6 Kt/yr) could feasibly meet most of their national ammonia demand through locally sourced biomass. For a smaller producer such as Mauritania (4.6 Kt/yr), biomass-based ammonia may not fully replace imports but could support localized production schemes or serve as demonstration pilots for green fertilizer.

The results suggest that biomass-based ammonia is not a one-size-fits-all solution; it holds transformative potential. Larger countries could pursue an industrial-scale project, and smaller countries could benefit from a modular or community-level system.

3.2.6 Estimation of Urea Production

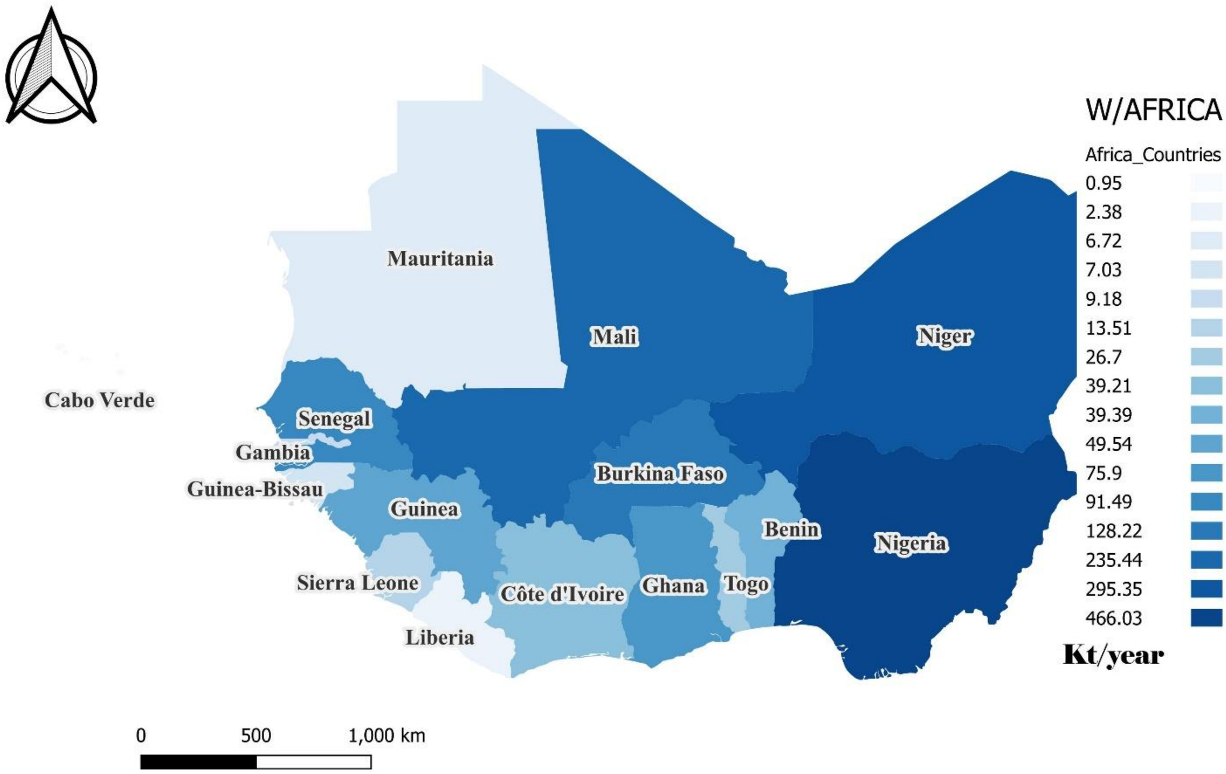

Figure 3.7: Estimates of Technical Urea Production

Figure 3.7 shows the technical urea production in kilotons per year (Kt/yr) across the West African countries, derived from the conversion of biomass-based hydrogen into ammonia and later urea. The figure outlines the disparities between and among countries, primarily driven by the agricultural residues. Most of the ammonia is converted to urea by reacting to carbon dioxide (CO_2).

Nigeria is the most prominent with a potential of 466 Kt/yr, showing its large-scale agricultural output and extensive residue streams from crops like maize, sorghum, and rice.

Niger (295.3 Kt/yr) and Mali (235.4 Kt/yr) also indicate considerable potential, attributed to vast cultivated areas and higher residue.

Burkina Faso (128.2 Kt/yr) and Ghana (75.9 Kt/yr) follow, indicating significant yet moderate capacities linked to diversified farming systems.

In contrast, countries such as The Gambia (9.2 Kt/yr), Guinea-Bissau (7.0 Kt/yr), and Cabo Verde (0.9 Kt/yr) present relatively modest figures, consistent with their smaller agriculture footprints. Nonetheless, even these lower values are notable when compared to local fertilizer demands. The Gambia's potential of 9.2 Kt/yr could feasibly meet or exceed its annual urea requirements, enabling self-reliance and reducing import dependency.

3.3 Economic Analysis

3.3.1 Estimation of Surplus/Gap and Substitutional Percentages from the Technical Urea Production

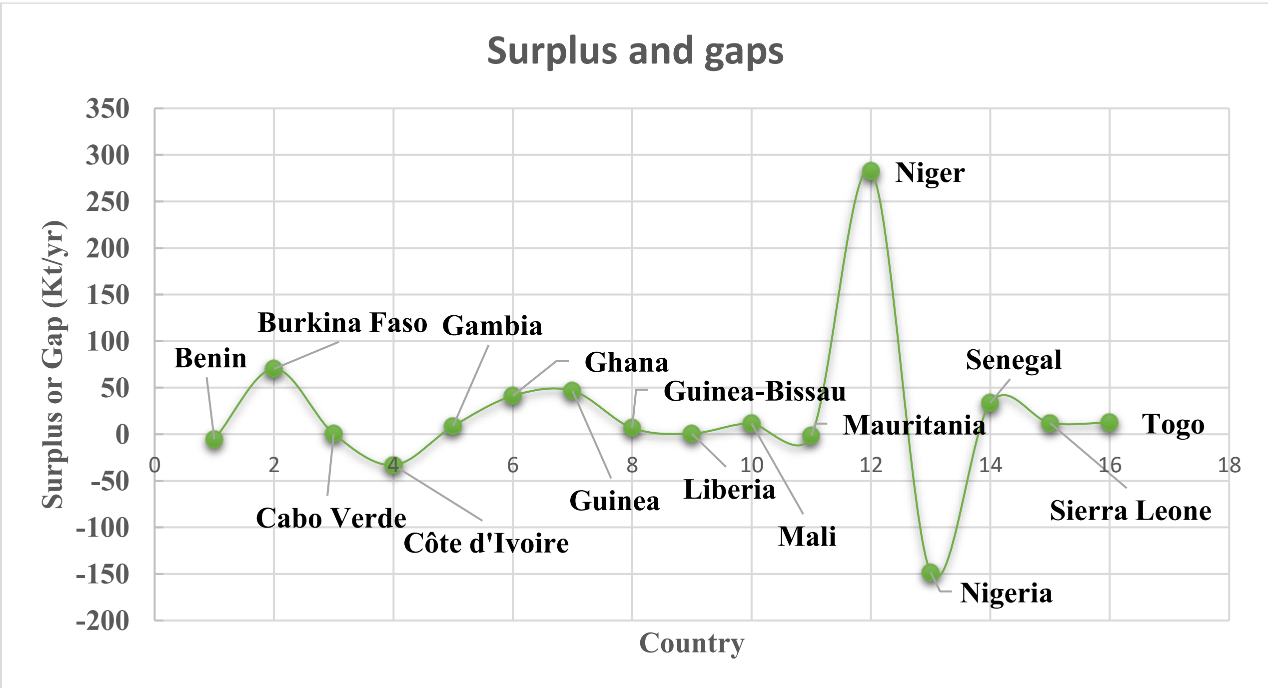

Figure 3.8: Mapping of Surplus and Gap produced from technical urea production

Table 3.1: Mapping of Substitutional percentages

Country	Urea Demand (Kt/yr)	Technical Urea Production (Kt/yr)	Substitution Percentage (%)
Benin	44.85	39.39	87.82
Burkina Faso	57.96	128.22	221.23
Cabo Verde	0.33	0.95	288.52
Côte d'Ivoire	72.30	39.21	54.23
Gambia	0.45	9.18	2,056.39
Ghana	34.64	75.90	219.12
Guinea	2.91	49.54	1,702.94
Guinea-Bissau	0.26	7.03	2,677.26
Liberia	1.64	2.38	145.47
Mali	223.76	235.44	105.22
Mauritania	8.30	6.72	80.97
Niger	12.69	295.35	2,326.80
Nigeria	614.23	466.03	75.87
Senegal	57.75	91.49	158.42
Sierra Leone	1.33	13.51	1,019.38
Togo	14.12	26.70	189.09

Table 3.1 shows the comparative analysis of the technical urea production against national demand, revealing that Niger, Burkina Faso, Guinea, and the Gambia have a substitute percentage of more than 2000%.

Despite the higher substitute percentage, Niger stands out in West Africa with a surplus gap of +282.66Kt/yr, making it the most suitable candidate for the regional hub biomass urea production. It also indicates its immense capacity for multiple decentralizing plants close to biomass sources, reducing the logistics cost and supply to the neighboring markets.

which can serve as a buffer against price shocks. Benin and Mauritania fall just below Burkina Faso and Ghana have a production potential of almost twice their local need. This suggests that they are suitable for domestic demand and reserve, self-sufficiency; this indicates that they can create an importation cut with only a little external source needed. Small biomass facilities would reduce import reliance to under 20%, which is a major improvement.

In Figure 3.8, Nigeria and Cote d'Ivoire show the opposite, with a supply gap of -148.20Kt/yr and -33.09Kt/yr. Cote d'Ivoire reflects a sharper imbalance, with a local biomass meeting on 54% of its requirements, indicating a substantial reliance on imports or the need for alternative domestic production. Nigeria can cover 76% of its demands, the gap is significant in absolute terms, suggesting that the country adopt complementary measures to meet the energy demand.

3.3.2 Net Economic Impact

Based on the substitution percentages and the cost of urea stated in [81], the top 5 countries in West Africa with export opportunities to dominate the regional market are shown in Figure 3.9

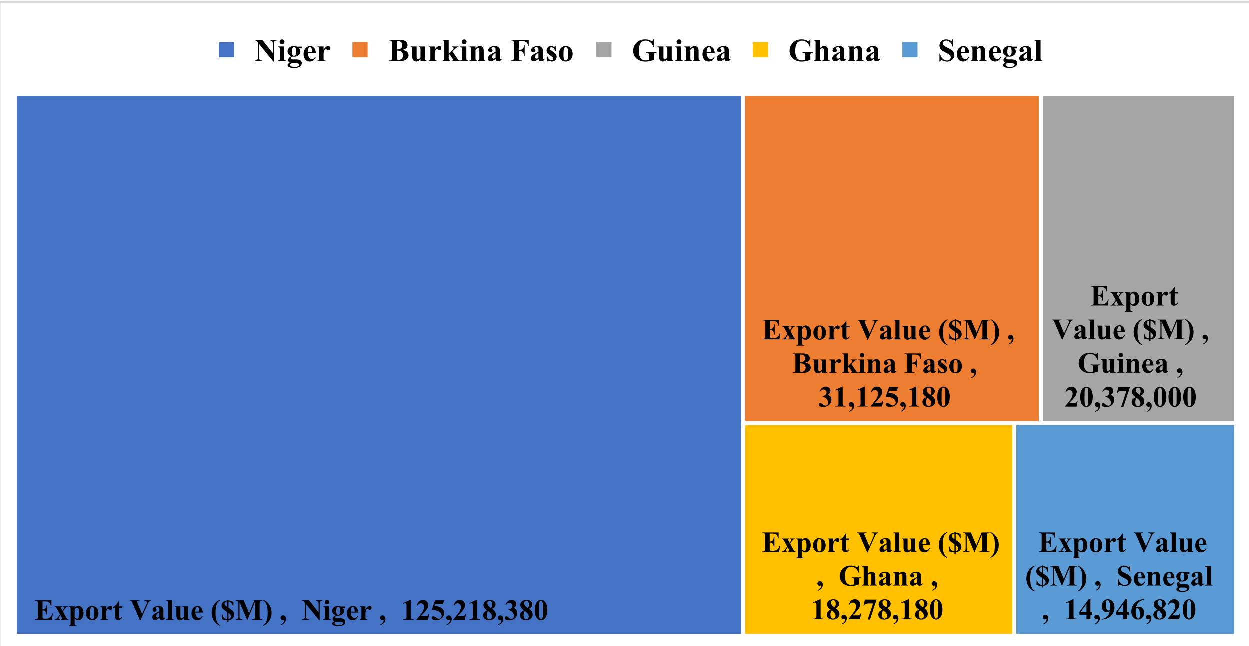

Figure 3.9: Top 5 Countries in West Africa for Export Opportunities

Figure 3.9 clearly shows Niger leading with $125 million in export value, with over 50% compared to Burkina Faso, Guinea, Ghana, and Senegal. Burkina Faso comes in second with an Export value of $31million, followed by Guinea, Ghana, and Senegal with values ranging from $21million to $15million. The chart confirms Niger as a regional anchor for green urea trade with the potential to export to other West African countries. Burkina Faso shows a strong capacity for an export hub while Guinea, Ghana, and Senegal can be secondary suppliers and possibly focus on local market trades and regional strategic trade. For implementation, Guinea and Burkina Faso can engage in bilateral trades with deficit neighbors, whilst Senegal and Ghana can be allocated maritime export scaling due to their coastal access.

Import and Export Pairs based on Surplus and Gap Analysis

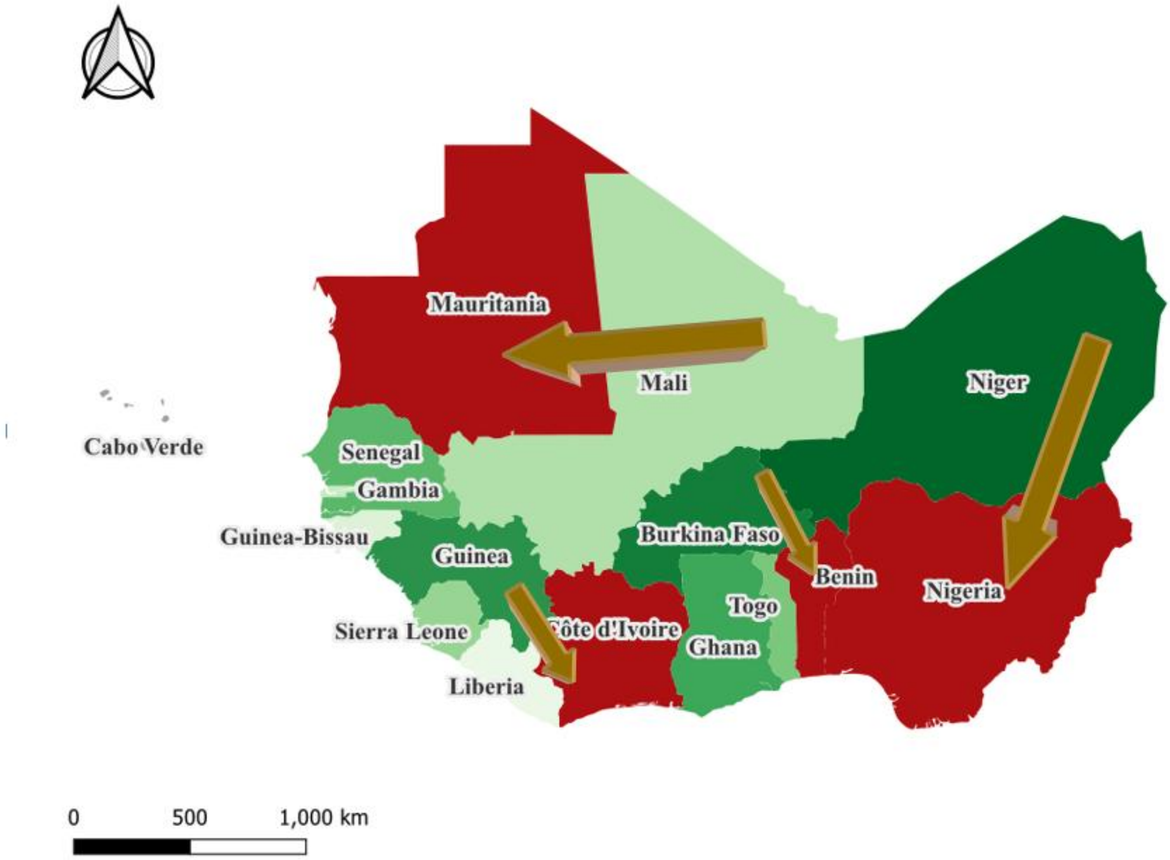

Figure 3.10: Countries for Import and Export of Technical Urea Production based on Surplus and Gaps.

Figure 3.10 shows local urea import and export within West African countries based on the surplus and gap analysis shown in Figure 3.8. As illustrated, Niger shows a surplus value of 283.66Kt/yr, and Nigeria records a gap of -148.2Kt/yr. This shows that Niger can export to

Nigeria and still have a surplus of 134.46Kt/yr. The same scenario is seen for Mali being the exporter of a surplus value 11.68Kt/yr to Mauritania with a gap of -1.58Ktons/year, and Guinea and Burkina Faso with recordings surplus values of 46.63Kt/yr and 70.26Kt/yr respectively being exporters to Côte d'Ivoire and Benin with gaps recording -33.09Kt/yr and -5.46Kt/yr respectively.

Domestic Coverage Supply Percentage

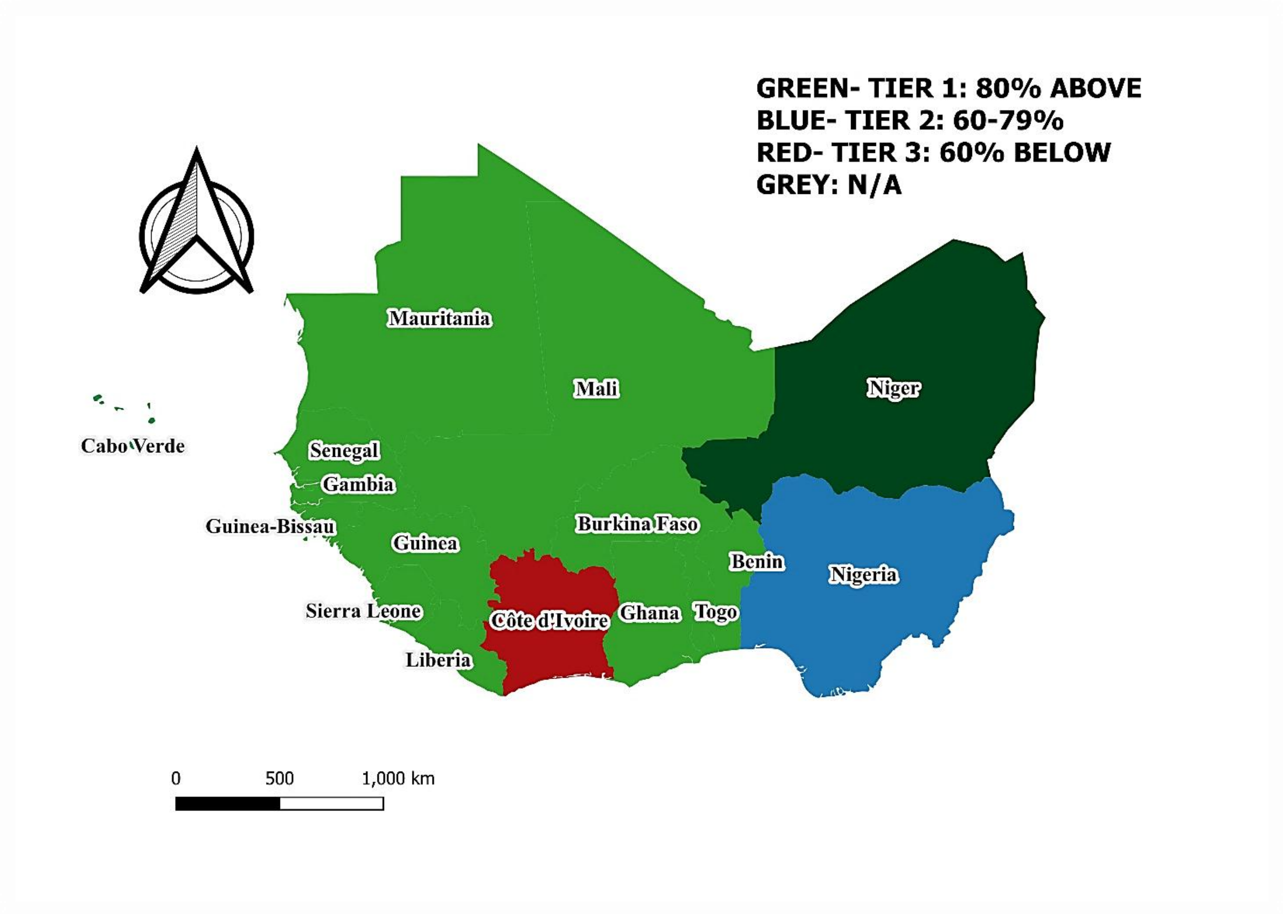

Figure 3.11: Tier Level Based on Domestic Coverage Percentage

Table 3.1: Domestic Coverage Supply percentages

Country	Domestic Supply Coverage %
Benin	88
Burkina Faso	221
Cabo Verde	288
Côte d'Ivoire	54
Gambia	2040
Ghana	219
Guinea	1702
Guinea-Bissau	2704
Liberia	145
Mali	105
Mauritania	81
Niger	2327
Nigeria	76
Senegal	158
Sierra Leone	1016
Togo	189

Figure 3.11 shows Tier 1 with high dominance throughout the 16 West African states. These nations reveal a strong domestic supply coverage of urea, with percentages often exceeding 100, showing that they could produce more than they can consume.

In Tier 1, Guinea-Bissau, Niger, and The Gambia, all recording above 2000% show a massive self-sufficiency and ideal export hub. Burkina Faso, Ghana, and Guinea show consistent surplus production with coverage less than 2000%.

In Tier 2, Nigeria shows a domestic supply coverage of 76% despite its high production of 466Kt/year of urea. As West Africa's largest fertilizer consumer, Nigeria stands out as a priority market for substitution strategies.

In Tier 3, Côte d'Ivoire falls short with a coverage of 53% which shows a significant gap between demand and supply. The nation can benefit from regional imports.

Overall outlook, West Africa shows a strong regional potential for locally produced bio-urea, with countries that fall in Tier 1 acting as hubs for export and regional stabilization, while Tier 2 and 3 can serve as target markets for intervention.

In previous literature, [85], [86], focus was put on trade and production, market forecasts, policy frameworks, and granular urea adoption, while missing a scoring system based on countries domestic supply coverage. This study introduces a novel Tiered Benchmark Scoring Framework linked to ECOWAS investment priorities to quantify domestic urea supply coverage and hence fills a gap in the literature.

3.4 DISCUSSION

3.4.1 Average Cereal Production in West Africa

This study shows that crop dominance is directly related to agroecological conditions, where the cereal type varies depending on the region's climatic zones. These findings relate to the study of [87], [88] [89] focusing on the performance of different cereal crops across Africa's diverse climatic zones. Humid Tropical countries like Nigeria and Ghana show dominance in rice and maize cultivation due to the humid climate, which is favorable for the cultivation of these crops. This has been confirmed by the study of [87].

In Semi-arid zones like the Sahel, which comprises countries like Niger, Burkina Faso, and Mali, Sorghum and millet dominate as primary cereal crops due to their resilience to harsh conditions like drought. This is confirmed by [88], showing a decline in crop yield due to no adaptive strategy. The disparities observed in the cereal crop production across the 16 West African countries can be tackled through region-specific intervention by putting a focus on breeding programs for stress-resilient varieties, improving soil fertility, and the sensitization of farmers, and introducing extension services.

3.4.2 Biomass Residues from Cereal Crops in West Africa

The study made it observable that cereal crop residues such as maize, millet, rice, and sorghum showed abundance in the region and are hence underutilized. This is also confirmed by the crop residue report from [90], which stressed the abundant and underutilized cereal residue due to poor conservation and marketing. Similarly, [91] investigated agricultural residue in the circular economy, also reinforced the abundance of biomass residue like maize and its mismanaged nature, often burned or dumped, causing pollution. Another study from [92] also came up with the same finding, showing Africa to have abundant biomass resources that can be suitable for biofertilizer production. In the study of [93] biomass allocation and carbon storage in cereal crops, the maize crop has the highest variability in total biomass.

The study also showed disparities in theoretical and technical biomass availability, and this can be attributed to the useful biomass used in soil fertility and livestock used. This notion has been seen in the study of [94], which showed that the mulching of crop residue into the soil can improve soil fertility and hence can reduce the grazing biomass for livestock. This highlights social conflict over residue access. All the findings confirm the importance of cereal residue in the region.

3.4.3 Biohydrogen Potentials in West Africa

The study highlights country-level quantification and stresses the need to improve residue management and conversion efficiency, which is in line with [95], which also stresses the technology context of improving the conversion efficiency for an improved technical biohydrogen potential. This finding had been shown in the study of [96], looking into the Global estimates of Biohydrogen potential from cereal crops. Their findings support the gap between theoretical and technical biohydrogen shown in the results of this study. [96] also agreed to the notion that biohydrogen could offset nitrogen fertilizer demand.

The study showed biohydrogen potential of Liberia from cereal residue to be 0.1M/tons/year, which has a close comparison to the results of [97], which showed biohydrogen potential of 81,430 tons/year from crop residue.

3.4.4 Estimation of Ammonia Production in West Africa

The study supports the renewable transition to a green ammonia base for urea production and gives a baseline for ammonia production through the identification of countries that have high potential for green ammonia transition. Nigeria, Niger, and Mali as the lead ammonia output countries in the region, with recordings of 303.8Ktons/year, 192.5Ktons/year, and 153.5Ktons/year from the use of biohydrogen-based feedstock for the Haber Bosch Process.

The study showed that biomass-driven hydrogen production is an alternative compared to other renewables like solar and wind. The study classified Ghana as a mid-range producer of green ammonia with an output of about 49.48Ktons/year, which agrees with the study of [98], which showed green ammonia projects starting in Ghana with solar and wind being the renewable source for a decentralized fertilizer production. [99] also supports the finding of technical ammonia production by stressing the technical challenges associated with the limited conversion of the process.

Overall, the study showed technical feasibility to produce green ammonia plants. A small-scale unit could be deployed in countries like Liberia and Cabo Verde with less than 10Ktons/year output. This feasibility can be confirmed by [100], which highlights West Africa's first green ammonia plant with a plant capacity of 100tons/year using PV and battery storage system for stable hydrogen production.

3.4.5 Estimation of Urea Production

The study shows the potential of biohydrogen-based urea production in West Africa, which provides a regional perspective on the scaling of green urea production. The region's vast cereal residues to produce biohydrogen, which in turn is used in the Haber Bosch process for the green ammonia production and hence a feedstock for the urea synthesis, could reduce the emission of greenhouse gases and achieve a low-carbon urea synthesis.

This is confirmed by [101] showed an achievement of 38% reduction in fossil fuel depletion and a 16% lower global warming potential. Similarly, [102] also confirmed a 97% lower operational emission by simulating a green urea plant using renewable electricity coupled with a carbon capture unit.

Efficient biomass supply chains, investment in biomass to hydrogen to urea plant, and policies that encourage residue harvesting without compromising soil health are critical. Decentralized small-scale urea facilities will be more appropriate for countries with lower but locally sufficient biomass potentials, reducing transport costs and promoting rural industrialization.

3.4.6 Estimation of Surplus and Gap

The study investigated the geographic surplus and gap of West African countries, given relevance to green urea production via renewable sources like biomass cereal residues. The uniqueness of this study complements the techno-economic surplus modeling in recent literature. As illustrated [101], [103], [104] and [105], green urea production is economically viable in regions with access to renewable energy sources by supporting dynamic surplus and modelling for countries with biomass availability. Their studies went on to suggest that with the advancement in technology, green urea production can be a long-term venture for surplus zones with strong policy support. Therefore, as recorded by this study, surplus zones could become regional hubs for low-carbon fertilizer production and exports, especially when coupled with renewable energy sources for the operating systems.

3.4.7 West Africa Export Opportunities

The findings of the study align with [106], which shows that Niger depends on main commodities and advocates for the growth of the agricultural sector, which supports the pathways of biohydrogen-based urea production. Moreover, [107] in their study noted 50% intra-African exports from Niger, which strengthens the role of Niger as a regional trade hub and validates the export potential shown in the study. The study shows novelty in the focus on biohydrogen-based urea production. This field has not been researched extensively in literature, and no one has precisely quantified regional potential to produce green urea via biohydrogen in West Africa. Therefore, a new focus has been highlighted through this study by integrating biomass innovation with regional economic planning.

3.4.8 Import and Export Pairs based on Surplus and Gap Analysis

The results showed potential import and export pair of local urea production based on biomass-driven biohydrogen feedstock. The importation is based on surplus and gap analysis, and strategic corridors are being chosen based on existing and ECOWAS trade corridors.

As shown in Figure 3.10, Mali showed the potential due to its recorded surplus, and Mauritania showed a gap. These two countries have a shared border, which makes it easy for the importation of the local urea fertilizer from Mali to Mauritania. The existing road infrastructure that would be accessible for the transportation of the urea could be the Bamako-Nioro-Kiffa-Nouakchott route [108]. This route facilitates the movement of the imported urea fertilizer from Mali's central agricultural Zones like Bamako, a strategic access to rice and millet feedstock to produce biohydrogen from it reduces through biomass gasification, to Mauritania's port.

Guinea to Côte d'Ivoire is another import-export pair county for intra-region trade. According to [109], Kankan-Man-Yamoussoukro-Abidjan gives the best route for import and export within these two countries, since this route is part of the West African Growth Ring. Kankan will be an ideal location for a urea plant and transportation zone based on the region's significant rice husk and maize residue for biohydrogen-based urea [84].

Burkina Faso to Benin shows an ideal import of urea route, which has been prioritized for the movement of agricultural inputs under the ECOWAS corridor strategy [108]. The corridor for importation from Burkina Faso to Benin is from Ouagadougou-Fada N'Gourma-Kandi-Cotonou. This route is short and hence minimizes transportation cost.

The Trans-Saharan highway shows an ideal route for the transportation of urea imports from Niger to Nigeria. Though Nigeria is the only West African country with a urea production plant on an industrial scale, it still has not met its demand and hence will need to import from neighboring countries like Niger, which shows a surplus of more than twice what it needs. The findings of the results of Nigeria's demand are in line with [13], which showed Nigeria exceeding its demand by 1.5million tons. The corridor for this trade will be ideally from Zinder-Kano-Kaduna.

Corridors selected show regional complementary and trade efficiency, that is, geographical closeness, and align with ECOWAS infrastructural plan and existing networks. For the implementation of such a strategy, the following points need to be addressed:

- Regional hubs, border infrastructure, and digital systems for customs need collaborations and investment to facilitate the implementation of a biohydrogen-based urea production in West Africa.
- The scaling of local urea production in gap countries to meet regional demand using renewable sources by expanding pilot projects
- The integration of SDG metrics that align with the trade flow, such as SDG2, which highlights zero hunger, SDG7: clean energy, and SDG13: climate action.

4. CHAPTER 4: CONCLUSION AND PERSPECTIVE

The study highlighted the persistent need to improve fertilizer self-sufficiency in West Africa within a volatile market and rising demands. It reveals that while the region contains vast untapped agricultural residues for a suitable biohydrogen-based urea synthesis, there remains a gap in converting the resources into locally manufactured urea produced for sustainable fertilizer. The study investigated two key aspects, namely, Technical Analysis and Economic Analysis.

A technical analysis was done by utilizing secondary data for biomass assessment through obtaining a decade long data (2014-2023) of four major cereal crops (Maize, Millet, Rice and Sorghum) from FAOSTAT and ultimate, proximate analysis, RPR and SAF from literature reviews. The study showed the disparities on the availability of biomass across the 16 nations and attributed it to unused biomass, land availability, crop of preference and agroecological zones.

Using stoichiometric modelling, geospatial analysis, and net economic impacts (surplus and gaps analysis, substitutional percentages, and domestic coverage supply), the study identifies key potential countries like Nigeria and Niger, whose technical biomass availability and biohydrogen potentials recorded 421.7Kt/year and 228.0Kt/year, respectively. These values are notable, with Niger exceeding national urea demand by over 2000% with a local urea output of 295.3Kt/year. Other nations such as Ghana, Mali, and Burkina Faso also recorded substantial amounts of local urea, which can offset their urea demand. The study went further to highlight key potential counties whose surplus can be used for exports and gaps registering needs for importation through regional hubs.

Niger stands out from the rest with a surplus gap that is more than twice the country's demand, positioning it as a strategic regional hub for importation to other countries of deficits. The study confirms that using biomass-driven hydrogen through the gasification process is not only technically feasible but also strategically viable. With the proper investment in decentralized modular bio-refiners and prioritizing infrastructural development, the development of an export-oriented hub can be fostered, and hence enhance the promotion of the circular economy, where biomass plays a vital role in West Africa’s agricultural sector.

Perspectives

The research lays the foundation for a transformative shift in West Africa fertilizer landscape. For the results of its potential to evolve into a regional blueprint, the finding opens several future exploration, technological deployment and policy formulation.

The study was based on stoichiometry-based approach, it is imperative to conduct in-dept experimental studies to make these results accessible and applicable. The following points are key insights that could be invested in future research in the basis of the results outcome from this research work.

- This study inspires to carried out on advanced techno-economic optimization and environmental impact extension to assess the viability of the study and hence implementation to selected West African countries for a pilot scheme as regional hubs.
- A community impact assessment and social adoption could be an insight to carry out for future perspective by overlooking how decentralized urea systems might influence local economies the employment rate, and gender equity.
- Policy simulation and incentive design is future research base. Policy scenarios such as feed in tariffs for biomass supply, subsidies for decentralized urea production and regional investment incentives for surplus-exporting hubs could be a build-on for the economic analysis.
- Integrating climate resilience and agroecological mapping can be a way for a long-term forecasting for feedstock stability.

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