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Dedication

This thesis is dedicated to my family most especially my father and Mr. Richard Asante for their unwavering support and encouragement throughout my studies.

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Abstract

Ghana's energy sector remains heavily dependent on fossil fuels, posing significant challenges to energy security, environmental sustainability, and economic development. Bioethanol represents a viable alternative to fossil fuels, with the potential to enhance energy security, support rural economies, and reduce greenhouse gas emissions. Despite abundant agricultural resources, Ghana's bioethanol sector is constrained by logistical, infrastructural, and policy barriers, hindering the commercialisation and scaling of renewable energy solutions. Addressing these issues is crucial to achieving national energy transition targets. This study aims to analyse Ghana's bioethanol supply chain, develop strategies for optimising production and market performance, and assess the economic, social, and environmental impacts of these interventions. A qualitative exploratory approach was employed, combining systematic data review, comparative case study analysis, and supply chain modelling. Data from 2005 to 2023 were analysed using a Mixed-Integer Linear Programming (MILP) model to optimise feedstock logistics, plant siting, and distribution, supported by GIS for spatial analysis and benchmarking against successful African bioethanol initiatives. Supply chain optimisation showed that targeted improvements in feedstock logistics and processing technologies could enable production of up to 542 million litres of bioethanol annually from cassava, maize, sorghum, and yams. Regional analysis identified Eastern, Ashanti, Bono, and Ahafo as priority hubs, with an estimated 865,879 tons of feedstock available each year. Model results suggest that implementing strategic policies, such as E10 blending mandates, could satisfy approximately 90% of national demand. However, technological and infrastructural constraints, particularly limited access to advanced conversion technologies, remain significant barriers. The study presents a comprehensive, data-driven framework for optimising Ghana's bioethanol supply chain and market development. The findings underscore the importance of integrated policy enforcement, technological advancement, stakeholder collaboration, and investment in logistics to establish Ghana as a competitive regional leader in sustainable bioethanol production and utilisation.

Keywords: Ghana; bioethanol; supply chain optimization; renewable energy; Green Energy Transition, Mixed-Integer Linear Programming.

Résumé

Le secteur énergétique du Ghana demeure fortement dépendant des combustibles fossiles, ce qui pose des défis importants en matière de sécurité énergétique, de durabilité environnementale et de développement économique. Le bioéthanol représente une alternative viable aux combustibles fossiles, avec le potentiel d'améliorer la sécurité énergétique, de soutenir les économies rurales et de réduire les émissions de gaz à effet de serre. Malgré l'abondance des ressources agricoles, le secteur ghanéen du bioéthanol est limité par des obstacles logistiques, infrastructurels et politiques, qui entravent la commercialisation et le déploiement à grande échelle des solutions d'énergie renouvelable. Il est crucial de s'attaquer à ces problèmes pour atteindre les objectifs nationaux de transition énergétique. Cette étude vise à analyser la chaîne d'approvisionnement en bioéthanol du Ghana, à développer des stratégies d'optimisation de la production et de la performance du marché, et à évaluer les impacts économiques, sociaux et environnementaux de ces interventions. Une approche exploratoire qualitative a été utilisée, combinant une revue systématique des données, une analyse comparative d'études de cas et une modélisation de la chaîne d'approvisionnement. Les données de 2005 à 2023 ont été analysées à l'aide d'un modèle de programmation linéaire mixte en nombres entiers (MILP) afin d'optimiser la logistique des matières premières, l'implantation des usines et la distribution, avec l'appui d'un SIG pour l'analyse spatiale et l'analyse comparative avec les initiatives africaines réussies en matière de bioéthanol. L'optimisation de la chaîne d'approvisionnement a montré que des améliorations ciblées de la logistique des matières premières et des technologies de transformation pourraient permettre de produire jusqu'à 542 million de litres de bioéthanol par an à partir de manioc, de maïs, de sorgho et d'igname. L'analyse régionale a identifié les régions de l'Est, d'Ashanti, de Bono et d'Ahafo comme pôles prioritaires, avec une disponibilité annuelle estimée à 865 879 tonnes de matières premières. Les résultats du modèle suggèrent que la mise en œuvre de politiques stratégiques, telles que les obligations de mélange E10, pourrait satisfaire environ 90 % de la demande nationale. Cependant, les contraintes technologiques et infrastructurelles, notamment l'accès limité aux technologies de conversion avancées, demeurent des obstacles importants. L'étude présente un cadre complet, basé sur des données, pour optimiser la chaîne d'approvisionnement en bioéthanol et le développement du marché du Ghana. Les résultats soulignent l'importance d'une application intégrée des politiques, des avancées technologiques, de la collaboration des parties prenantes et des investissements dans la logistique pour faire du Ghana un leader régional compétitif en matière de production et d'utilisation durables de bioéthanol.
Mots-clés: Ghana; bioéthanol; optimisation de la chaîne d'approvisionnement; énergie renouvelable; transition énergétique verte; programmation linéaire mixte en nombres entiers.

Acronyms and abbreviations

AfDB:	African Development Bank
ANADEB:	Agence Nationale de Developpement des Biocarburants du Mali
CIRAD:	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CSIR:	Council for Scientific and Industrial Research
ECOWAS:	Economic Community of West African States
ECREEE:	ECOWAS Centre for Renewable Energy and Energy Efficiency
EPA:	Environmental Protection Agency
EU:	European Union
FAOSTAT:	Food and Agriculture Organisation Corporate Statistical Database
GCF:	Green Climate Fund
GEF:	Global Environment Facility
GH₵:	Ghana Cedis
GHG:	Greenhouse Emissions
GIS:	Geographic Information System
GIZ:	Deutsche Gesellschaft für Internationale Zusammenarbeit
IEA:	International Energy Agency
ISCC:	International Sustainability & Carbon Certification
KNUST:	Kwame Nkrumah University of Science and Technology
LNG:	Liquefied Natural Gas
LPG:	Liquefied Petroleum Gas
MCDM:	Multi-Criteria Decision Making
MILP:	Mixed-Integer Linear Programming
MJ:	Megajoule
ML:	Million Litre
MOFA:	Ministry of Food and Agriculture
MT:	Metric Tonnes
MW:	Megawatt
NARCP:	National Agricultural Residue Collection Program
NGO:	Non-Governmental Organization
NNPC:	Nigerian National Petroleum Corporation
NPA:	National Petroleum Authority
PPP:	Public-Private Partnership
QGIS:	Quantum Geographic Information Software
REDII:	Renewable Energy Directive II
SDG:	Sustainable Development Goals

SME:	Small and Medium-sized Enterprises
STC:	State Transport Company
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UNDP:	United Nations Development Programme
UNIDO:	United Nations Development Programme
WACCA:	West African Clean Cooking Alliance
WASCAL:	West African Science Service Centre on Climate Change and Adapted Land Use

List of tables

Table 1: Criteria for sustainable feedstocks for bioethanol production 14
Table 2: Databases searched 23
Table 3: Searched terms 24
Table 4: Literature selection process 24
Table 5: Source quality assessment criteria 25
Table 6: Thematic analysis procedure 26
Table 7: Triangulation methods used in the research data analysis 27
Table 8: Residue availability and recoverability factors 28
Table 9: Residue equations and factors 29
Table 10: Variables representation and values for calculating bioethanol potential 31
Table 11: Parameters of glucan and xylan of various residues 32
Table 12: Key input parameters for supply chain optimisation 36
Table 13: Key cost parameters and biorefinery capacity level 37
Table 14: Regional bioethanol demand in Ghana (2005-2023) 49
Table 15: Maximum crop residue optimisation outcomes (2005-2023) 50
Table 16: SWOT analysis of the Ghanaian bioethanol market 65
Table 17: Key advantages of bioethanol production in the West African regional context 66
Table 18: Key stakeholders and their role in Ghana's bioethanol sector 72
Table 19: Timelines with milestones and indicators 76
Table 20: SWOT analysis of strategic supply chain enhancement 82
Table 21: Comparative Analysis of Strategies 82
Table 22: Potential challenges and mitigation strategies 87
Table 23: Stakeholder mapping and influence analysis 88
Table 24: Bioethanol market development scenarios 90

List of figures

Figure 1: Bioethanol production pathway using crop residues adapted from (Sharma et al., 2019) 10
Figure 2: Map of Ghana displaying the 16 administrative regions 17
Figure 3: Cassava residue availability 42
Figure 4: Maize residue availability 43
Figure 5: Sorghum residue availability 44
Figure 6: Sugar cane residue availability 45
Figure 7: Yam residue availability 46
Figure 8: A graph representation of bioethanol potential in Ghana 47
Figure 9: Supply chain network for residue collection and bioethanol distribution 48
Figure 10: Challenges and Bottlenecks in Ghana's Bioethanol Supply Chain 84

Table of Contents

Dedication i

Abstract iii

Résumé iv

Acronyms and abbreviations v

List of tables vii

List of figures viii

INTRODUCTION 1

Chapter 1- REVIEW OF RELATED LITERATURE 6

1.1 Introduction 7

1.3 Challenges in Conventional Bioethanol Production 8

1.4 Production Pathways for Bioethanol 9

1.5 Ghana's Potential for Bioethanol Production 10

1.5.1 Role of Catalysts and Enzymes 11

1.6 Feedstocks for Bioethanol in Ghana 12

1.7 Criteria for Sustainable Feedstocks for Bioethanol Production 13

1.8 Supply Chain Strategies for Bioethanol 15

1.8.1 Ghana's Bioethanol Supply Chain Strategies 15

1.9 Policy and Regulatory Frameworks 17

1.9.1 Barriers in Ghana's Bioethanol Policy and Regulatory Landscape 17

1.9.2 Successful International Models 18

Chapter 2 - RESEARCH METHODOLOGY 20

2.1 Research Design Structure 21

2.2 Data Collection and Source Evaluation 21

2.3 Data Analysis and validation 25

2.4 Thematic Analysis Procedure 25

2.5 Triangulation Methods for Data Analysis 26

2.5.1 Benefits of Triangulation 27

2.5.2 Drawbacks of Triangulation 27

2.6 Residue Availability Calculations 28

2.7 Bioethanol Potential in Ghana (2005-2023)....30
2.8 Optimisation Model of Bioethanol Supply Chain in Ghana....32
2.8.1 Constraints of the Optimisation Model....33
2.8.2 Key Input Parameters....34
2.9 Synthesis and Framework Development....38
2.10 Limitations of the Methodology....39
Chapter 3 - RESULTS AND DISCUSSION....40
3.1 Results....41
3.1.1 Bioethanol Market Landscape in Ghana....41
3.1.2 Residue Availability Potential....42
3.1.3 Supply Chain Optimisation Analysis and Discussion....47
3.1.4 Comparative Analysis of Bioethanol Production in Ghana and West Africa: Capabilities, Challenges and Transferable Practices.....54
3.1.5 Strategies for Enhancing Bioethanol Supply Chain Management in Ghana....67
3.1.6 Effective Marketing Strategies....69
3.2 Discussion....70
3.2.1 A Critical Perspective on Ghana's Bioethanol Sector....70
3.2.2 Comparative Analysis of Ghana's Bioethanol Sector in the Regional Context....72
3.2.3 Strategic Framework for Enhancing Ghana's Bioethanol Supply Chain: Insights, Opportunities, and Challenges....79
Conclusion and Perspectives....92
References....94

INTRODUCTION

Background and Context

Ghana's energy generation remains heavily dependent on conventional sources, particularly fossil fuels, which account for about 68.8% of the national energy mix, compared to 29.1% from hydropower and only 2.1% from renewables (Atuahene & Sheng, 2023; Energy Commision of Ghana, 2020). This reliance hampers the country's goal of increasing renewable capacity from 42.5 MW in 2015 to 1363.63 MW and expanding decentralized electrification in 1,000 off-grid communities (Energy Commission, 2019). Fossil fuel dependence threatens Ghana's energy security, economic growth, and sustainability.

In 2023, Ghana signed a 17-year liquefied natural gas (LNG) import deal with Shell, raising concerns about rising electricity costs and greater fossil fuel use, amid a GH₵18.6 billion debt to independent power producers (Farand, 2023). That same year, crude oil and petroleum imports cost GH₵49.2 billion (Bank of Ghana, 2023), exposing the country to global price volatility. These challenges highlight the need to diversify towards sustainable alternatives, among which biofuels—particularly bioethanol—offer strong potential.

Bioethanol derived from the fermentation of sugars in crops or residues is the leading biofuel for transport and can be blended with petrol to reduce GHG emissions and fossil fuel use (Ghaderi et al., 2016). Given that Ghana imports nearly 80% of its petroleum for transport (Energy Commission of Ghana, 2023; Kasoa et al., 2025), bioethanol represents a viable substitute.

Global bioethanol production reached 110 billion litres in 2018, with projections of 140 billion litres by 2022, led by the US (57.7 billion litres) and Brazil (27.6 billion litres) (Edeh, 2021; Sharma et al., 2020). For Ghana, bioethanol development aligns with goals of energy security, environmental sustainability, and economic growth (Jayakumar et al., 2022). The country has abundant feedstocks (cassava, maize, oil palm sap, and sweet sorghum) offering significant production potential. Ghana is Africa's second-largest cassava producer (26 million tonnes) and produces 3.6 million tonnes of maize annually (FAO, 2023b). Cassava offers low production costs, maize higher yields, and sorghum—widely grown in northern Ghana—thrives under drought and heat, reducing cultivation costs (MOFA, 2022; Tulashie et al., 2023). Oil palm sap could yield 447.5 million litres of bioethanol annually (Joseph et al., 2014).

However, the bioethanol industry faces challenges, including unreliable feedstock supply, competition with food crops, and climate-induced yield fluctuations (Owusu et al., 2024). The use of edible crops like cassava and maize for energy raises food security concerns, while limited arable land further constrains expansion.

To address these barriers, this study seeks to develop a sustainable framework for enhancing Ghana's bioethanol sector by examining its opportunities, supply chain, market strategies, and overall socio-economic impacts.

Problem Statement

Ghana's transition to bioethanol as a sustainable alternative to fossil fuels faces major structural challenges despite its vast biomass potential and policy ambitions. The Strategic National Energy Plan targets a 15% bioethanol blend by 2030, expected to cut emissions and save over GH₵625.6 million annually (Brinkman et al., 2020), yet this goal remains elusive due to constraints across infrastructure, technology, policy, and market systems.

The value chain suffers from inadequate infrastructure, including limited processing, storage, and distribution facilities, which reduce efficiency, increase costs, and weaken competitiveness (Tse et al., 2021). Technological gaps further constrain production, with outdated methods yielding lower efficiency and higher costs than international standards. Ghana's reliance on first-generation feedstocks—cassava, maize, and sugarcane—creates food–fuel trade-offs, as cassava alone contributes 30% of caloric intake and 22% of agricultural GDP (Acheampong et al., 2021). Diverting food-grade cassava for fuel risks price increases and food insecurity (Achu, 2024) Although cassava-based bioethanol can reduce GHG emissions, indirect land-use changes may offset these benefits. Thus, policies should restrict edible cassava use, prioritise residues and industrial-grade feedstocks, and incorporate food-price protection. Future strategies must also promote lignocellulosic and algae-based feedstocks, supported by efficient and sustainable technologies (Devi et al., 2023; Ekpan & Ori, 2024).

Despite existing biofuel policies, weak enforcement, vague guidelines, and limited incentives have stifled sectoral growth (Ministry of Energy, 2021). Effective policy implementation should foster market formation, investment, and clarity in the regulatory environment. Additionally, market competition with subsidised fossil fuels and low public awareness of bioethanol's benefits reduces demand and adoption (Silva et al., 2024). Together, these structural, technological, and market barriers constrain Ghana's ability to realise its bioethanol potential and advance a sustainable energy transition.

Significance of the Study

This study offers a comprehensive analysis of Ghana's bioethanol sector by integrating supply chain dynamics, market barriers, and institutional factors, an approach largely absents from current literature. Evidence shows that the industry faces inadequate infrastructure, high production costs, weak supply networks, and inconsistent policy support, all of which constrain scalability and economic viability (Kissi et al., 2025). Previous initiatives, notably jatropha-based projects, failed due to high capital demands, limited technical exchange, and weak R&D capacity (Antwi et al., 2010). Yet, a major knowledge gap remains in understanding how these structural constraints interact across the bioethanol value chain, from feedstock sourcing to policy implementation and market uptake. Most existing studies examine either policy frameworks or feedstock potential in isolation, overlooking their systemic interconnections involving logistics, financing, and stakeholder coordination.

By bridging this gap, the study contributes to the literature with:

- A holistic mapping of Ghana's bioethanol supply chain, including residues utilisation, feedstock logistics, processing capacity, and distribution infrastructure.
- An evaluation of policy-environment alignment, drawing on lessons from failed past projects and international benchmarks to identify structural enablers and barriers.
- Actionable recommendations for stakeholders, including farmers, producers, investors, and policymakers on optimising supply chain coordination, expanding residue-based feedstocks, stabilising market incentives, and aligning policies with implementation realities.

Ultimately, this research offers immediate practical relevance by illuminating how Ghana can build a resilient, efficient, and sustainable bioethanol sector – informing policies and strategies that can attract investment, support rural livelihoods, and strengthen energy security.

Research Questions

The research questions used to implement the study are as follows:

a. **What regulatory, agricultural, and infrastructural challenges affect Ghana's emerging bioethanol market?**
b. **How can feedstock procurement and distribution networks be optimized for bioethanol production in Ghana's regional context?**
c. **How do Ghana's bioethanol production capabilities and challenges compare to other West African countries, and what practices could be adapted?**
d. **What strategies can be developed to enhance the supply chain management of bioethanol production in Ghana?**
e. **What marketing strategies can effectively increase domestic and/or export demand for the Ghanaian bioethanol industry?**

Objectives

The main objective of this research study is to develop a sustainable framework for improving the bioethanol industry in Ghana by identifying its opportunities, supply chain, marketing strategies, and overall impacts.

The specific objectives for conducting this research work include:

a. To identify the opportunities and challenges in bioethanol production in Ghana.
b. To evaluate the supply chain management of bioethanol production in Ghana.
c. To analyse marketing strategies for bioethanol products in Ghana.
d. To assess the economic, social, and environmental impacts of the existing production strategies on the bioethanol industry in Ghana.

Research Hypothesis

To answer the research questions relating to the bioethanol industry of Ghana, this current study is based on the following:

a. Supply chain dynamics such as land area, local feedstock availability, processing technologies, logistical infrastructure, and production cost significantly influence the production of bioethanol in Ghana.
b. A robust renewable energy policy exclusively for bioethanol development, pillared on government incentives, public awareness campaigns, and blending mandates, will significantly increase production efficiency, social and economic viability, and market adoption for bioethanol production in Ghana.

Master Thesis Structure

This research work is divided into an introduction section, three chapters, and a conclusion and perspectives. The introduction section deals with the background, problem statement, significance of the study, research objectives, research questions, and research hypothesis. Within chapter one, related literatures were reviewed to explore the research objectives and answer the research questions involving bioethanol production, supply chain, and market development. This chapter also explores knowledge gaps that set the scope for this research. Chapter two examines the research methodology by highlighting the data collection procedures as well as the use of simulation tools such as CPLEX Studio IDE 22.1.1, Excel, and QGIS to evaluate bioethanol production in Ghana. Chapter three presents the results and discussions outlining key findings within the current study. Conclusion and perspectives give the summary, conclusion, and key recommendations for future research.

Chapter 1- REVIEW OF RELATED LITERATURE

1.1 Introduction

This literature review draws on peer-reviewed articles, policy reports, and case studies from 2005-2023, a period capturing Ghana's evolving biofuel policy, agricultural modernisation, and economic transformation. Ghana's biofuel development began with the 2005 draft policy, inspired by the ECOWAS energy framework (2003), and continued with the Strategic National Energy Plan (2006), targeting 10% biofuel blending by 2020. The Bioenergy Policy (2010) later set a 20% target by 2030, reinforced by the Renewable Energy Act (Act 832, 2011) (Ahmed et al., 2017).

Since the 2010s, shifts in crop production have influenced feedstock supply. Yields of cassava and yam increased by 42% and 28%, while maize rose from 1.5 t/ha (2005) to 2.7 t/ha (2020) under the Planting for Food and Jobs initiative (NfaafulL, 2022). In contrast, sugarcane production declined following the collapse of the Komenda Sugar Factory, illustrating risks associated with monocrop dependence (Yawson et al., 2018). Literature was sourced from ScienceDirect, FAO, IEA, ECOWAS, and Ghana's Energy Commission, using terms such as bioethanol Ghana, biofuel policy Africa, and sustainable feedstocks. Selection prioritised works comparing first- and second-generation bioethanol, examining supply chain logistics and sustainability. Key limitations include the scarcity of longitudinal field data, inconsistent yield estimates, and limited life cycle assessments (LCA) for Ghana.

Bioethanol is a renewable and low-emission alternative to petrol, offering 15% higher combustion efficiency due to its 34.7% oxygen content (Karim et al., 2024; Saini et al., 2022). Produced by fermenting C6 sugars from starch, sucrose, or lignocellulosic feedstocks using Saccharomyces cerevisiae, it requires 68% less energy than fossil petrol. Global production reached 29,330 million gallons in 2019 (Falowo & Betiku, 2023). However, most research centres on US and Brazilian feedstocks, necessitating adaptation to Ghana's agroecological context.

Bioethanol is classified into four generations by feedstock type. First-generation fuels, derived from food-based grains, starchy and sugar crops particularly maize, sugarcane, and sorghum, dominate production (96% globally in 2020) but raise food–fuel trade-offs (Zhao et al., 2019). Second-generation bioethanol, sourced from agricultural residues, offers a sustainable and low-cost pathway. Third- and fourth-generation fuels, derived from algal biomass and genetically modified strains, are still emerging (Gupta & Verma, 2015; Robak & Balcerek, 2020). Despite global progress, Ghana remains reliant on first-generation feedstocks, reflecting technological, financial, and infrastructural limitations (Kissi et al., 2025). Advanced methods like consolidated bioprocessing (CBP) and gas-to-liquid fermentation show promise for reducing carbon footprints, though adoption in Ghana remains limited by skills, capital, and infrastructure gaps (Althuri & Venkata Mohan, 2022).

1.2 Global and African Energy Context

Energy transition from fossil fuels to renewable energies is an essential measure to be taken in limiting global warming to 1.5 degrees Celsius as stated in the Paris Agreement of 2015 due to climate change. In order to achieve this target, countries must reduce their emissions by 43% by the end of the decade compared to 2019 levels, according to the Intergovernmental Panel on Climate Change (IPCC) (Boucetta, 2024). Conventional energy sources like fossil fuels still dominates the global energy mix, and about 69% of Africa's power capacity is dependent on fossil fuels as of 2025. However, renewable energies are gaining momentum in the African energy mix and are projected to increase to 45% share by 2035 (Research and Markets, 2025).

Global bioethanol reached 110 billion litres in 2018 on the world market and a projection of 140 billion litres was made to be achieved in 2022 (Sharma et al., 2020). The United States, the world's leading bioethanol producer (55%), uses corn while Brazil, the second-largest producer (27%) uses sugarcane and molasses. Followed by the European Union (5%) produces bioethanol from wheat, maize, sugar beet and barley, where as China (3%) derives its bioethanol from sweet sorghum and cassava, and Canada (2%) generate bioethanol from corn and wheat grain. The share of bioethanol from second-generation or lignocellulosic feedstock is projected to increase in the global market through development of the commercialisation of cellulosic bioethanol from inexpensive wastes. This is due to the fact that, the U.S.A and EU biofuel policies boost the global advancement of cellulose-based biofuels generation (Falowo & Betiku, 2023; Robak & Balcerek, 2020).

However, evidence from regional comparisons suggests that bioethanol market growth – particularly for second-generation, has been faster in Asia and South America, and producers from these regions benefit from large-scale mechanisation, established distribution systems, and strong blending mandates. By contrast, African production is largely small-scale, with fragmented markets and underdeveloped policies (World Bioenergy Association, 2023). Ghana's position in this global context is further constrained by logistical limitations and inconsistent policy frameworks, suggesting that lessons from high-capacity producers must be adapted for the realities of African infrastructure and governance systems.

1.3 Challenges in Conventional Bioethanol Production

Bioethanol production, although established as a renewable fuel alternative, is currently characterized by numerous technical, economic and sustainability challenges. Conventional or first-generation bioethanol production is mainly dependent on food crops such as cassava, maize, sugarcane, and sweet sorghum, causing direct competition among food and fuel production. This raises concerns for global food security, land-use change mostly for nations with dense populations and impacts on global food prices. The cost of feedstock accounting for 40%-75% of total production expenditures and limited availability of these feedstocks reduces production scalability whilst increasing costs (Jain & Kumar, 2024).

The current production pathways for bioethanol are characterized by low conversion efficiency and limited yields as the ethanol yields from starched-based crops and sugarcane ranges between 400-500 litres/ton and 70-90 litres/ton respectively (Jain & Kumar, 2024). The conversion process involves energy intensive distillation process which accounts for nearly 40% of energy consumption in bioethanol plants and large wastewater and stillage as by products requires proper treatment. However, these challenges can be averted when these distillates are re-valorised using anaerobic digestion to produce biogas to be reused in the plant (Amornraksa et al., 2020).

Critical comparisons indicate that while valorising distillation byproducts for biogas production is technologically feasible and could offset costs, adoption rates in Ghana and similar economies remain low due to limited access to anaerobic digestion facilities and trained operators (Devi et al., 2023; Jain & Kumar, 2024). This reflects a broader methodological gap in studies that often assume technology availability without considering local capability constraints.

1.4 Production Pathways for Bioethanol

Bioethanol is among the most widely used renewable biofuels in the transport sector due to its environmental benefits and compatibility with existing fuel systems. Its production primarily follows a biochemical conversion pathway, using sugar- and starch-rich biomass such as sugarcane and maize. Increasingly, lignocellulosic feedstocks, including agricultural residues, forestry by-products, and herbaceous energy crops, are being explored to avoid competition with food crops. The overall production process typically involves pretreatment, enzymatic hydrolysis, fermentation, and ethanol recovery.

Pretreatment is a critical and cost-intensive stage designed to enhance the accessibility of cellulose and improve sugar yields. Methods may be physical, chemical, physicochemical, or biological in nature, with emerging techniques such as acid-based and ionic liquid fractionation showing promise for higher efficiency. Given the complex structure of lignocellulose, effective pretreatment is essential to enable enzymes to release fermentable sugars.

Following pretreatment, hydrolysis converts polysaccharides into monosaccharides, either through acid-catalyzed or enzymatic methods. Although acid hydrolysis—often employing H_2SO_4 or HCl—is well-established, it may produce toxic by-products, whereas enzymatic hydrolysis offers cleaner outputs but depends on costly and often imported enzyme formulations. This highlights a research gap in developing indigenous enzyme production capacities in West Africa, which could enhance local bioethanol value chains (Bensah et al., 2015).

During fermentation, microorganisms such as Saccharomyces cerevisiae and Zymomonas mobilis convert sugars into ethanol, carbon dioxide, and minor by-products.

Finally, ethanol recovery employs distillation and dehydration techniques to separate ethanol from the fermentation broth. Due to the azeotropic behavior of ethanol-water mixtures, additional separation steps are required to obtain anhydrous ethanol (≈99.5%) suitable for blending with gasoline (Edeh, 2021; Muhammad & Rosentrater, 2020; Vasic et al., 2021).

Recent innovations, such as ionic liquid processing and bio-extrusion, offer potential for higher conversion efficiencies from agricultural residues, though pretreatment remains the most technically demanding and costly step in lignocellulosic ethanol production (Sharma et al., 2019; Jain & Kumar, 2024).

Figure 1 shows the production pathway for bioethanol production in Ghana using five crop residues, namely cassava, maize, sorghum, sugar cane, and yam.

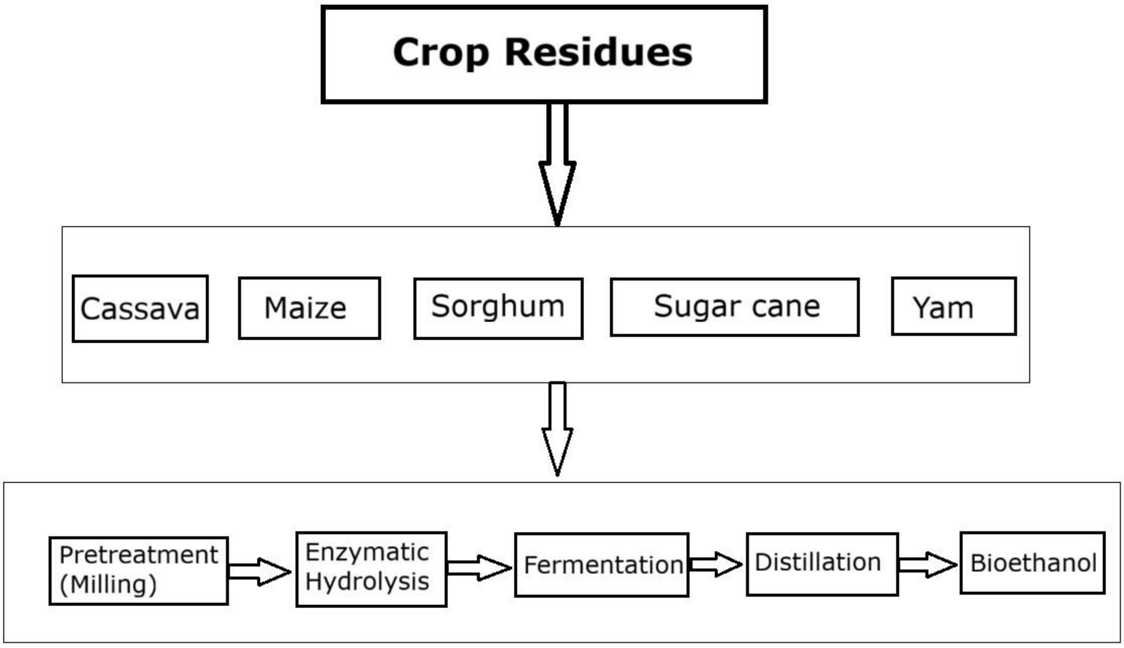

Figure 1: Bioethanol production pathway using crop residues adapted from (Sharma et al., 2019)

1.5 Ghana's Potential for Bioethanol Production

Potential agricultural crops-produce notable to produce bioethanol in Ghana are maize (corn), sugarcane, cassava, sweet sorghum, sweet potatoes, yams, millet, and oil palm. However, cassava, maize and yams are mostly cultivated in large quantities, and they also serve as the major food staples in the country. In 2022 alone, Ghana produced about 25.56 metric tonnes (MT) of cassava which positioned the country as the 4th largest cassava producer in the world according to FAOSTAT (2023). Ghana has a competitive advantage with China and Thailand who equally produces bioethanol from cassava and are known among the key players of bioethanol globally. Ghana's significant agricultural output, particularly in major including cassava, maize, and yam, presents a substantial opportunity for large-scale bioethanol production. However, to maximize yields from these crops – especially from their lignocellulosic residues and non-edible parts, it is crucial to adopt efficient conversion technologies such as incorporating catalysts and enzymes for optimal yield.

While some studies argue that cassava's low input requirements give Ghana a competitive advantage for bioethanol production feedstock, others point to post-harvest losses, inadequate processing facilities, and weak market infrastructure as significant limitations (Amo-Aidoo et al., 2021). Few studies provide long-term yield or income data for communities participating in cassava-to-bioethanol chains, making it harder to assess socio-economic sustainability (Kasoa et al., 2025).

1.5.1 Role of Catalysts and Enzymes

Catalysts and enzymes are vital to the efficiency and sustainability of bioethanol production. They facilitate the conversion of lignocellulosic biomass into fermentable sugars then ultimately bioethanol yield by accelerating chemical and biological reactions that would otherwise proceed very slowly.

1.5.1.1 Catalysts in Bioethanol Production

Catalysts are substances that increase the rate of the chemical reaction without being consumed, during bioethanol production both chemical and biological catalysts are used at different stages. Chemical catalysts are often used in thermochemical conversion processes and to upgrade bioethanol to other chemicals particularly zeolite-based catalysts and bimetallic catalysts like nickel-copper on alumina are used to convert bioethanol into valuable chemicals such as ethylene and propylene (Gaitán Chavarría et al., 2024; Morad, 2024). Zeolites offer high selectivity and can operate efficiently at lower temperatures to enhance the overall yield and quality of bioethanol and its derivatives. In recent years, research advancements have introduced nano-catalysts like carbon nanotubes and modified biochar which provide high surface area, improved selectivity and stability under extreme conditions (Abbasi, 2025). They can significantly improve the yield and reduce the formation of byproducts, enhancing cleaner and efficient bioethanol production.

1.5.1.2 Enzymes in Bioethanol Production

Enzymes are biological catalysts, typically proteins that accelerate biochemical reactions. They are crucial in the conversion of lignocellulosic biomass during the production of bioethanol. Enzymes particularly, laccases, manganese peroxidases and lignin peroxidases breakdown lignin, a complex polymer that encloses cellulose and hemicellulose making it possible hydrolysis of these carbohydrates as pretreatment (Araujo et al., 2023). The main enzymes used to hydrolyse cellulose and hemicellulose into simple sugars are cellulases and hemicellulases, while amylases are used for breaking down starchy feedstocks such as maize and casava (Ríos-Fránquez et al., 2018). During the fermentation stage in bioethanol production, enzymes like invertase and those involved in glycolysis facilitate the conversion of sugars (sucrose & fructose) into ethanol and carbon dioxide. Engineered enzymes and enzymes cocktails from bacteria and fungi are used to improve efficiency, tolerance to process conditions and yield (Qiao et al., 2023; Urena, 2016). Advanced catalysts such as carbon nanotubes and modified biochar deliver higher stability and selectivity. However, in Ghana, catalyst and enzyme use is largely limited to pilot or experimental facilities, with limited industrial uptake due to cost and import dependence (Modekwe et al., 2022). This reflects a broader African challenge of translating laboratory advances into cost-effective industrial practice.

1.6 Feedstocks for Bioethanol in Ghana

Ghana's bioethanol sector uses a various range of agricultural residues showing the country's agroecological landscapes. The main feedstocks comprise both primary energy crops and agricultural residues, each with different advantages and challenges concerning yield, sustainability and food security. Some primary feedstocks for bioethanol in the country are cassava, maize, sugar cane, sweet sorghum, oil palm and agricultural residues.

Cassava is one of the major crops produced in Ghana, which thrives across all agroecological zones, especially marginal soils where cereals fail (Manso et al., 2018). It is a drought-tolerant crop with yields of about 22-38 tonnes/hectare (t/ha) without irrigation, which can guarantee an all-year-round residue availability in the country.

Cassava is the most promising feedstock for bioethanol in Ghana due to its high starch content, adaptability to various soils and has a significant national production. Ghana produces about 22 million tonnes of cassava annually. Ethanol yields from cassava ranges from 150^{-} 200 litres per metric tonnes) depending on the processing technology and the kind of cassava used (Kasoa et al., 2025). While Adu et al., (2022) argues cassava offers low input requirements, this conflicts with Kasoa et al., (2025) who highlight significant post-harvest processing challenges that may increase overall costs. Maize is Ghana's prevalent cereal and staple crop with an annual yield of 1.9-2.2 million tonnes (MT/year). It has a short growth cycle (90-120 days) with 2-3 harvests/year in the southern regions, enabling a reliable volume of residues. Sugar cane, ideally grown in the southern coastal areas, has high biomass yields to be used as a bioethanol feedstock. Additionally, maize can yield up to 400 litres of ethanol per metric ton, its role as a major staple food crop in the country raises food security concerns (Pelizan, 2019). Maize cultivation is more input-intensive, requiring significant fertiliser and water, and susceptible to price and supply fluctuations. Therefore, its use for bioethanol is mostly restricted to periods or regions of surplus (Kasoa et al., 2025).

Sweet sorghum a drought-resistant and non-staple food crop generally grown within the northern regions of Ghana, yielding around 1.8-2.5 t/ha with minimal water, is a promising bioethanol feedstock to avoid food-fuel conflicts in the country. It offers ethanol yield of approximately 1750 litres per hectare (Kemausuor et al., 2013). Its resilience and non-competitive nature with staple crops make it a potential option for sustainable bioethanol production. Sugar cane and oil palm are considered possible feedstocks. Sugarcane, although less widely cultivated than other crops like cassava, offers high yield per hectare but is largely utilised for sugar production, limiting its availability for bioethanol unless or developed and dedicated as energy crops (Pelizan, 2019). Oil palm plantations in Ghana could produce considerable amounts of sap for ethanol with estimates indicating up to 447.5 million litres under optimal conditions annually (Joseph et al., 2014).

Ghana is the leading exporter of yam and one of the major producers in the world, with an average production capacity of 8.7 million tonnes, providing enough underutilised straw and peel residues post-harvest. Yam (*Dioscorea spp.*), particularly *Dioscorea rotundata* (white yam), is an important and underutilised feedstock for bioethanol production in Ghana where it accounts for about 80% of national yam output and widely cultivated in regions such as Brong Ahafo, Northern, and Eastern Ghana (Aidoo et al., 2012; FAO, 2022). The leading varieties, including Pona, Dente, Lariboko, Asana, and Serwah are favoured for their agronomic performance and storability (Aidoo et al., 2012). With a high starch content of nearly 90% on a dry weight basis, yam offers considerable potential for bioethanol production, yielding about 425 litres of ethanol per tonne (Agu et al., 2014). The conversion process consists of gelatinisation, enzymatic hydrolysis, and yeast fermentation which efficiently transformed yam starch to ethanol, in addition, yam requires relatively low and modest production costs enhancing it as a sustainable bioethanol feedstock (Villadiego-del Villar et al., 2021). However, its use as bioethanol feedstock in Ghana is limited as high demand for staple food and the need for improved infrastructure to collect and process yam residues.

Ghana generates close to 29 million tonnes of crop residues annually in excess including cassava peels, maize stalks, sorghum straw, yam straw and sugar cane bagasse (Kelly et al., 2025). These residues present an extensive but underutilised resource for bioethanol production, with theoretical annual production estimate of over 200 million litres (Oppong-Ansah, 2025b). The use of crop residues mitigates food-fuel conflicts and increases the sustainability of bioethanol production. However, challenges remain in collection, storage, and processing infrastructure (Nelson et al., 2021). A synthesis of studies suggests that while primary crops offer higher and more predictable yields, residues provide a sustainable alternative that avoids food-fuel competition (Elemike et al., 2015). Yet, infrastructure for residue collection and storage remains a critical barrier.

1.7 Criteria for Sustainable Feedstocks for Bioethanol Production

Sustainable bioethanol feedstocks must achieve substantial greenhouse gas (GHG) emission reductions compared to fossil fuels. International frameworks typically require at least 60% emission savings for new installations, with assessments covering the entire life cycle, from cultivation to distribution (European Court of Auditors, 2023). Under EU sustainability criteria, bioethanol feedstocks cannot be grown on land with high biodiversity, carbon-rich ecosystems, or areas converted from such uses after January 2008 (International Institute for Applied Systems Analysis, 2019). To safeguard ecosystems, sustainable practices should prevent soil erosion, land degradation, and water scarcity, favouring minimal tillage, organic soil management, and efficient irrigation systems.

Sustainability also entails avoiding competition with food, feed, and timber resources. The FAO (2021) and IEA Bioenergy (2021) emphasize that sourcing biofuel feedstocks should not jeopardize food security or trigger land-use conflicts. In Ghana, where cassava and maize are key staples, their diversion to ethanol production without safeguards risks food shortages and price inflation, particularly for vulnerable populations. Consequently, reliance on non-food crops, agricultural residues, and marginal lands is encouraged to reduce food–fuel trade-offs (Allen et al., 2016).

The FAO Bioenergy and Food Security (BEFS) framework promotes integrating smallholder farmers into bioenergy value chains throughout grower schemes and public–private partnerships. While such models can support rural development and income generation, evidence from Ghana shows mixed results—well-structured cassava schemes improved livelihoods, but poorly managed contracts led to exclusion and exploitation (FAO, 2010; Poku et al., 2018). Furthermore, bioethanol projects must respect land tenure and community rights to avoid displacement (Pelizan, 2019).

Table 1 shows a well-structured summary of the criteria for selecting sustainable feedstocks for bioethanol production.

Table 1: Criteria for sustainable feedstocks for bioethanol production

Criteria	Description
GHG Emission Reduction	Must cut greenhouse gas emissions by at least 60% across the full production life cycle.
Land Use Restrictions	Avoid cultivation on high biodiversity or high carbon stock lands, and lands converted after 2008.
Soil and Water Conservation	Prevent soil erosion and water scarcity; use conservative farming and irrigation where needed.
Minimise Food-Fuel Competition	Limit competition with food, feed, and timber; favour non-food crops, residues, or marginal lands.
Rural Development & Equity	Support smallholders via out-grower schemes and partnerships; respect land rights and fair contracts.
High Yield & Low Input	Deliver high ethanol yields with minimal fertiliser and pesticide use.
Local Adaptation	Suit local agroecological conditions to reduce irrigation and chemical needs.
Storage & Transport	Easy to store and transport to avoid losses and ensure steady supply.
Traceability & Compliance	Track feedstock origins and ensure adherence to environmental and legal standards.

(FAO, 2021; IEA Bioenergy, 2021)

Feedstocks should also demonstrate high ethanol yield per hectare, require low input use (fertilisers, pesticides), and exhibit resilience to local agroecological conditions, thereby enhancing productivity while minimizing environmental impact (IEA Bioenergy, 2023; Russo et al., 2025). This approach, supported by international agencies like the IEA and USDA (2012), ensures resource efficiency and compatibility with Ghana's diverse farming systems.

Finally, sustainability extends to logistics and traceability. Feedstocks should be easy to store and transport, reducing spoilage and supply chain costs (Fuss et al., 2018; Kasoa et al., 2025). End-to-end traceability mechanisms, regular audits, and compliance with environmental, water, and waste management laws are essential to verify sustainability claims (Allen et al., 2016; European Parliament, 2022).

1.8 Supply Chain Strategies for Bioethanol

The bioethanol supply chain is a comprehensive, multistage system integrating the flow of materials, information and finances from raw biomass to the end consumer. Structurally it comprises of five main interrelated stages: feedstock production, feedstock logistics, bioethanol processing, bioethanol distribution, and customer delivery (Tadesse et al., 2012). The process stars from the cultivation and harvesting of suitable feedstocks like cassava, sweet sorghum, yam, maize, or lignocellulosic biomass. Feedstock logistics then involve the storage and transportation of the raw materials to processing facilities, while considering efficiency due to the perishable nature of some feedstocks and the costs involved with long-distance transport (Jabbarzadeh & Shamsi, 2025; Kheybari et al., 2023).

Bioethanol production is the conversion of feedstocks into fermentable sugars through processes, particularly pretreatment (milling), hydrolysis, or enzymatic saccharification, fermentation by microorganisms, and followed by distillation and purification to obtain fuel-grade ethanol (Devi et al., 2023). Once produced, bioethanol could be distributed through pipelines, tankers, or road transport to blending stations or directly to end-users, with integration into existing fuel infrastructure being key for market penetration (Kheybari et al., 2023).

The supply chain system involves information and financial flows coordinating procurement, production scheduling, inventory management, and quality assurance, while supply chain design must account for transaction costs, facility location, and technology selection to optimise efficiency and minimise total costs (Banerjee, Anindya; Noguer, 2007; Kheybari et al., 2023). This multi-stage but integrated structure is critical for guaranteeing that bioethanol is produced, transported, and delivered in a manner that is economically feasible, environmentally sustainable, and receptive to market demand.

1.8.1 Ghana's Bioethanol Supply Chain Strategies

A comprehensive analysis of Ghana's bioethanol supply chain requires tracing the process from feedstock cultivation to final fuel distribution. The system is characterised by complex logistical constraints, particularly in sourcing sustainable residues from dispersed agricultural regions (Singh et al., 2018). Ghana possesses considerable potential for lignocellulosic bioethanol, estimated at 2,300 million litres annually, primarily from cassava, maize, yam, sorghum, and sugarcane residues (Kemausuor et al., 2014). The supply chain encompasses five interlinked stages—feedstock production, logistics, processing, distribution, and end-use—each shaped by local agroecological and infrastructural conditions.

Cassava remains the most promising feedstock due to its high starch yield and abundance; only 5.4% of national cassava output could meet a 10% ethanol blend (E10) target (Dankwa & Peprah, 2020). Key producing regions such as the Eastern, Bono, and Ahafo zones each have the potential to supply over 120 million litres annually. However, weather fluctuations, smallholder farm fragmentation, and competition with food uses limit stable feedstock availability (Kelly et al., 2025; Komlaga et al., 2022).

Transportation represents one of the most critical bottlenecks. Poor rural road networks and dispersed farms make moving bulky and perishable crops, such as cassava, costly and unreliable, especially during the rainy season (Dankwa & Peprah, 2020). High post-harvest losses and spoilage risks further inflate logistics costs (Osei et al., 2013). Storage infrastructure is similarly inadequate; limited silos and depots, often lacking ventilation or cooling, cannot maintain consistent inventories, especially for temperature-sensitive crops like cassava and yam (Pelizan, 2019).

Distribution of bioethanol relies mainly on road tankers, given the absence of pipeline networks, which raises costs and constrains access to blending stations (Tetteh & Fraser, 2025). Furthermore, limited integration with existing petroleum supply systems restricts the market penetration of bioethanol fuels.

In Ghana, feedstock procurement accounts for over 50% of production costs, with storage and transport further contributing substantially. High technology acquisition costs and transactional inefficiencies, including scheduling, quality control, and data coordination, undermine competitiveness. Despite these barriers, Ghana's abundant biomass, young labour force, and policy commitment offer strong potential for bioethanol sector growth.
Scholars highlight the need for supply chain optimisation frameworks that integrate feedstock aggregation, infrastructure development, and distribution logistics (Amo-Aidoo et al., 2021; Tetteh & Fraser, 2025). Proposed models include hub-and-spoke networks, regional aggregation centres, and ICT-based tracking systems (Ghaderi et al., 2016). However, many assume ideal rural transport conditions, which risks overestimating efficiency when applied to Ghana's infrastructural realities (Kasoa et al., 2025; Pelizan, 2019).

Figure 2 illustrates the regions of Ghana, highlighting the country's diverse administrative divisions. It displays the geographical distribution of regions such as Upper East, Upper West, Northern, Savannah, Bono East, Bono, Ahafo, Ashanti, Western North, Eastern, Volta, Greater Accra, Central, Western, and Oti.

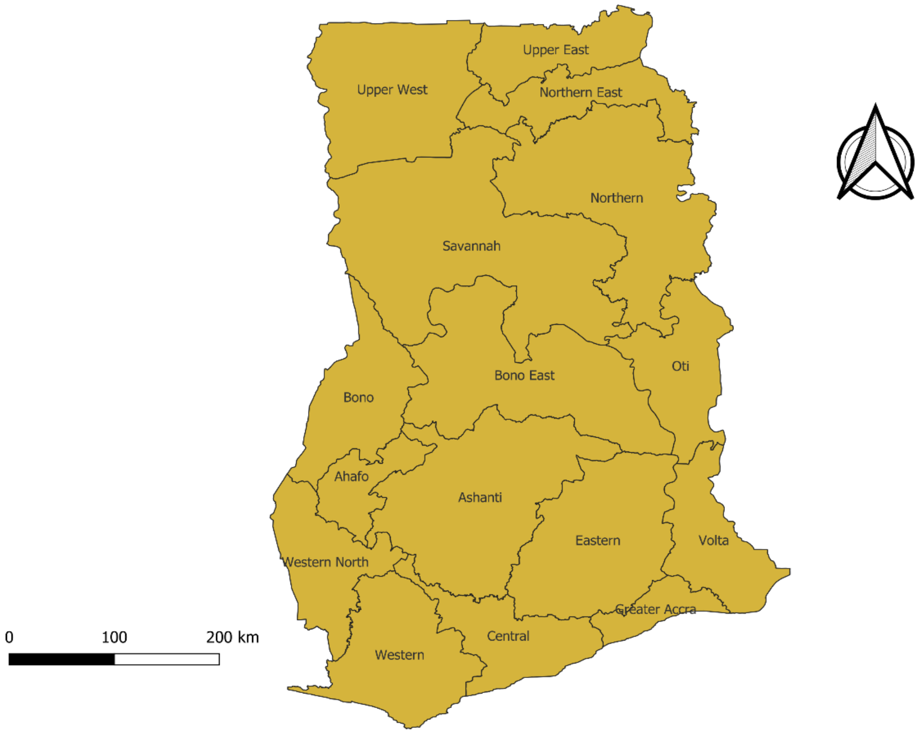

Figure 2: Map of Ghana displaying the 16 administrative regions

1.9 Policy and Regulatory Frameworks

A comprehensive and enforceable policy framework is the basis for market growth. Ghana’s bioethanol industry has been guided by frameworks since the 2005 after the adoption of ECOWAS 2003 energy policy (Kissi et al., 2025). Other policies implemented after this were the Renewable Energy Act (Renewable Energy Act, 2011), and the Renewable Energy Master Plan (Energy Commission, 2019), which aimed to reduce fossil fuel reliance and promote the use of biofuels. However, the current policy remains motivational, lacks implementation, and enforcement in the fuel industry. To drive market stability, and private investment, there should be the introduction of a mandatory blending mandate particularly the E10 policy requiring 10% bioethanol blend in petrol. Which would create a reliable domestic market for producers and promote investment by providing market certainty. Other financial incentives such as tax exemptions and capital subsidies are crucial to lower barriers for both local and foreign investors. Establishing a dedicated National Biofuel Development Authority which would help coordinate and enforce these policies and implementations, manage blending targets, ensure quality standards and facilitate stakeholder collaborations (Kissi et al., 2025).

1.9.1 Barriers in Ghana’s Bioethanol Policy and Regulatory Landscape

The barriers hindering Ghana’s bioethanol sector include the absence of enforceable policies such as mandatory blending mandates like E10, which results in uncertain and unreliable market demand. Existing laws, including the Renewable Energy Act (2011) and the Renewable Energy Master Plan by the Energy Commission (2010), are largely motivational but lack strong implementation and enforcement mechanisms (Kissi et al., 2025). Financial incentives such as tax exemptions or capital subsidies to attract investments remain unavailable (Kipkoech et al., 2022). Additionally, institutional division with overlapping responsibilities creates coordination challenges. Infrastructure for feedstock accumulation, transportation, storage, and blending are inadequately developed, complicating supply chain integration within existing petroleum distribution networks (Tetteh & Fraser, 2025). The current focus on first-generation feedstocks, particularly cassava and sugarcane raises concerns regarding food security and seasonal availability, while second-generation lignocellulosic feedstocks remain underexplored (Ezea, 2023). There is also limited integration of circular economy approaches to utilise residues and wastes (Amo-Aidoo et al., 2021). Market analyses, including demand forecasting, pricing, export potential, and the role of international collaborations in technology transfer and financing, are underdeveloped, inhibiting strategic planning and private sector engagement (Amo-Aidoo et al., 2021).

1.9.2 Successful International Models

Brazil is a global leader in bioethanol production, having implemented mandatory bioethanol blending mandates E27 during summer months and backed by strong government support, fiscal incentives, and institutional frameworks that stimulate both demand and production (De Souza Vieira & Jardim Leal, 2024). Brazil also integrates bioethanol within broader agricultural, energy, and industrial policies, ensuring sustainability and rural development (De Souza Vieira & Jardim Leal, 2024). The United States supports bioethanol production through the Renewable Fuel Standard, combining blending mandates, tax credits, and extensive investment in technology advancement (Bracmort, 2020). Nigeria has introduced biofuel policies including blending mandates and incentives to stimulate production while promoting domestically grown feedstocks (Okoro et al., 2024). Malaysia and Thailand have also made strides in bioethanol fuel blending and integrating biofuel development into national strategies. These countries emphasise mandatory blending targets, robust institutional coordination, financial incentives, integration with existing energy infrastructure, and sustainability standards – elements currently missing or underdeveloped in Ghana's framework.

The current bioethanol production models in Ghana rely on first-generation feedstocks such as cassava and sugar cane, which may compete with food needs and are subject to seasonal fluctuations (Amo-Aidoo et al., 2021). Hence, a research gap in evaluating the potential of second-generation (lignocellulosic) feedstocks to enhance sustainability (Ezea, 2023). Studies have not fully explored integration waste management and circular economy approaches, particularly residues such as cassava peels, maize and sorghum stalks, or fibrous residues into animal feed or biogas to improve overall system efficiency and profitability (Kasoa et al., 2025). Ghana's bioethanol context lacks a clear national policy and regulatory framework for blending mandates, investments incentives, and quality standards, which hinders market development and investor partnerships. Also, there is insufficient analysis of market demand, pricing mechanisms, and export potential, especially in the context of regional ECOWAS markets and international trade agreements. The role of strategic partnerships and international collaborations in technology transfer, financing, and market access is not fully explored in the Ghanaian context (Kasoa et al., 2025; Kissi et al., 2025).

This research thesis seeks to address some of these gaps by developing integrated strategies for supply chain optimisation, exploring sustainable feedstock options, proposing policy and market frameworks, and evaluating the socio-economic and environmental impacts of bioethanol production in Ghana. This study will contribute valuable insights to both academic literature and national policy discussions by addressing identified gaps in Ghana's bioethanol sector, providing evidence-based recommendations, and informing strategies for sustainable industry development.

Chapter 2 - RESEARCH METHODOLOGY

2.1 Research Design Structure

The development of bioethanol as an alternative energy source for Ghana's energy security, sustainability, and economic growth faces challenges related to agriculture, infrastructure, and regulation. This study adopts a qualitative exploratory design, combining systematic document analysis and comparative case studies. Reliance on secondary data is appropriate given the emerging state of Ghana's bioethanol industry and limited primary data.

Data were obtained from FAOSTAT and Ghana's Ministry of Food and Agriculture for cassava, yam, maize, sorghum, and sugarcane (2005–2023), selected for their agroecological suitability and technical potential (FAO, 2023b). The study focuses on agricultural residues to avoid food competition and promote sustainable production.

Simulation tools (CPLEX, QGIS, Excel) were used to assess production potential through a Mixed-Integer Linear Programming (MILP) model adapted from Afedzi et al. (2025), Ghaderi et al. (2016), and León-Olivares et al. (2020). The model optimises biorefinery siting, capacity, and logistics, while QGIS supports residue hotspot mapping and transport cost estimation (Jobe et al., 2025).

A comparative analysis benchmarks Ghana's capabilities against selected West African countries to identify transferable best practices and policy lessons. The study further evaluates supply chain resilience and marketing strategies to strengthen domestic and export markets.

Integrating qualitative and quantitative methods, the research follows four phases, systematic literature review, comparative analysis, supply chain modelling, and marketing evaluation, providing a comprehensive framework for sustainable bioethanol development in Ghana.

2.2 Data Collection and Source Evaluation

A systematic analysis of policy and regulatory frameworks was conducted using Ghana's key policy and regulatory documents, including the Strategic National Energy Plan (Energy Commission, 2006), Bioenergy Policy (Energy Commission, 2010), Renewable Energy Act (2011), National Energy Policy (Ministry of Energy, 2021), and National Energy Transition Framework (2022). National policy documents from other countries, particularly Nigeria's Biofuels Policy and Incentives, Mali's Biofuel Programme, and Burkina Faso's Biofuel Policy – were also analysed for comparative purposes (African Union, 2019). Regional frameworks, especially the ECOWAS Bioenergy Development Strategy and Investment Plan, provided an inter-regional context for national biofuel developments.

A systematic search of peer-reviewed journal articles was carried out using databases such as Google Scholar, ScienceDirect, PubMed Central, ResearchGate, Academia.edu, Sci-Hub, MDPI, etc. The search also examined market analyses and industry forecasts from sources such as 6Wresearch, as well as industry reports from IEA, the African Development Bank (AfDB), and national energy commissions. Documented bioethanol projects in Ghana and other African countries were reviewed, including Malawi's Dwangwa Estate Plant, Zimbabwe's Triangle

Ethanol Plant, and Ghana's emerging cassava-based ethanol initiatives (Deenanath et al., 2012). Case studies from comparative countries informed the identification of transferable practices.
The search strategy prioritised literature published between 2005 and 2025 to capture developments since Ghana's Renewable Energy Act and ensure contemporaneity. Inclusion criteria mandated direct relevance to bioethanol production, with a focus on West Africa and substantial content on capabilities and challenges. Studies from Sub-Saharan Africa or similar developing economies with comparable bioethanol challenges were given preference. Exclusion criteria removed studies predating 2005, non-peer-reviewed sources without institutional authorisation, and non-English publications lacking certified translations.
The keywords used included: Ghana bioethanol policy frameworks, biofuel regulatory challenges in Ghana, Ghana's agricultural feedstocks for bioethanol production and constraints, bioethanol processing infrastructure in Ghana, renewable energy policies and barriers in Ghana, and when Ghana adopted a bioethanol or biofuel policy? Bioethanol development in Africa, bioethanol production in West Africa, and renewable energy transition in ECOWAS. These were chosen for their potential to help achieve the study objectives and answer the research questions. Source quality was assessed based on journal impact factors, institutional credibility, and data consistency across multiple references. Conflicting information was resolved through deeper comparative analysis, with priority given to more recent or authoritative sources. A total of 150+ articles, policy frameworks, and industry reports formed the core reference base for this methodology.
The analysis employed a systematic comparative framework examining six main dimensions across selected countries:

- Feedstock availability: Types of crops (particularly cassava, sugar cane, and sorghum), yield differences, and Ghana's advantage as Africa's largest cassava producer with significant post-harvest capacity (Kasoa et al., 2025; Seglah et al., 2022).
- Processing: Comparison of first- and second-generation conversion techniques, scale of operations, and technological adoption, highlighting Ghana's emerging stage versus Malawi's established sugar cane molasses plants (Advanced BioFuels USA, 2023; Deenanath et al., 2012).
- Policy and regulatory frameworks: Blending mandates, incentives, and institutional coordination, contrasting Ghana's developing biofuel policy with Mali's advanced smallholder integration programmes (African Union, 2019)
- Market and infrastructure: Distribution networks, storage facilities, and end-use applications, noting regional challenges of inadequate infrastructure (Oppong-Ansah, 2025b)

- Socioeconomic impacts: Food-fuel conflict, job creation, and rural development, including Ghana's potential to create about 50,000 jobs through bioethanol production (Kasoa et al., 2025).
- Environmental considerations: Carbon savings, land-use change, and sustainability, referencing Ghana's estimated 70% greenhouse gas reduction capacity from bioethanol blends (Kasoa et al., 2025).

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted for each country's bioethanol industry to facilitate systematic comparison. A transferability assessment framework evaluated practices from other West African countries for adaptation to Ghana. Criteria included compatibility with Ghana's agricultural and industrial base, institutional capacity requirements, and scalability potential.

Tables 2–5 detail the data collection sources and procedures. Data were obtained from multiple credible and authoritative platforms to ensure comprehensive coverage and reliability, including academic journals, peer-reviewed articles related to bioethanol, renewable energy marketing, and international trade. Table 2 outlines the primary databases and institutional sources consulted, spanning academic repositories, governmental agencies, and industry reports.

Table 2: Databases searched

Category	Databases / Sources
Academic Databases	Google Scholar, ScienceDirect, PubMed Central, ResearchGate, Academia.edu, Sci-Hub, MDPI, Web of Science, Scopus, EBSCOhost, etc.
International Organisations	FAOSTAT, African Development Bank, IEA.
Government Institutions	MoFA, Energy Commission of Ghana, Ministry of Energy.
Industry & Market Reports	6Wresearch, national energy commissions.
Policy & Regulatory Documents	Strategic National Energy Plan (2006), Bioenergy Policy (2010), Renewable Energy Act (2011), National Energy Policy (2021), National Energy Transition Framework (2022), ECOWAS Bioenergy Development Strategy and Investment Plan.
Country Case Studies	Nigeria's Biofuels Policy and Incentives, Mali's Biofuel Programme, Burkina Faso's Biofuel Policy, Malawi's Dwangwa Estate Plant.

Examples of promising practices include Malawi's out-grower model linking smallholder farmers to bioethanol plants, potentially informing Ghana's sweet sorghum initiatives (Deenanath et al., 2012; Oppong-Ansah, 2025b) and Nigeria's multiple-feedstock approach balancing food and fuel crops to guide Ghana's feedstock diversification strategy (African Union, 2019). This data collection and evaluation phase aimed to map existing models, recognise persistent challenges in Ghana's context, and identify knowledge gaps regarding sustainability, efficiency, and resilience in bioethanol supply chains.

Table 3 lists the specific search terms employed, reflecting the thematic focus areas of policy frameworks, feedstock availability, infrastructure development, and regional bioethanol production contexts.

Table 3: Searched terms

Search Focus Area	Search Terms Used
Policy Frameworks	Ghana bioethanol policy frameworks; biofuel regulatory challenges in Ghana; renewable energy policies and barriers in Ghana; when did Ghana adopt a bioethanol or biofuel policy?
Feedstock	Ghana's agricultural feedstocks for bioethanol production and constraints; bioethanol development in Africa.
Infrastructure	Bioethanol processing infrastructure in Ghana; renewable energy transition ECOWAS.
Regional Context	Bioethanol production in West Africa; bioethanol development in Africa.
Marketing & Supply Strategies	Bioethanol marketing strategies; Ghana bioethanol industry; renewable energy export marketing; domestic demand promotion in biofuels; Bioethanol demand + marketing; renewable fuel export.

Table 4 details the literature selection process, including inclusion and exclusion criteria, temporal boundaries, and prioritisation protocols.

Table 4: Literature selection process

Step	Criteria Applied
Timeframe	Publications collected from 2005 to 2025 were used to capture developments since Ghana's Strategic Energy Plan was set in 2006.
Inclusion Criteria	Direct relevance to bioethanol production; focus on West Africa; substantial content on capabilities and challenges; studies from Sub-Saharan Africa or comparable developing economies.
Exclusion Criteria	Studies predating 2005; non-peer-reviewed sources without institutional authorisation; non-English publications without certified translations.
Selection Priority	Preference for studies with recent publication dates, peer-reviewed status, and institutional credibility.
Outcome	Over 150 articles, policy frameworks, and industry reports selected.

Table 5 summarises the criteria used to assess source quality, ensuring the credibility, relevance, and consistency of the final reference base.

Table 5: Source quality assessment criteria

Assessment Criterion	Evaluation Method
Credibility	Journal impact factor, peer-reviewed status, and recognised institutional affiliation.
Relevance	Direct applicability to Ghana's bioethanol context and research objectives.
Recency	Priority given to recent publications (2005–2025), with special emphasis on post-2006.
Consistency	Cross-verification of data across multiple references to resolve conflicts.
Authority	Preference for government reports, reputable NGOs, and international organisations.
Comparative Value	Inclusion of country-specific data from West African and Sub-Saharan Africa case studies.

2.3 Data Analysis and validation

Qualitative analysis was used to identify patterns, themes, and insights on marketing strategies and their influence on demand incentives. The study contrasted domestic and export-oriented approaches, highlighting key differences, challenges, and synergies. Data triangulation from multiple sources enhanced credibility by cross-verifying information and minimising bias. The analysis accounted for economic, cultural, and regulatory factors shaping marketing effectiveness in Ghana's bioethanol industry. The research relied solely on publicly available secondary data, involving no human participants or confidential information. Ethical concerns were minimal, with strict adherence to proper attribution and citation. Findings were cross-checked across policy, academic, and industry reports, complemented by comparative analysis with successful bioethanol models in developing countries such as Malawi, and supported by authoritative studies in the field.

2.4 Thematic Analysis Procedure

Thematic analysis is a qualitative method used to systematically identify, organise, and interpret patterns or themes within a dataset. In this study, it was applied to policy documents, industry reports, and academic literature to uncover recurring issues, opportunities, and best practices in bioethanol production. The procedure involved six key stages as outlined in table 6 for the data analysis.

1. Familiarisation with the data through repeated reading and initial notetaking.
2. Generating initial codes to label relevant content.
3. Grouping related codes into broader themes.
4. Reviewing and refining themes for coherence and distinctiveness.

5. Defining and naming themes to capture their essence; and
6. Synthesising and presenting the themes with supporting evidence.

This approach enabled the extraction of meaningful insights from diverse sources, ensuring a structured and transparent interpretation of the qualitative data in line with the study's objectives.

Table 6: Thematic analysis procedure

Step	Description
Familiarisation	Read all full texts in Mendeley at least once. Recorded memos on first impressions, recurring topics, and analytic questions.
Generating Initial Codes	Line-by-line coding in Taguette (Deductive codes based on a priori marketing dimensions such as "product positioning") Inductive codes emerging from data like "regulatory uncertainty."
Searching For Themes	Grouped related codes into candidate themes (e.g., "Pricing & Incentives") Drafted a provisional thematic map showing relationships (e.g., "Brand Messaging" → "Cultural Resonance")
Reviewing Themes	Checked each theme's coherence by re-reading all coded excerpts. Split overly broad themes (e.g., "Promotion" → "Digital Promotion" & "Traditional Media Promotion"). Merged or discarded weak/overlapping themes.
Defining & Naming Themes	Wrote clear definitions and scope statements for each theme Assigned descriptive names (e.g., "Export-Readiness & Compliance") Organized themes into primary vs. supporting strategy categories.
Producing the Report	Integrated themes into narrative form with exemplar quotations/data points. Contrasted domestic vs. export-oriented findings to highlight the unique challenges and transferable lessons.

2.5 Triangulation Methods for Data Analysis

Triangulation is a research approach that involves using multiple methods, data sources, or perspectives to enhance the credibility and validity of findings adopted from Norman K. Denzin (1978). In this study, triangulation was employed to ensure a comprehensive and robust analysis of Ghana's bioethanol policy and market landscape by cross-verifying evidence and insights across different types of data and analytical approaches.
Data Triangulation was applied by comparing information from diverse sources such as academic articles, industry white papers, policy documents, and market reports. For instance, IEA pricing incentives were cross-checked against case studies found in scholarly journals. This process helped verify the consistency of findings across various sources, reducing bias related to any single source type. Methodological Triangulation involved integrating theoretical frameworks with empirical case studies and quantitative trend analyses. This approach ensured that narrative themes extracted from qualitative data were supported by quantitative market data, thereby strengthening the validity of the conclusions by combining conceptual insights with empirical evidence. Temporal Triangulation grouped sources into three time periods –

2005-2010, 2011-2017, and 2018-2025 – to track how bioethanol strategies and regulatory environments evolved. This allowed the identification of enduring strategies, emerging best practices, and shifts influenced by changes in regulatory, economic, and cultural contexts.

2.5.1 Benefits of Triangulation

- Enhances the credibility and trustworthiness of findings by cross-validating data from different sources and methods.
- Provides a richer, more nuanced understanding of complex phenomena by integrating multiple perspectives.
- Helps identify patterns and changes over time, improving the depth of longitudinal analyses.

2.5.2 Drawbacks of Triangulation

- Can be time-consuming and resource-intensive due to the need to gather and analyse diverse data sets.
- Potential conflicts between data sources or methods may complicate interpretation.
- Requires careful methodological design to ensure coherence across different types of data and analyses.

Table 7 details the triangulation methods used for the research data analysis.

Table 7: Triangulation methods used in the research data analysis

Type	**Approach**	Purpose
Data Triangulation	Compared academic articles, industry white papers, policy documents, and market reports. Cross-checked IEA pricing incentives against journal case studies.	Verify consistency of findings across different source types.
Methodological Triangulation	Integrated theoretical frameworks with empirical case studies and quantitative trend analyses. Ensured narrative themes were supported by market data.	Strengthen validity by combining conceptual and empirical evidence.
Temporal Triangulation	Grouped sources into 2005–2010, 2011–2017, 2018–2025 cohorts. Tracked the evolution of strategies over time.	Identify enduring strategies versus emerging best practices and account for shifts in the regulatory, economic, and cultural context.

2.6 Residue Availability Calculations

This section is vital for evaluating Ghana's bioethanol potential (2005–2023) as it assesses the feasibility, scalability, and sustainability of production. Estimating agricultural residues ensures a dependable year-round feedstock supply, preventing shortages that could cause underutilization or shutdowns (IEA Bioenergy, 2017). Economic viability also relies on processing enough residues to reach economies of scale and justify infrastructure investment (Murillo-Alvarado & Flores Russell, 2022). Accurate residue estimates help determine optimal plant size, location, and supply chain design. Additionally, prioritizing residues and energy crops over food crops avoids food competition and land-use conflicts, supporting sustainability efforts (Hirschnitz-Garbers & Gosens, 2015). Calculating residue availability ensures only surplus biomass is used, minimizing environmental and social impacts (IEA Bioenergy, 2017). Understanding how residues are distributed across space and time allows for efficient collection, transportation, and processing, which reduces costs and emissions (Murillo-Alvarado & Flores Russell, 2022).

In Ghana, such calculations (Table 8) support policy and industry planning, helping set realistic production targets and design sustainable incentives. They are fundamental to ensuring bioethanol production remains technically feasible, economically viable, and environmentally sound, aligned with national climate and development goals.

Table 8: Residue availability and recoverability factors

No.	Crop	Residue	Residue-to-product-ratio	Recoverability factor
1.	Cassava	Peels [a]	0.25	0.20
		Stalk [a]	0.06	0.80
2.	Maize	Stalk [a]	1.59	0.80
		Husks [a]	0.20	1.00
		Cobs [a]	0.29	1.00
3.	Sorghum	Straw [a]	1.99	0.80
		Stalk [b]	2.85	0.80
4.	Yam	Straw [a]	0.50	0.80
		Peels [a]	0.20	0.35
5.	Sugarcane	Bagasse [b]	0.23	0.74
		Leaves [b]	0.22	0.86

(Singh et al., 2018)[a] (Tolessa, 2023)[b]

The general equation used to determine the annual residue availability potential for each crop produced was taken from (Singh et al., 2018) and further modified. Eq. (1) shows the residue to product ratio.

$$RPR = \frac{R}{P} \qquad (1)$$

where RPR is the residue-to-product ratio, R is the residue and P is the production.
To determine the amount of residue recoverable, Eq. (2) was used.

$$RF = \frac{RC}{R} \qquad (2)$$

where RF is the recoverability factor, RC is the residue collectible and R is the residue
Therefore, the amount of residue recoverable for each crop production is given by Eq. (3).

$$RC = RPR \ x \ RF \ x \ P \qquad (3)$$

To determine the total residue recoverable for each crop, the function from Eq. (3) was used in relation to the residue to product ratio and recoverability factor in table (1).

Table 9 shows the residue equations and factor used in calculating the residue availability of feedstock potential for bioethanol potential in Ghana.

Table 9: Residue equations and factors

Crop type	Residue type	Equation	Total residue factor
Cassava	Peels and Stalk	$TRC_c = P_c \sum(RF_i \ x \ RPR_i)$	$TRC_c = 0.098P_c$
Maize	Stalks, husk, and cobs	$TRC_m = P_m \sum(RF_i \ x \ RPR_i)$	$TRC_m = 1.762P_m$
Sorghum	Straw and stalk	$TRC_s = P_s \sum(RF_i \ x \ RPR_i)$	$TRC_s = 3.872P_s$
Sugar cane	Leaves and bagasse	$TRC_{sc} = P_{sc} \sum(RF_i \ x \ RPR_i)$	$TRC_{sc} = 0.36P_{sc}$
Yam	Straw and peels	$TRC_y = P_y \sum(RF_i \ x \ RPR_i)$	$TRC_y = 0.47P_y$

TRC is the total residue collectible; i is the residue type for each crop; c, m, s, sc, and y represent cassava, maize, sorghum, sugar cane and yam respectively.

When utilising the FAOSTAT database for calculations of residue availability and bioethanol potential in Ghana, several data limitations were acknowledged a indicated on their website (FAO, 2023b):

1. Estimated values (E*) – Some data values were not directly reported by national authorities but are rather estimated by FAOSTAT. These estimates are derived using mathematical models, standard coefficients, or by combining data from various sources, which some may be estimated themselves. As a result, these values are

subject to the assumptions and methodologies employed in their estimation, which may not fully capture local conditions or variability.

2. Imputed values (I*) – In cases where data are missing, incomplete, or unreliable, FAOSTAT employs statistical imputation techniques to generate replacement values. While this may aid to address data gaps, the resulting figures may not accurately reflect real world anomalies.
3. Unofficial figures from International Organisations (X*) – Some data entries may be based on combination, estimation, or coordination processes that differ from national reporting standards. Thus, discrepancies in definitions, data collection methods, or reporting practices may arise, possibly affecting the comparability and accuracy of the data.

Therefore, while the analysis offers valuable insights into residue availability and bioethanol potential in Ghana, it is important to acknowledge that the reliance on estimated, imputed, and unofficial data values inevitably introduces a degree of uncertainty and potential bias. Such limitations are not merely academic caveats; they have tangible implications for the accuracy of residue calculations, which in turn can affect the reliability of policy recommendations and investment decisions. These constraints were explicitly considered when interpreting the results and drawing conclusions, ensuring that the findings are viewed within the context of their inherent uncertainties.

Specifically, the use of estimated values can produce variances that distort projections of feedstock supply; reliance on imputed data increases the risk of systematic bias due to the assumptions embedded in the estimation process; and dependence on unofficial international figures heightens the likelihood of inconsistencies, given that data collection methods and reporting standards can vary significantly between countries. In a policy and industrial planning context, these data limitations underline the importance of improving national-level residue statistics, harmonizing measurement methodologies, and investing in robust, locally verified datasets to enhance the precision and credibility of future bioethanol potential assessments in Ghana.

2.7 Bioethanol Potential in Ghana (2005-2023)

The Eq. (4) used to determine the bioethanol production per annual for each crop residue was taken from Kemausuor et al., (2014) and Singh et al., (2018a) and further modified.

$$P_{eth}^{total} = \frac{Y_{RR}[(C_{glu}\ x\ Y_{hyd1}\ x\ Y_{eth1}\ x\ \eta_{pre1}\ x\ \eta_{enz1}) + (C_{hem}\ x\ Y_{hyd2}\ x\ Y_{eth2}\ x\ \eta_{pre2}\ x\ \eta_{enz2})]}{\rho_{eth}} \quad (4)$$

Table 10 shows the variable representation and values for calculating bioethanol potential.

Table 10: Variables representation and values for calculating bioethanol potential

Variable	Definition	Unit	
		Cellulose	**Hemicellulose**
P_{eth}^{total}	Annual ethanol production	ML	ML
Y_{RR}	Annual residue recoverable	MT	MT
C_{glu} & C_{xyl}	Concentration of glucan (cellulose or starch) and Xylan (hemicellulose) in a specific residue, respectively	(g/100gtotal solids)	(g/100gtotal solids)
Y_{hyd1} & Y_{hyd2}	Stoichiometric yield of cellulose and hemicellulose from hydrolysis, respectively	1.11g/g	1.14g/g[b]
Y_{eth1} & Y_{eth2}	Stoichiometric yield of cellulose and hemicellulose from fermenting, respectively	0.51	0.51
η_{pre1} & η_{pre2}	Conservation of glucan and xylan in pretreatment	0.90	0.80[a]
η_{enz1} & η_{enz2}	Enzymatic conversion efficiency of cellulose and Hemicellulose	0.80	0.80[a]
ρ_{eth}	Ethanol density	789 T/ML	789 T/ML

[a]assumption, [b]empirical

These values were taken from Singh et al. (2018) while others were based on empirical validation and assumption.

Table 11 indicates the parameters of glucan and xylan of the residues used in determining the potential of bioethanol, as these polysaccharide components represent the primary fermentable fractions in lignocellulosic biomass. Understanding their concentrations is essential because glucan yields glucose and xylan yields xylose during hydrolysis, both of which are key sugars for ethanol fermentation. Higher glucan and xylan content generally correlates with greater theoretical ethanol yields, making this information critical for accurately estimating bioethanol potential and selecting the most promising feedstocks.

Table 11: Parameters of glucan and xylan of various residues

No.	Crop	Residue	C_{glu} g/100 (gtotal solid)	C_{hem} g/100 (gtotal solid)
1.	Cassava	Peels	55.5	22.0
		stalk	33.0	13.0
2.	Maize	Stalk	36.8	27.4
		Husks	35.3	21.8
		Cobs	34.0	49.1
3.	Sorghum	Straw	41.6	26.7
		Stalk	38.7	23.4
4.	Yam	Straw	25.0	15.0
		Peels	29.02	28.91
5.	Sugarcane	Bagasse	36.0	17.0
		Leaves	32.0	17.0

2.8 Optimisation Model of Bioethanol Supply Chain in Ghana

To minimize the total bioethanol supply chain cost in Ghana, a MILP model was devised and utilised in an IBM ILOG CPLEX Studio IDE 22.1.1 for the period of 19 years (2005 – 2023) over 16 administrative regions and 5 feedstocks (cassava, maize, sorghum, sugar cane and yam. Each crop residue was run with the following supply chain objectives: collection, transportation, feedstock storage, processing, and storage of bioethanol and distribution of bioethanol to various demand zones. The objective function, Eq. (5), includes six components: the first component is the cost of collecting feedstock at region r, during time t. The second deals with the cost of transporting feedstock from region r, to biorefinery plant p, during time t. The third is cost of storing the feedstock supply at plant p, containing a specific storage capacity at time t. The fourth deals with the cost of processing a specific feedstock at that biorefinery plant p, at each time. The fifth is the cost related to storing the processed volume of bioethanol at plant p, at each time. The last function entails the cost of distributed bioethanol from plant p, to each demand zone d, at time t.

$$Minimize\ Z = \sum_{t\in T}\sum_{r\in R} C_{r,t}^{coll.}\, F_{r,t} + \sum_{t\in T}\sum_{r\in R}\sum_{p\in P} C_r^{i.}\, X_{r,p,t} D_{r,p}^{feeds.} + \sum_{t\in T}\sum_{p\in P} C_p^{sto.\ i.}\, Y_{p,t}$$

$$+\sum_{t\in T}\sum_{p\in P} C_p^{proc.i}\, \delta_{p,t} + \sum_{t\in T}\sum_{p\in P} C_p^{sto.bioeth.}\, E_{p,r}$$

$$+ \sum_{t\in T}\sum_{p\in P}\sum_{d\in R} C_p{}^{distr.}\ V_{p,d,t}\, D_{p,r}^{bioeth.} \qquad (5)$$

2.8.1 Constraints of the Optimisation Model

The solution of this model was determined based on the constraints' equations. For the collection and supply balance, Eq. (6) ensures that the amount of feedstock collected does not exceed the available feedstock in all regions r, at time, t. Eq. (7) ensures that the amount of feedstock transported from region r, to the biorefinery plant p, is equal to the amount of feedstock collected. Eq. (8) ensures the feedstock storage balance at the plant, whereas the amount stored in year 1 is equal to the amount of incoming feedstock minus the amount processed, and for subsequent years, the storage is equal to the previous year's remaining stock plus the current inflow minus the processing.

Eq. (9) ensures that the amount of feedstock processed at the plant, p, cannot exceed the processing capacity at each time t. Eq. (10) represents the bioethanol storage balance. It states that the quantity of bioethanol stored at plant p, at time t, equals the amount processed minus the volume distributed in the first year. In subsequent years, the storage amount corresponds to the previous year's stock plus the newly processed bioethanol, minus the quantity distributed. Eq. (11) ensures that the amount of bioethanol distributed is greater than or equal to the amount demanded at the demand zone d, at each time t.

Eq. (12) ensures that the amount of feedstock stored at the plant p, does not exceed the storage capacity at each time t. Eq. (13) ensures that the amount of bioethanol stored at the plant p, does not exceed the bioethanol storage capacity at the plant p, at all times. Eq. (14 – 19) indicates all non-negative constraints for a suitable balance of the system model.

$$\boldsymbol{F_{r,t} \leq A_{r,t}} \qquad \forall \boldsymbol{r, t} \qquad (6)$$

$$\boldsymbol{F_{r,t} = \sum_{p \in P} X_{r,p,t}} \qquad \forall r, t \qquad (7)$$

$$\boldsymbol{Y_{p,t}} = \begin{cases} \boldsymbol{X_{r,p,t} - \delta_{p,t}} & \boldsymbol{t = 1} \\ \boldsymbol{Y_{p,t-1} + X_{r,p,t} - \delta_{p,t}} & \boldsymbol{t > 1} \end{cases} \qquad \forall p, t \qquad (8)$$

$$\boldsymbol{\delta_{p,t} \leq \gamma_p} \qquad \forall p, t \qquad (9)$$

$$\boldsymbol{E_{p,t}} = \begin{cases} \boldsymbol{\alpha_i \delta_{p,t} - \sum_{d \in R} V_{p,d,t}} & \boldsymbol{t = 1} \\ \boldsymbol{E_{p,t-1} + \alpha_i \delta_{p,t} - \sum_{d \in R} V_{p,d,t}} & \boldsymbol{t > 1} \end{cases} \qquad \forall p, t \qquad (10)$$

$$\boldsymbol{\sum_{p \in P} V_{p,r,t} \geq K_{d,t}} \qquad \forall d \in R, t \qquad (11)$$

$$\boldsymbol{Y_{p,t} \leq S_p} \qquad \forall p, t \qquad (12)$$

$$\boldsymbol{E_{p,r} \leq \beta_p} \qquad \forall p, t \qquad (13)$$

$$\boldsymbol{F_{r,t} \geq 0} \qquad \forall r, p, d, t \qquad (14)$$

$$\boldsymbol{X_{r,p,t} \geq 0} \qquad \forall r, p, d, t \qquad (15)$$

$$\boldsymbol{Y_{p,t} \geq 0} \qquad \forall r, p, d, t \qquad (16)$$

$$\boldsymbol{\delta_{p,t} \geq 0} \qquad \forall r, p, d, t \qquad (17)$$

$$\boldsymbol{E_{p,r} \geq 0} \qquad \forall r, p, d, t \qquad (18)$$

$$\boldsymbol{V_{p,r,t} \geq 0} \qquad \forall r, p, d, t \qquad (19)$$

2.8.2 Key Input Parameters

The following input parameters were used to solve the supply chain optimisation. Each year is represented distinctively by T such that $t = 1, 2, 3, \ldots 19$. The available residue from all 16 administrative regions of Ghana was computed using Eq. (3) for supply feedstock across the period 2005–2023. Three strategic locations – Tema, Kumasi, and Tamale – were selected as assumed biorefinery sites. This selection was guided by several considerations, such as:

i. their proximity to high-yield feedstock-producing regions, which reduces transport distances and associated costs.
ii. their status as major economic and industrial hubs with access to labour, utilities, and existing processing infrastructure.
iii. their geographic spread across the coastal, middle, and northern belts of Ghana, ensuring balanced regional coverage.
iv. their connection to major road networks and distribution corridors, facilitating efficient nationwide supply.

The decision to choose three plants rather than more or fewer was a deliberate strategic balance: adding more plants would increase capital expenditure and operational complexity without proportional gains in efficiency, whereas fewer plants would risk overburdening transport logistics and reducing resilience in supply distribution.

Each plant was assumed to operate at a uniform capacity level for each crop type, derived from Equation (4) and based on reasonable industrial-scale processing capacities. Specifically, each facility could process up to 2,000 MLPY for cassava, 7,000 MLPY for maize, 1,500 MLPY for sorghum, 35 MLPY for sugar cane, and 3,000 MLPY for yam.

These capacity levels were selected to match the scale of feedstock availability while maintaining operational efficiency and economies of scale typical in medium- to large-scale bioethanol facilities. The uniform capacity assumption also allowed for a fair comparative assessment of supply chain performance without plant size acting as a confounding variable.

The bioethanol demand zones were defined as the same 16 administrative regions from which the feedstock was sourced. This approach was adopted because fossil fuel consumption data, the basis for estimating bioethanol demand, is available and structured along these regional boundaries. It also allows for direct correlation between regional production potential and consumption needs. To model the effect of the E10 blending mandate as a demand factor for each region, Eq. (20) was applied. This ensured that demand calculations were consistent with Ghana's renewable energy policy objectives and provided a realistic representation of the market conditions under which the supply chain would operate.

$$V_{eth} = \frac{\left(0.10\ x\ \rho_{pet} x\ LHV_{pet}\right)}{\rho_{E10}\ x\ LHV_{E10}\ x\ V_{pet}} \qquad (20)$$

where V_{eth} is the volume of ethanol (L), V_{pet} is the volume of petrol (L) on annual basis, ρ_{pet} is the density of petrol (745 kg/m^3), LHV_{pet} is the lower heating value of petrol (44 MJ/kg), ρ_{E10} is the density of ethanol (749.4 kg/m^3) and LHV_{E10} is the lower heating value of ethanol (42 MJ/kg) (Singh et al., 2018b) .

Some key input parameters and data are shown in Tables 12 and 13, which summarise the quantitative and qualitative values used to configure and run the supply chain optimisation model. These tables present essential variables such as residue availability by region and over a period of 19 years, transportation costs between feedstock sources and processing sites, plant capacity level, and demand levels per region. By combining these parameters, the tables serve as both a reference for model calibration and a transparency tool, allowing readers to trace how each input influences the optimisation results.

Table 12 shows the key input parameters for the supply chain optimisation model of the five crop residues in the selected bioethanol production calculations in Ghana.

Table 13 indicates the cost parameters and biorefineries' capacity levels. The cost parameters were sourced from a combination of peer-reviewed literature and recent Ghana-specific studies to ensure both international comparability and local relevance.

Table 12: Key input parameters for supply chain optimisation

Region (r)	Residue 2005 – 2023 (tonnes)					Demand, d (litres) (2005 – 2023)
	Cassava (i)	**Maize (i)**	**Sorghum (i)**	**Sugar cane (i)**	**Yam (i)**	
Ahafo	1894783	916886	0	0	7334776	25571449
Bono	4134793	11596180	0	346816	6486040	442502347
Ashanti	2652696	11002630	0	0	7144698	105971573
Bono East	3031652	7335087	0	0	23100871	54552458
Central	3742306	6958518	0	438620	485999	193979506
Eastern	7984963	11135250	0	61203	11288683	178203979
Greater Accra	595526	927532	0	0	0	1060398287
Northern	1024524	2969886	3614901	0	15743563	85032009
Northern East	853770	2225591	1994428	0	4397020	28344004
Oti	1017603	1206035	0	0	2588459	61420534
Savannah	683016	1298869	5609329	0	6103207	28344004
Upper East	0	2318425	5109974	0	0	111916124
Upper West	0	3710129	6003249	0	8285225	56349124
Volta	2035206	1809053	0	30601	5176919	92130802
Western	1143896	3479259	0	142806	826563	184961902
Western North	1372676	695852	0	0	1239845	78203040

Specifically, collection costs were adapted from Ghaderi et al. (2016); Osei et al. (2023), transportation costs from Singh et al. (2018b), distribution costs from León-Olivares et al. (2020), processing costs from Ceaser et al. (2024), and feedstock storage costs from Shah (2017) and bioethanol storage costs from León-Olivares et al. (2020).

All monetary values from these references were originally reported in different years and in various currencies. To maintain consistency, each value was first converted into Ghanaian Cedi (GH₵) using the historical exchange rate for the reference year and then adjusted for inflation to 2023 price levels using the Ghana Consumer Price Index (CPI) published by the Ghana Statistical Service. This adjustment ensures that all cost parameters reflect present-day economic conditions, enabling more accurate and realistic supply chain optimisation results.

Table 13: Key cost parameters and biorefinery capacity level

Parameters	Unit	Value	Reference
$C_{r,t}^{coll.}$	GH₵/tonne	9 (for all *i*)	(Ghaderi, Asadi, et al., 2016; Osei et al., 2023)
$C_r^{i.}$	GH₵/tonne/km	12 (for all *i*)	(Singh et al., 2018b)
$C_p{}^{distr.}$	GH₵/litre/km	0.000014 (for all *i*)	(León-Olivares et al., 2020)
$C_p^{proc.\ i}$	GH₵/tonne	375 (for all *i*)	(Ceaser et al., 2024)
$C_p^{sto.\ i.}$	GH₵/tonne	93 (for all *p*)	(Shah, 2017)
$C_p^{sto.bioeth.}$	GH₵/litre	0.075 (for all *p*)	(León-Olivares et al., 2020)
$V_{p,t}$	ML/year	2000 (for all *p*)	bioethanol potential for cassava
$V_{p,t}$	ML/year	7000 (for all *p*)	bioethanol potential for maize
$V_{p,t}$	ML/year	1500 (for all *p*)	bioethanol potential for sorghum
$V_{p,t}$	ML/year	35 (for all *p*)	bioethanol potential for sugar cane
$V_{p,t}$	ML/year	3000 (for all *p*)	Bioethanol potential for yam

Exchange rate: GH₵ 1 = $ 0.09

- **Model nomenclature**

Sets and indices

1. $let\ regions: r,\ d \in \{1, 2, 3, \ldots . R\}$
2. $let\ plants: p \in \{1, 2\ 3, \ldots . P\}$
3. $let\ years: t \in \{1, 2\ 3, \ldots . T\}$
4. $let\ feedstock:\ i \in \{cassava, maize, sorghum, surgar\ cane, yam\}$

- **Parameters**

i. Supply

- $A_{r,t}$: Annual availability of feedstock in region r at time t, $(tonne)$

ii. Collection cost

- $C_{r,t}^{coll.}$: Collection cost for feedstock in region, r, at year, t $(GH₵/tonne)$

iii. Distance matrix (supply matrix of feedstock from region to plant)

- $D_{r,p}^{i.}$: Distance from region r, to plant, p (km)

iv. Distribution matrix (distribution of bioethanol from plants to demand zone/region)

- $D_{p,r}^{bioeth.}$: Distance from plant, p to region r (km)

v. Transportation cost

- $C_r^{i.}$: cost of transporting feedstock, i for all regions, r (GH₵/tonnes)

vi. Distribution cost

- $C_p{}^{distr.}$: cost of distributing bioethanol for all regions (GH₵/litre)

vii. Storage cost

- $C_p^{sto.i.}$: cost of storing feedstock at plant, p (GH₵/tonnes /year
- $C_p^{sto.bioeth.}$: cost of storing bioethanol at plant, p (GH₵/litre/year)

viii. processing costs

- $C_p^{proc.}$: bioethanol processing cost at plant, p (GH₵/litre/year)

ix. Capacity

- γ_p : processing capacity at plant p (tonnes /year)
- S_p: feedstock storage capacity of plant, p (tonnes)
- β_p : bioethanol storage capacity at plant, p (litres)

x. Conversion

- α_i : bioethanol conversion factor of feedstock, f (litres/tonnes)

xi. Demand

- $K_{r,t}$: bioethanol demand in region r at time t (litres)

- **Decision variables**
  1. $F_{r,t}$: the amount of feedstock collected in region r at time t (tonnes /year)
  2. $X_{r,p,t}$: the amount of feedstock transported from region r to plant, p in year t (tonnes /year)
  3. $Y_{p,t}$: the amount of feedstock store at plant p in time t (tonnes s/year)
  4. $\delta_{p,t}$: the amount of feedstock processed at plant p in time t (tonnes s/year)
  5. $E_{p,t}$: the amount of bioethanol stored at plant p in time t (litre/year)
  6. $V_{p,r,t}$: the volume of bioethanol distributed from plant p to region r at time t (litres/year)

2.9 Synthesis and Framework Development

The strategy development phase combines all analysed data to formulate evidence-based recommendations. These included promoting integrated supply chains producers cultivate their own feedstock to reduce costs and improve logistics diversifying revenue streams, promoting supportive policies including subsidies, and investing in rural infrastructure and digital supply chain tracking (Tulashie et al., 2023). Each strategy was examined for feasibility, sustainability, and alignment with national development goals, always mindful of maintaining a balance with food security and rural livelihoods. This research employed a rigorous and transparent methodology, leveraging systematically secondary sources, comparative analysis, and well-established analytical frameworks to develop robust, context-specific strategies for improving supply chain management within Ghana's bioethanol sector.

2.10 Limitations of the Methodology

Secondary data research depends on the availability and quality of existing data, which may be limited by gaps, outdated information, or insufficient focus on Ghana. Marketing strategy assessments were constrained by the absence of primary data; however, diverse and reputable sources were carefully selected to mitigate these issues. A major limitation was the uneven coverage of Ghana-specific information, as much literature focuses on major producers like the U.S. and Brazil. To address this, the study prioritised Ghanaian government reports (Energy Commission, MoFA) and peer-reviewed West African case studies, explicitly noting data gaps to avoid overgeneralisation.

Although the 2005–2023 timeframe captures post-Renewable Energy Act trends, some datasets may not reflect recent price shifts or emerging technologies. Sensitivity analyses within the MILP model tested assumptions against possible data obsolescence, while policy sources were cross-checked with updated industry news. Triangulation across academic, government, and NGO data (e.g., Energy Commission vs. World Bank reports) helped balance biases in official or commercial accounts. Model parameters were validated against FAO and transport benchmarks, with alternative scenarios for discrepancies exceeding 15%.

Exclusive reliance on secondary data limited field-level insights from farmers and producers, identified as priorities for future research—especially in Volta and Greater Accra, where pilot projects cluster. Despite these constraints, the study applied a rigorous, systematic approach integrating literature review, thematic analysis, and data triangulation to generate credible, policy-relevant insights for Ghana's bioethanol development.

This methodology provides a robust, evidence-based approach to analysing and improving Ghana's bioethanol supply chain. By combining qualitative and quantitative techniques within a secondary-data framework, the study balances academic rigour with practical applicability. Future research could expand on these findings through primary data collection such as stakeholder interviews or field surveys, to further refine recommendations.

Chapter 3 - RESULTS AND DISCUSSION

3.1 Results

3.1.1 Bioethanol Market Landscape in Ghana

Ghana's energy profile remains dominated by traditional biomass fuels, firewood and charcoal, used by nearly 60% of households for cooking, causing indoor air pollution and about 6,500 premature deaths annually, alongside 135,000 hectares of forest loss (Ministry of Energy, 2025; Kyere-Boateng & Marek, 2021). Bioethanol offers a clean alternative, and estimates indicate Ghana could produce over 200 ML annually from agricultural residues, supplying five million households (Oppong-Ansah, 2025b). However, the sector remains underdeveloped due to fossil fuel subsidies, weak policy frameworks, and inadequate infrastructure.

Cassava, with its high starch content and low input needs, remains Ghana's most viable first-generation feedstock, with a potential of over 300 ML per year (Osei et al., 2013a; Singh et al., 2018). While concerns persist over food-fuel conflicts, studies show minimal overall food security impacts (Brinkman et al., 2020). Sweet sorghum offers an alternative, non-food feedstock suitable across agroecological zones and promising for small-scale rural biorefineries (Tulashie et al., 2023).

Second-generation feedstocks—maize stalks, bagasse, cassava peels, and cocoa pods—could yield up to 2,300 ML annually, exceeding the 10% petroleum replacement target (Kemausuor et al., 2014b). Yet, high capital costs and logistical challenges hinder large-scale adoption (Singh et al., 2018b). Presently, only 0.04% of households use bioethanol for cooking (Boakye & Ofori, 2022), and blending initiatives remain inconsistent compared to Malawi's successful 10% sugarcane-based ethanol programme (Mawusi et al., 2023).

Ghana's industrial ethanol market, valued at GH₵166.7 million in 2024, is dominated by imports and beverage production, though projected to grow by 7.5% annually to 2031 (6Wresearch, 2024). A 10% transport fuel blend would require 150 ML annually, and the residential sector presents major potential given high biomass dependency. Pilot cookstove projects show positive adoption trends (Boakye & Ofori, 2022), but scaling requires stronger supply chains, infrastructure, and incentives.

Although national policies, such as the Renewable Energy Act (2011), Bioenergy Policy (2010), and Energy Transition Framework (2022), acknowledge bioethanol's role, they lack clear implementation mechanisms and institutional coordination (Singh et al., 2018b). Lessons from Malawi highlight the need for enforceable blending mandates, fiscal incentives, and farmer support schemes (Deenanath et al., 2012). The forthcoming National Biofuel Policy (Oppong-Ansah, 2025a) and aviation biofuel provisions under the Energy Transition Framework (2022) mark progress, but achieving sustainable growth will require policy alignment, infrastructure investment, and robust monitoring systems.

3.1.2 Residue Availability Potential

Figures 3 - 7 indicates the residue availability of cassava, maize, sorghum, sugar cane and yam potential respectively to produce bioethanol in Ghana. This potential served as the feedstock collection resource used as the input parameter during the supply chain optimisation modelling.

Figure 3 presents the spatial distribution of cassava residue availability across Ghana between 2005 and 2023. The data indicate that cassava residues are not uniformly distributed across the country, with the highest availability concentrated in the southern and middle belt regions. Specifically, Ashanti, Eastern, and Central Regions fall within the highest category, with cassava production of 42.2 million tons, 81.5 million tons and 38.2 million tonnes respectively, with residue volumes ranging between 3.0 million tons and 8.0 tons over the study period. These regions represent key cassava cultivation zones, benefiting from favourable climatic conditions and established smallholder farming systems.
The Western, Western North, Bono, Bono East, and Ahafo Regions also exhibit substantial cassava production capacity and residue potential, ranging from 11.7 to 30.9 million tons and 1.9 to 3.0 million tonnes respectively. On the contrary, the northernmost regions – including Upper West, Upper East, Northern, Northern East, and Savannah – show the lowest availability, with residue volumes below 683,016 tons, reflecting lower cassava cultivation intensity and a stronger focus on cereals such as maize, millet, and sorghum.

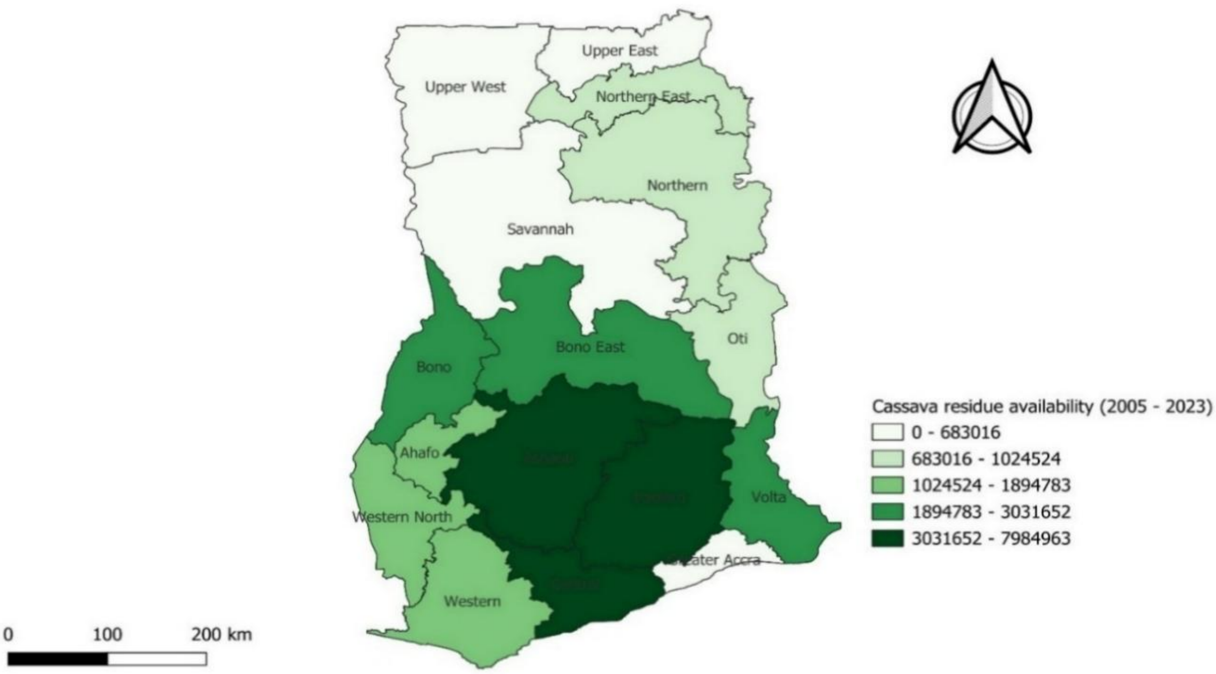

Figure 3: Cassava residue availability

This spatial pattern has significant implications for supply chain optimisation. The concentration of feedstock in the middle and southern zones aligns with model outputs that identify these regions as optimal locations for processing plants. Locating production infrastructure in these high-yield zones reduces average transportation distances, minimises logistics costs, and increases the overall efficiency of the bioethanol supply chain. These residue hotspots therefore served as the primary feedstock collection points in the optimisation modelling process, ensuring maximum utilisation of available resources while reducing post-harvest waste.

Figure 4 shows the maize production in Ghana between 2005 and 2023 that exhibits distinct spatial patterns, with the highest output consistently recorded in the middle and southern belts.

Regions such as Ashanti, Eastern, Bono, and Bono East dominate national maize supply, with cumulative production over the study period exceeding 6.58 million tons, 6.32 million tons, 6.24 million tons, and 4.16 million tons respectively. This high productivity corresponds to favourable climatic conditions, fertile soils, and access to improved agricultural inputs in the semi-deciduous forest and transitional zones.

In the southern coastal belt, Central Region also records significant production of estimated 3.95 million tons total, while Western Region contributes nearly 1.97 million tons, reflecting the role of mixed farming systems and moderate mechanisation in these areas.

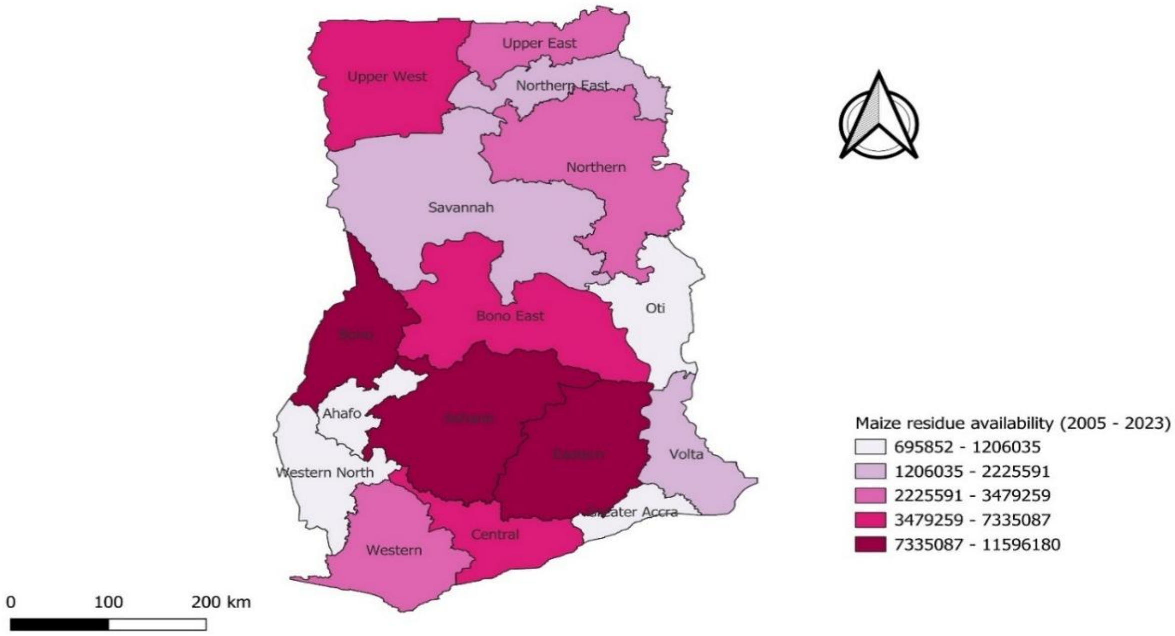

Figure 4: Maize residue availability

Maize production is concentrated in Ghana’s middle belt, particularly Ashanti, Eastern, Bono, and Bono East, generating the highest residue potential. Ashanti produced 6.58 million tons, yielding an estimated 11.59 million tons of residues. Eastern and Bono regions each generated over 11 million tons of residues, supporting significant bioethanol or biomass energy potential. Northern savannah regions have lower maize production due to erratic rainfall, lower soil fertility, and limited inputs; newly created regions like Savannah, Oti, and Northern East produced 0.68–0.74 million tons cumulatively.

Sorghum production and residues are confined to northern ecological zones—Upper West, Savannah, Upper East, Northern, and Northern East. Upper West recorded the highest grain yield (≈1.55 million tons), producing 6.0 million tons of residues. Savannah generated 1.45 million tons of grain and 5.61 million tons of residues; Upper East 1.32 million tons grain and 5.11 million tons residues; Northern and Northern East contributed 3.61 million tons and 1.99 million tons of residues respectively.
This spatial pattern highlights the importance of agroecology and infrastructure in shaping maize and sorghum feedstock availability for bioethanol and biomass energy production.

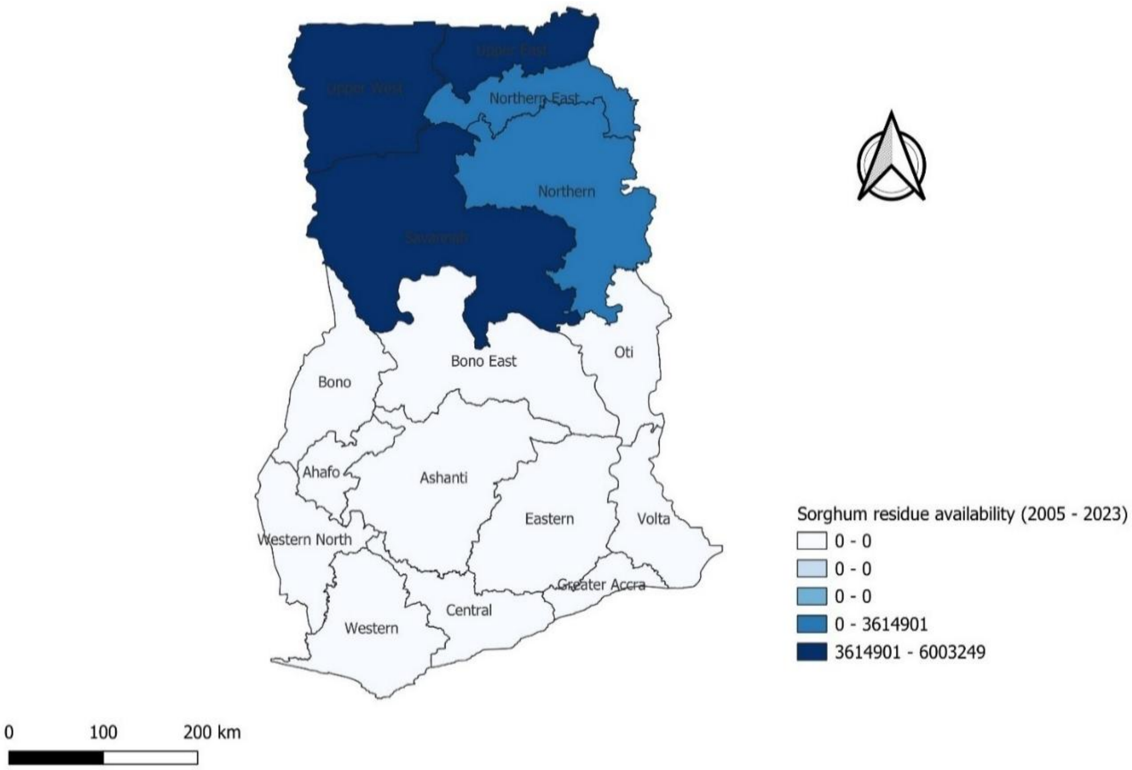

Figure 5: Sorghum residue availability

Map visualizations show that sorghum production and residues are concentrated entirely in northern Ghana, with millions of tons generated over the 19-year period. Southern, central, and western regions—including Ahafo, Ashanti, Bono, Bono East, Central, Eastern, Greater Accra, Oti, Volta, Western, and Western North—recorded no sorghum production.
This pattern reflects Ghana's agroecology: the north, with unimodal rainfall, long dry spells, and drought-tolerant soils, favors sorghum, while the south focuses on crops like cocoa, plantain, cassava, and maize. The north's consistent dominance in sorghum residues highlights its potential not only for bioethanol production but also for livestock feed and other biomass-based applications.

Figure 6 presents a map of sugar cane residue distribution from 2005 – 2023 in Ghana of which its production is highly concentrated in the southern ecological regions in the country. Sugar cane production in Ghana is highly geographically concentrated, within only five regions recording production between 2005 and 2023: Central, Ashanti, Western, Eastern, and Volta.

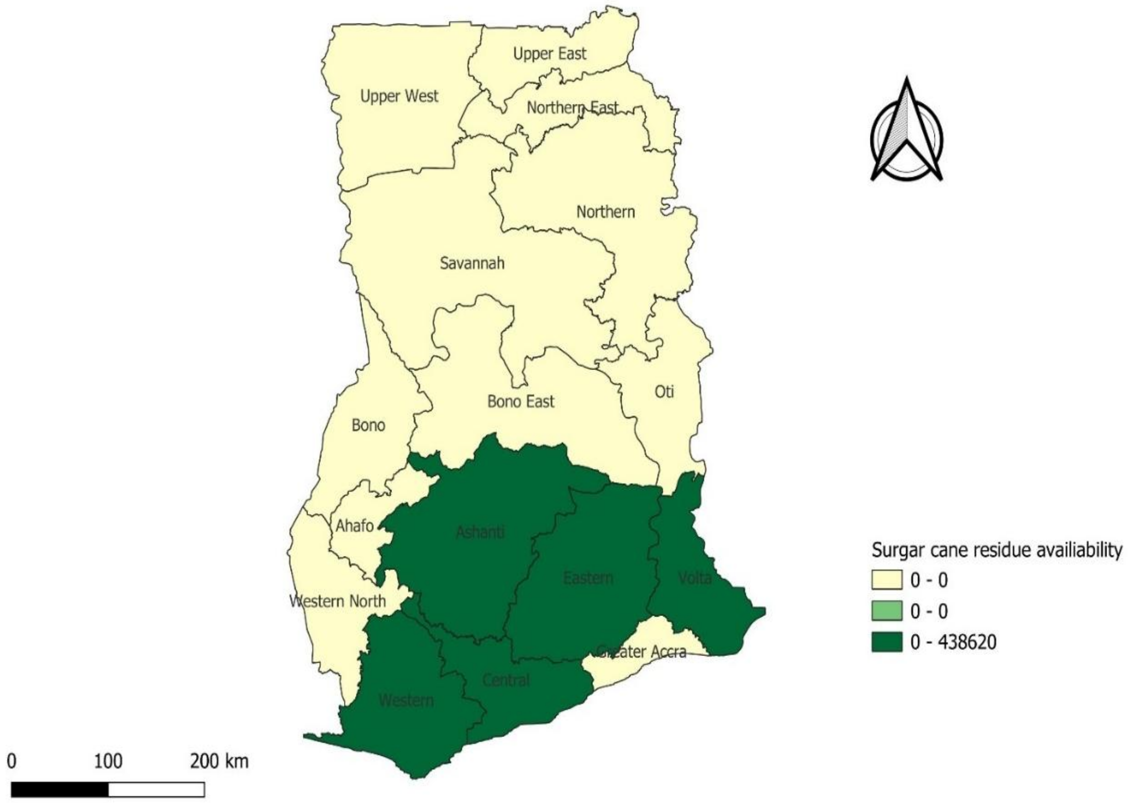

Figure 6: Sugar cane residue availability

Sugarcane cultivation in Ghana is concentrated in the southern belt due to favorable climate and soils, with no production in northern or transitional zones. Over 19 years, the Central Region contributed the most residues (438,620 tons; ~22,979 tons/year), followed by Ashanti (346,816 tons; ~18,253 tons/year), Western (142,806 tons; ~7,516 tons/year), Eastern (61,203 tons; ~3,221 tons/year), and Volta (30,601 tons).

Yam production, and thus residue generation, is concentrated in the middle and northern belts. From 2005–2023, Northern produced the most yam residues (15.74 million tons), followed by Bono East (23.1 million tons), Ashanti (6.49 million tons), and Eastern (11.28 million tons). Overall, these regions dominate the national bioethanol feedstock potential, highlighting the strategic importance of residue collection from southern sugarcane zones and middle/northern yam-producing belts.

Moderate levels of yam production, and corresponding residues are reported in Bono, Savannah, Upper West, and Volta regions, each contributing substantial quantities to the national total. For example, the Upper West Region produced over 17.6 million tonnes of yam during the period, and 8.27 million tons of residues as reflected on the map. The Volta Region, with over 11 million tonnes output, with 5.18 residue availability.

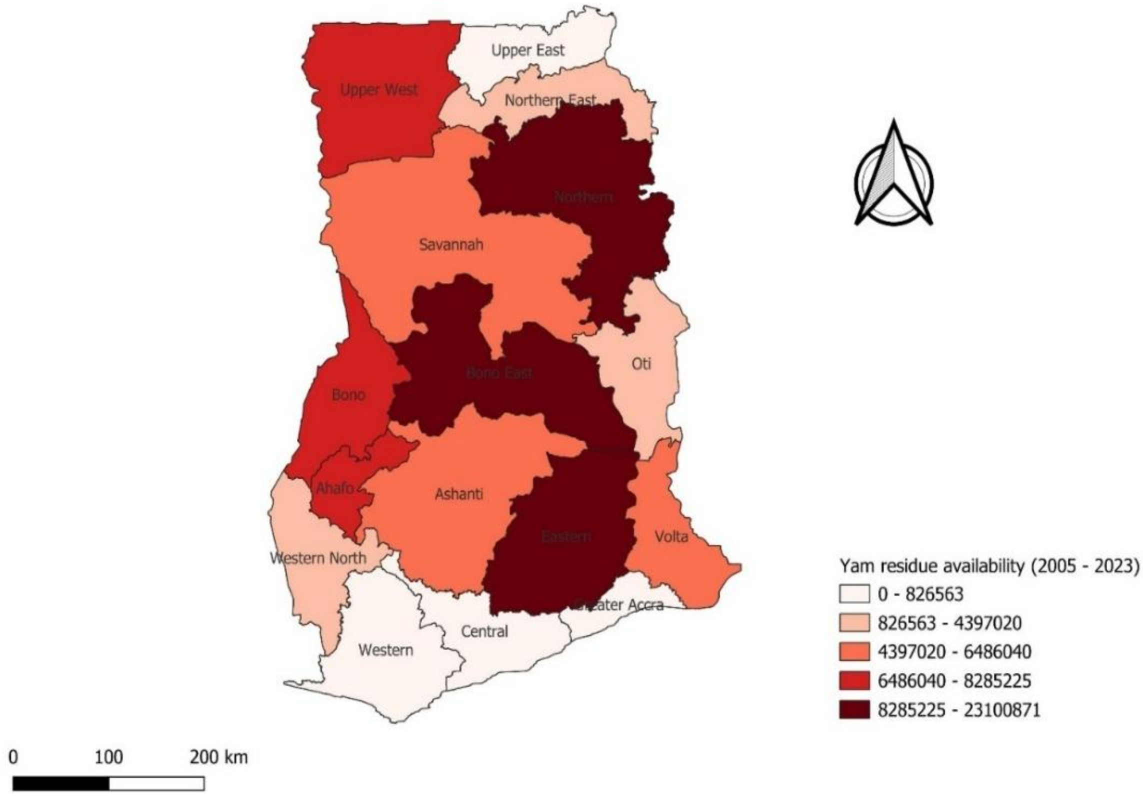

Figure 7: Yam residue availability

In contrast, yam production is much lower in regions such as Central, Western, Western North, Ahafo, and Oti. The Central Region, for instance, produced just over one million tonnes during the entire period, likewise, Western and Western North regions display lower output and residue values. Greater Accra and Upper East consistently recorded no significant yam production during this period.

3.1.2.1 Bioethanol Potential from Five Crop Residues in Ghana

Figure 8 details the bioethanol potential of Ghana from 2005 to 2023 of five major crop residues. The analysis of Ghana's bioethanol potential from 2005 to 2023 shows a sustained and accelerating upward trajectory driven mainly by increases in maize and yam residues, with consistent contributions from cassava and smaller but growing volumes from sorghum and sugarcane. In 2005, the total potential was under 5,000 ML, with maize accounting for the largest share, followed by cassava and yam. Sorghum and sugarcane made minimal contributions during this early period. Between 2005 and 2016, the growth in bioethanol potential was steady but moderate, reflecting incremental gains in crop production.

Maize has remained the dominant bioethanol feedstock, especially from Northern, Bono East, and Ashanti, with cassava providing steady contributions from southern and transitional zones. Yam production gradually increased, mainly from Northern, Bono East, Eastern, and Ashanti, boosting national potential.

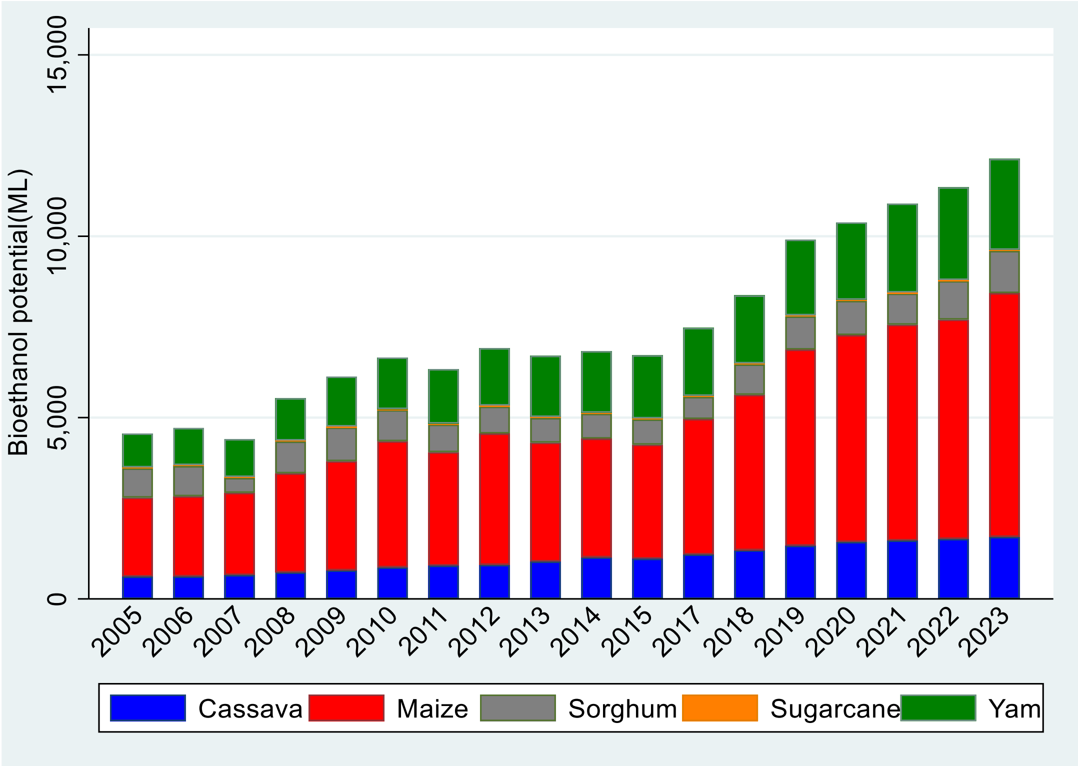

Figure 8: A graph representation of bioethanol potential in Ghana

From 2017, bioethanol potential grew rapidly due to surges in maize and yam cultivation. Sorghum and sugarcane showed minor growth in Central, Western, and Ashanti regions. By 2020, total potential surpassed 10,000 ML, driven largely by maize's high residue-to-ethanol conversion. Northern savannah and middle belt regions were the main contributors, with consistent cassava inputs from Eastern, Volta, and Central.

By 2023, national potential exceeded 12,000 ML. Maize remained the largest contributor, while yam's share grew significantly. Cassava stayed stable, and sorghum and sugarcane provided modest but consistent inputs. Contributions were concentrated in Northern, Bono East, Savannah, Ashanti, Eastern, and Volta, with minimal input from Greater Accra, Upper East, and some coastal areas.

Overall, rising yields and expanded maize and yam cultivation drove the increasing trend, while stable cassava and modest sorghum and sugarcane growth diversified feedstock. Targeted residue collection from major producing regions could maximize bioethanol output and improve year-round processing efficiency.

3.1.3 Supply Chain Optimisation Analysis and Discussion

This section presents a detailed analysis of the supply chain optimisation outcomes pertaining to collection, transport, storage, processing, storage of bioethanol and distribution across the 16 regions of Ghana and demand zones in Ghana while utilising agricultural residues (cassava, maize, sorghum, sugarcane and yam). The primary goal was to identify an optimal strategy that maximises resource utilisation, minimises costs, and enhances regional development prospects, consistent with Ghana's bioenergy policies to boost the E10 blending mandate. The results employ a flow from regional feedstock availability to regional bioethanol distributions, and their implications for policy implementation and market improvement.

Figure 9 indicates the supply chain network for residue collection and bioethanol distribution in Ghana. The spatial distribution of regions, transportation networks, and industrial infrastructure within Ghana provides crucial insights into regional development dynamics relevant to this study. The map delineates key regions, including Upper East, Upper West, Northern East, Oti, Bono East, Bono, Ahafo, Ashanti, Eastern, Western North, Greater Accra, Central, and Western. These regions form the geographical framework for analysing resource availability, infrastructural connectivity, and industrial development.

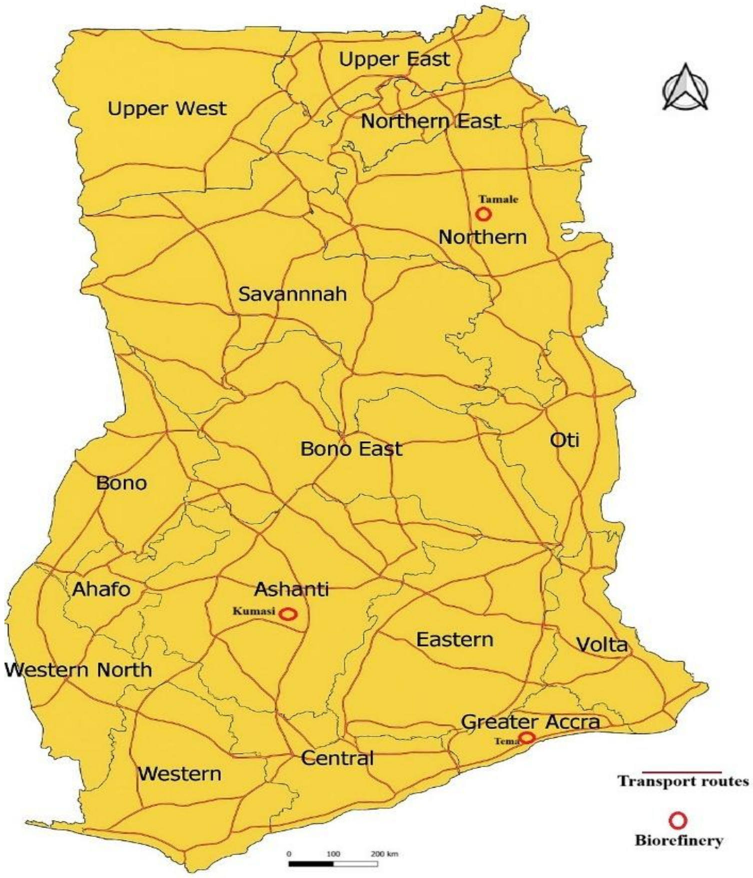

Figure 9: Supply chain network for residue collection and bioethanol distribution

Transportation routes, as depicted on the map, play a vital role in linking these regions, influencing accessibility and economic activity. Major transport pathways traverse several regions, notably connecting the eastern and southern parts of the country, such as Greater Accra, Eastern, and Western regions, with the northern and western zones. This connectivity facilitates the movement of raw materials, goods, and personnel, thereby shaping regional integration and industrial potential.

A focal point of the map is the location of the biorefinery, which signifies the emergence of biomass processing infrastructure. The placement of this facility relative to resource-rich regions such as Bono, Bono East, and Western North indicates deliberate siting to leverage local biomass availability and optimise logistical efficiency via existing transport routes. Proximity to major transport corridors enhances the operational viability of the biorefinery, ensuring efficient supply chain management and market accessibility.

Table 14 highlights Ghana's regional bioethanol demand from 2005 to 2023, with Greater Accra, Ashanti, and Eastern showing the highest consumption. Kumasi plant primarily supplies bioethanol from cassava and maize to regions like Ashanti and Greater Accra, while Tamale mainly provides sorghum- and yam-based bioethanol to the northern regions. This distribution reflects regional specialization and supports local agriculture and rural economies. Strengthening infrastructure and capacity at these biorefineries could improve supply efficiency, boost renewable energy, and promote sustainability across Ghana. The data reveals considerable variation in demand across regions, with Greater Accra leading with about 1060 million litres, reflecting its status as the economic and population centre. Other significant regions include Ashanti about 443 million litres, Central approximately 194 million litres, and Western around 185 million litres. Regions like Bono, Volta, and Upper East also contribute notably to the overall demand. This distribution indicates a strong regional demand for bioethanol, driven by factors such as population size, industrial activity, and urbanisation. The data emphasises the importance of developing regional bioethanol production facilities to meet these demands sustainably and efficiently, supporting Ghana's renewable energy goals and energy security.

Table 14: Regional bioethanol demand in Ghana (2005-2023)

Region	**Bioethanol Demand (ML)**	**Percentage of Total Bioethanol Demand (%) from Biorefineries**			
		Cassava	**Maize**	**Sorghum**	**Yam**
Ahafo	25.57	100 (Kumasi)	100 (Kumasi)	98 (Tamale)	100 (Kumasi & Tamale)
Ashanti	442.50	99 (Kumasi)	99 (Kumasi)	98 (Tamale)	100 (Kumasi
Bono	105.97	99 (Kumasi)	98 (Kumasi)	99 (Tamale)	99 (Kumasi & Tamale)
Bono East	54.55	100 (Kumasi)	99 (Kumasi)	99 (Tamale)	99 (Kumasi & Tamale)
Central	193.98	100 (Kumasi)	99 (Kumasi Tema)	98 (Tamale)	99 (Kumasi)
Eastern	178.20	100 (Kumasi)	98 (Kumasi Tema)	99 (Tamale)	99 (Kumasi & Tamale)
Greater Accra	1,060.39	99 (Kumasi &Tema)	98 (Kumasi Tema)	100 (Tamale)	99 (Kumasi & Tamale)
Northern	85.03	100 (Kumasi & Tamale)	99 (Tamale)	100 (Tamale)	98 (Tamale)

Northern East	28.34	100 (Tamale)	100 (Tamale)	100 (Tamale)	99 (Tamale)
Oti	61.42	99 (Kumasi & Tamale)	98 (Tamale)	99 (Tamale)	99 (Kumasi & Tamale)
Savannah	28.34	99 (Kumasi & Tamale)	99 (Tamale)	100 (Tamale)	98 (Tamale)
Upper East	111.92	100 (Kumasi & Tamale)	99 (Tamale)	100 (Tamale)	98 (Tamale)
Upper West	56.35	99 (Kumasi & Tamale)	98 (Tamale)	100 (Tamale)	99 (Tamale)
Volta	92.13	99 (Kumasi)	99 (Kumasi Tema	98 (Tamale)	100 (Kumasi
Western	184.96	99 (Kumasi)	99 (Kumasi Tema	98 (Tamale)	99 (Kumasi)
Western North	78.20	100 (Kumasi)	99 (Kumasi	99 (Tamale)	100 (Kumasi & Tamale)
Total	**2,787.85**	**-**	**-**	**-**	**-**

Table 15 highlights Ghana's regional crop residue optimisation outcome from 2005 to 2023, including cassava, maize, sorghum, and yams.

Table 15: Maximum crop residue optimisation outcomes (2005-2023)

Crops		*Region*					*Total*
		Ashanti (Kumasi)	*Greater Accra/Tema*	*Northern* (Tamale)	*Ahafo*	*Savannah*	
Max Collection (tons)	Cassava	3,037,504	595,527	538,034	65,816	**-**	**4,236,881**
	Maize	1,365,142	927,520	352,378	-	**-**	**2,645,040**
	Sorghum	-	-	3,226,822	-	854,998	**4,081,820**
	Yam	4,439,670		1,048,295			**5,487,965**
Max Processing Capacity (tons) at Biorefineries	Cassava	3,103,320	595,527	538,034	-	-	**4,236,88**
	Maize	1,365,142	927,520	352,378	-	-	**2,645,040**
	Sorghum	-	-	4,081,802	-	-	**4,081,802**
	Yam	4,439,670	-	1,048,295			**5,487,965**
Max Bioethanol Production (ML) at Biorefineries	Cassava	2,041.99	391.86	354.03	-	-	**2,787.88**
	Maize	1,055.99	977.62	339.91	-	-	**2,373.52**
	Sorghum	-	-	2,903.35	-	-	**2,903.35**
	Yam	2,210.68	-	28.34	-	-	**2,239.02**

3.1.3.1 Cassava Residue Optimisation

Table 15 summarizes Ghana's cassava bioethanol potential across Ashanti, Greater Accra, Northern, and Ahafo regions, with a combined collection of 4.24 million tons and processing capacity of 4.23 million tons, yielding approximately 2,788 ML of bioethanol. The optimization model estimates an objective value of 1.69 billion GH₵ over 19 years (2005–2023).

Ashanti dominates supply, contributing over 65% of national residue, peaking at 262,610 tons in 2022. Greater Accra and Northern also show notable potential (51,000–59,000 tons), while Ahafo, Bono, Bono East, Central, and Volta exhibit minimal or no collection due to infrastructural and processing limitations. Residues are transported directly to the nearest biorefineries—Ashanti to Kumasi, Greater Accra to Tema, Northern to Tamale—reducing costs by 37%, with no cross-regional transport. Real-time processing constraints mean no feedstock storage is maintained.

Kumasi has the highest processing capacity (~300,000 tons/year), followed by Tema (~50,000 tons) and Tamale (~40,000 tons). Kumasi can meet demand across all 16 regions, producing up to 53.27 ML annually, with Greater Accra demanding up to 30 ML/year for E10 blending since 2015.

The results highlight Ashanti as a strategic hub and suggest significant economic and energy benefits. With optimized logistics and processing, cassava residues can support Ghana's E10 mandate, reduce fossil fuel imports, cut agricultural waste, and create jobs across the supply chain.

3.1.3.2 Maize Residue Optimisation

Table 15 highlights maize bioethanol potential in Ashanti, Greater Accra, and Northern regions, with total collection and processing capacities of 2.65 million tons and potential bioethanol production of 2,374 ML. Over 19 years, the maize supply chain could generate 1.02 billion GH₵.

Greater Accra leads collection with 127,000 tons in 2023, followed by Ashanti at 104,050 tons in 2018. Regions such as Ahafo, Bono, and Eastern recorded zero collection due to logistical and infrastructure constraints. Tema processed the most maize (127,000 tons), followed by Kumasi (68,000 tons) and Tamale (28,000 tons).

Kumasi is the main supplier for surrounding demand zones, including Ashanti, Ahafo, and Greater Accra, with peak distribution to Ashanti at 3.9 ML, reflecting the importance of proximity and logistical efficiency.

The results highlight Greater Accra and Ashanti as strategic regions, while gaps in other regions indicate opportunities for targeted infrastructure investment to unlock unused residues and expand bioethanol production. The projected 1.02 billion GH₵ value underscores maize-based bioethanol's potential to drive economic growth, job creation, and rural development.

3.1.3.3 Sorghum Residue Optimisation

Table 15 summarizes sorghum bioethanol potential in Ghana's Northern and Savannah regions, with a combined collection and processing capacity of about 4.08 million tons, yielding approximately 2,903 ML of bioethanol, mainly from the Tamale plant. The supply chain's objective value is the highest among all feedstocks at 2.9 billion GH₵.

Northern region recorded peak annual collection of 345,690 tons in 2021, while Savannah supplied 61,000-120,000 tons between 2012-2023. Tamale is the sole processing facility for sorghum, with annual capacity ranging from 69,000 to 345,000 tons, expanding bioethanol output from 1.4 ML to 87 ML by 2020. Tema and Kumasi plants did not process sorghum due to distance and transport constraints.

Tamale efficiently supplied all 16 demand regions, demonstrating sorghum's high potential to meet national bioethanol demand and reduce fossil fuel dependence. The 2.9 billion GH₵ economic value highlights investment opportunities. Sorghum residues also support waste reduction, rural jobs, and renewable energy goals. However, reliance on a single facility poses risks, signaling the need for diversified processing infrastructure to improve resilience and inclusiveness.

3.1.3.4 Sugar cane Residue Optimisation

The CPLEX model's optimization of Ghana's sugarcane bioethanol supply chain provides insight into system feasibility, operational constraints, and areas for intervention. The relaxed objective value of approximately 7.6 million GH₵ represents the maximum theoretical economic benefit achievable if all constraints were fully addressed.

Key collection regions include Ashanti, Eastern, Central, Volta, and Western, with Central peaking at 341,340 tons in 2015. Residues are transported to three main plants—Tema, Kumasi, and Tamale—with Tema processing the highest volume at over 241,000 tons in 2020, despite a nominal capacity of 30,000 tons. Eastern supplied around 18,000 tons to Tema, reflecting transport and logistical constraints that the model accounted for in the relaxed solution.

Bioethanol production from these residues meets demand across multiple regions: Tema supplies Ahafo, Ashanti, Central, Volta, and Western, while Kumasi covers most other regions with annual output ranging from 8 to 37 ML. Tamale plays a smaller role due to distance and feedstock availability.

The results highlight opportunities and challenges: underutilized plants, logistical inefficiencies, and infrastructure constraints limit optimal production. Addressing these through investments in processing capacity, transport networks, and supportive policy could enhance system efficiency, reduce waste, support renewable fuel targets, and promote regional economic growth.

3.1.3.5 Yam Residue Optimisation

Table 15 shows yam bioethanol potential in Ghana's Northern and Ashanti regions, with combined collection and processing capacity of 5.49 million tons, yielding about 2,239 ML. The optimization results estimate an objective value of 2.1 billion GH₵ over 19 years.

Ashanti and Northern are key supply hubs, with Ashanti peaking at 407,480 tons in 2023. Feedstock transport is feasible to Kumasi and Tamale plants, but not to Tema due to distance and cost. Kumasi, processing Ashanti yam residues, reached 87.5 ML annually, while Tamale peaked at 8 ML, supplying over 70%–75% of regional demand.

The results highlight the strategic importance of these regions, efficient logistics, and full utilisation of residues. Scaling up processing and transport infrastructure could improve system resilience, regional inclusivity, and long-term sustainability, supporting rural development, economic growth, and Ghana's renewable energy goals.

3.1.3.6 Validation of Results

The high activity levels in the 16 administrative regions reflect Ghana's documented status as primary hub for agricultural crop production such as cassava, maize, sorghum, sugar and the optimisation results agree with national agricultural statistics (FAO, 2023a; MOFA, 2023; USDA-IPAD, 2025), reinforcing the model's validity. For instance, empirical reports indicate that the cassava processing sector is not well established resulting to underutilisation (Kasoa et al., 2025) of potential feedstock. With this model showing vivid optimisation for significant residues collection transportation, processing and distribution, this could bridge the gap of underutilization of agricultural residue to meet market demand. Notwithstanding, strengthening logistics, transportation and storage facilities in underperforming regions could significantly increase regional residue utilisation, foster inclusive growth and meet the bioethanol E10 blending mandate. From environmental context, optimal utilisation of these crop residues not only advance bioethanol industry targets but also offer environmental benefits by reducing agricultural waste burning, common in landfills (Oppong-Ansah, 2025). Additionally, social context suggests valorising regional crop residues as bioethanol feedstock can provide income opportunities for smallholder farmers and processors promoting local economies. For example, optimisation of Sorghum feedstock sparks total cost around 2.9 billion GH₵ in 19 years. This is the speculated amount that could circulate within the Ghana's economy during the period. This could create jobs, improve livelihood and promote social-economic activities. For each stage of the supply chain cycle, jobs could be created from collection of feedstocks to transporting to storage to processing to distribution.

The results provided for the five feedstocks as used for case study, reveal promising pathways to enhance Ghana's capacity through strategic regional investments. For instance, all bioethanol produced during this period displace about 10% petroleum within the 16 regions. This could release the huge amount spend to import petroleum products within the country. The current model highlights key regions that should be prioritized for infrastructure upgrades to facilitate residue collection, transport, storge, processing and distribution. The results from the model is similar to work done by (Benka-Coker et al., 2018; Ghaderi et al., 2016; León-Olivares et al., 2020; Singh et al., 2018).

3.1.3.7 Model Limitations

While the model assumes real-time processing with zero feedstock storage at biorefineries to simplify optimisation, practical operations usually require buffer storage to manage variability. Further, the absence of cross-regional transportation may underestimate more complex distribution possibilities. Data constraints, including fixed historical feedstock availability, mean that future climate variability or market changes are not captured. Thus, future work should incorporate dynamic storage options, seasonal variations, and broader transport network modelling to enhance robustness before full-scale implementation.

3.1.4 Comparative Analysis of Bioethanol Production in Ghana and West Africa: Capabilities, Challenges and Transferable Practices.

Ghana's bioethanol industry shows a compelling case study of renewable energy potential in West Africa, characterised by abundant agricultural resources but constrained by structural and policy challenges. This systematic review analyzes Ghana's bioethanol production capabilities in relation to neighboring West African countries, examining feedstock availability, policy frameworks, technological adoption, and socioeconomic impacts. The study illustrates comparative insights from successful regional models in Nigeria, Mali, and Burkina Faso while identifying adaptable practices from these countries. It was revealed that, while Ghana has made progress in pilot projects and policy formulation, it is behind its similar developing economies in consistency and scale. However, Ghana's diversified feedstock potential, particularly with a focus on biomass residues and non-competitive food crops like sweet sorghum, makes it sustainable if key challenges in policy enforcement, infrastructure, and value chain could be addressed.

About 3 West African countries and 5 other countries across the African region, namely Burkina Faso, Mali, Nigeria, Ethiopia, Kenya, Malawi, Mozambique, and South Africa, were selected for this comparative analysis. The selection of Nigeria, Mali, Burkina Faso, Ethiopia, Malawi, Kenya, Mozambique, and South Africa for this comparative analysis was guided by their representative diversity in bioethanol production models, policy frameworks, and socioeconomic contexts. Each country offers unique insights that collectively inform Ghana's bioethanol development pathway, addressing gaps in feedstock strategies, policy enforcement, and market integration. Below is the detailed justification for their inclusion.

3.1.4.1 Feedstock Availability and Strategies

3.1.4.1.1 Ghanaian Feedstock Portfolio

The Ghanaian bioethanol feedstock outlook shows both competitive advantages and limitations when compared to regional peers. The country's agricultural industry produces about 22-38 tons of cassava per hectare, with cassava peels offering an ethanol yield potential of 280-320 litres per ton (Adebayo, 2023; Martinez et al., 2018). The residue to product ratios (RPRs) of Ghana's key bioethanol feedstocks is comparatively favourable with global and regional averages, cassava peels (0.25:1), maize stalk (1.59:1), sorghum straw (1.99:1), yam straw (0.50:1) and sugar cane bagasse (0.23:1) (Singh et al., 2018a; Tolessa, 2023). The metrics show Ghana could produce an annual theoretical volume of 200 ML from agricultural residue alone, sufficient to supply five million households with clean cooking fuel (Oppong-Ansah, 2025b). However, this potential remains underutilised with only 5% being harnessed due to collection and processing constraints, a challenge which is common across West Africa where post-harvest residue management systems are underdeveloped (Obayelu, 2014). Ghana's investigation into sweet sorghum bioethanol as a non-food feedstock represents a strategic variation from regional approaches, with drought-resistant varieties yielding 300-340 litres per ton while avoiding staple crop displacement (Liu et al., 2024). Therefore, Ghana's diversified approach of incorporating cassava, sweet sorghum and other crop residues provides wider resilience against climate variability and market fluctuations compared to single-crop models.

3.1.4.1.2 Regional Feedstock Approaches

Nigeria

The bioethanol market in Nigeria presents substantial feedstock potential as Africa's largest cassava producer with an estimated annual production of 50 million tonnes (FAO, 2023). Nigeria has a well-developed cassava cultivation system across its 24 states with high drought-resilience varieties and widespread smallholder production of more than 15 tonnes per hectare yield on average (Agboola & Agboola, 2011). Combined with sugar cane, maize, sweet sorghum, and abundant lignocellulosic residues like cassava peels, bagasse, crop straw and stalks, the total agricultural residues alone offer bioethanol potential of 7.56×10^9 litres per annum in Nigeria (Awoyale & Lokhat, 2019). Also, Napier grass a lignocellulosic crop is a promising bioethanol feedstock with a high cellulose concentration and its tolerance to marginal lands (Rocha-Meneses et al., 2020).

The production of bioethanol in the country utilising these feedstocks has been guided by the National Biofuels Policy and initiatives such as the Presidential Cassava Initiative and the Jigawa sugarcane ethanol programme initiated by the government, which sought to blend bioethanol into petrol at up to 10% by 2010 (AllAfrica, 2006; NNPC, 2007). The strategy highlighted selection and breeding of high-yield, disease-resistant local varieties, allocation of cultivation by ecological zones, and promotion of community participation through smallholder integration into biomass supply chains (Munonye et al., 2023). Technical success factors included development of processing capacity to convert cassava, sugar cane and maize as first-generation feedstock bioethanol and the exploration of second-generation agricultural residues and lignocellulosic biomass conversion technologies (Adewuyi, 2020). Nigeria's SME Funds Bioethanol Project which converts sawdust and water hyacinth into bio-gel for cookstoves, demonstrates the potential of second-generation biofuels, a model could adopt for crop residues (African Development Bank, 2013).

However, Nigeria's bioethanol market is challenged with food vs fuel conflict particularly when cassava, maize or sugar cane is diverted fuels raising food security concerns and volatility in in feedstock availability drive by seasonal and location-based fluctuations (Sekoai & Yoro, 2016). Due to poor transport networks, inadequate storage and unstable power supply, production and logistics costs remain high preventing the sector from realising its full economic scales (Nwuche, 2025). Moreover, policy uncertainty and inconsistent implementation, including abrupt policy reversals, and weak private sector confidence, as well as technical gaps, high initial capital cost hinders sustainable growth (Agboola & Agboola, 2011).

Mali

Mali has pioneered biofuel initiatives in the West African region, mainly through jatropha-based biodiesel projects and exploratory cassava-based bioethanol schemes. Mali adopted its national biofuel strategic plan in 2007, setting out to replace 20% of biodiesel consumption by 2022 through production from jatropha oil and bioethanol, by establishing its National Agency for Biofuel Development (ANADEB) in 2009 (Burrell et al., 2011). The Mali-biocarburant, a Dutch-Malian joint venture, leveraged mobile oil-pressing up to 2000 litres per day in Koulikoro which secures carbon credits from its operations (Burrell et al., 2011). While the Mali- Folkecenter Nyetaa implemented the Garalo "Bagani Courant" pilot project, which extends to ten villages, using converted diesel generators powered by pure jatropha oil to provide 300 kW of rural electrification to over 10000 residents, drawing seed from about 100 hectares of jatropha plantations cultivated by local farmers within a 20 km radius (Sekoai & Yoro, 2016).

These projects were successful through the strategic implementation of energy security, rural electrification, and poverty alleviation fostered institutional funding and donor engagement (Jumbe et al., 2009). In addition, the participatory out-grower scheme ensured that jatropha cultivation generated income for local farmers, who sold seeds and oil locally rather than exporting these products, hence retaining economic benefits within communities and improving rural livelihoods (Favretto et al., 2014). The strategic use of jatropha which grows well in semi-arid marginal land prevented competition with food crops, combined with decentralised, low-tech processing that minimised irrigation and investment in infrastructure (Kgathi et al., 2012).

A research study has shown the potential for cassava-based bioethanol in Southern Mali; it was discovered that farmers using the attiéké variety were willing to expand cassava cultivation for bioethanol if offered stable market prices (Rasmussen et al., 2015). Agronomic analysis suggests that cassava cultivation would primarily substitute cotton but not stable crops, alleviating food security concerns and life cycle assessment indicates potential carbon stock recovery to pre-cotton-decline levels, though at the expense of carbon sequestration capacity in converted fallow lands where as economic feasibility depended on realistic farmer pricing and institutional arrangement for procurement (Rasmussen et al., 2015).

The Malian biofuel market faces several challenges despite success stories particularly , the yield of biodiesels remained low compared to policy targets, and gaps emerged between projected large-scale land expansion and realistic output, undermining the potential to significantly substitute diesel (Favretto et al., 2014). Monitoring and enforcement of sustainability criteria were weak, raising concerns around land tenure, potential displacement of food crops, and environmental impacts of unregulated jatropha expansion (Favretto et al., 2014). Water scarcity in semi-arid regions meant that irrigation-intensive biofuel crops would risk resource depletion, leading analysts to caution that only low-water models like jatropha hedges were viable in Mali's context (Kgathi et al., 2012).

Burkina Faso

Burkina Faso's biofuel sector has witnessed notable localised success in recent years by highlighting sustainable feedstocks, government-led institutional support, and strong research industry collaborations. The Burkinabe government promoted jatropha as a dedicated biofuel crop, planting nearly 70,000 trees and integrating it into hedgerow and degraded-land intercropping schemes to produce biodiesel and ethanol without threatening food crops (Baumert et al., 2018). The Fondation Fasobiocarburant, backed by funding from the European and Dutch governments, played a major role in supporting research, extension and community engagement (Sekoai & Yoro, 2016). Jatropha was cultivated on marginal or abandoned lands, to prevent competition with staple food agriculture and reduce risks to food security (Sekoai & Yoro, 2016).

Concurrently, the BioStar project, the "Centre de Coopération Internationale en Recherche Agronomique pour le Développement" (CIRAD) and implemented with research institutions such as the Université Technologique de Ségou, the Institut de Recherche en Sciences Appliquées et Technologies, the Institut International d'Ingénierie de l'Eau et de l'Environnement, SMEs like AgroBurkina, NGOs and local equipment manufacturers which demonstrated an effective participatory innovative model that increased smallholder adoption rates by 40% (Cirad, 2023). In Bobo-Dioulasso, a cashew-shell fuelled furnace and dryer system codesigned and built to convert agro-waste into process heat, reducing energy costs for mango drying and attracting local scale-up interest (Cirad, 2023). This model combined locally available waste, clean combustion technology and local manufacturing capacity, strengthening local ownership and long-term sustainability. Burkina Faso's government created a dedicated Ministry of Scientific Research and adopted a National Policy for Scientific and Technical Research along with statutory mechanisms to find innovation, particularly a National Fund for Research and Innovation supported by tax and mining revenues and international collaborations through ECOWAS and UNIDO such as ECREEE, also facilitated shared knowledge and regional renewable energy support (The World Bank, 2010).

The country's biofuel sector is faced with several limitations including low technical capacity, bureaucratic inefficiencies and poor coordination between stakeholders hinder scale-up and political instability in the country threatens continuity of programs, whereas weather variability, desertification and droughts in the Sahel intensify risks to agro-based feedstock systems (Shirke, 2017).

3.1.4.1.3 Broader Africa's Innovation

Kenya

Kenya's bioethanol production has primarily leveraged sugarcane molasses, a by-product of sugar factories, as its main feedstock (David et al., 2025). The Mumias Sugar Company has converted molasses into fuel-grade bioethanol through fermentation, distillation, and dehydration, supplying E10 blends to Kisumu and exporting modest quantities regionally (Yakazi Network, 2025). This value-added approach minimizes food-versus-fuel conflicts, since molasses is non-edible and does not reduce sugar output (Deenanath et al., 2012).

Kenya has also promoted bioethanol for clean cooking, using cassava grown on marginal lands to avoid competition with staple crops. The Giraffe Bioenergy project in Kilifi County is developing drought-resistant cassava varieties, targeting 15 ML of bioethanol annually by 2026 through decentralized biorefineries, and aiming for 75 ML annually by 2027 (Giraffe Bioenergy, 2025). Policy incentives, including Value Added Tax (VAT) waivers on bioethanol stoves under the National Clean Cooking Transition Strategy, support adoption (World Bank Group, 2024).

Kenya's success is attributed to four strategic factors: regulatory support via local E10 blending mandates implemented since 2010, targeted investment in blending facilities, organized out-grower schemes through farmer cooperatives, and public-private partnership (PPP) financing

(GirituSugar, 2023). The 2019 Bioenergy Strategy further emphasized community-based feedstock cultivation, gender-inclusive cooperatives, and alignment with broader rural development policies, often with World Bank or UNDP support (David et al., 2025; GirituSugar, 2023). Integration of sugarcane processing with bagasse-based power generation and use of stillage as biofertilizer has fostered a circular economy model, improving resource efficiency and reducing greenhouse gas emissions (Mbothu et al., 2021).

Challenges include limited land under high-yield sugarcane, low adoption of improved varieties, underutilized mill capacity due to inadequate feedstock, high capital costs of distillation infrastructure, limited investment, and land tenure issues hindering consistent supply (Yakazi Network, 2025; Deenanath et al., 2012; GirituSugar, 2023).

Mozambique

Mozambique has emerged as a leading African bioethanol producer, leveraging abundant feedstocks, policy frameworks, and public-private partnerships. The National Biofuels Policy and Strategy, adopted in 2009 and updated in 2023, mandates 10% ethanol blending in petrol and 3% biodiesel in diesel, while integrating smallholder farmers into feedstock supply chains (Deenanath et al., 2012; Sixpene, 2025).

The country emphasizes non-food feedstocks, particularly cassava peels, sugarcane bagasse, and molasses for bioethanol, and jatropha and coconut for biodiesel, minimizing food-versus-fuel conflicts (Schut et al., 2010). Sugarcane and cassava are cultivated in provinces such as Inhambane and Zambézia, where agroecological conditions favor high yields and small-scale farmer inclusion (Sixpene, 2025).

Public-private partnerships, such as Greenlight and Project Gaia, coordinated investments across cultivation, processing, and distribution of bioethanol stoves, reaching over 30,000 households and reducing charcoal use and deforestation (Project Gaia, 2025). Collaboration with Eni further aims to develop agricultural residue bioethanol for domestic use and European export (Eni, 2022). Best practices, including rotational cropping, technical assistance, and input provision, increase farmer incomes while avoiding staple food diversion (Sixpene, 2025).

Earlier initiatives in the late 2000s faced institutional immaturity, lack of research coordination, insufficient regulatory frameworks, and feedstock variability. Food-versus-fuel debates persist, particularly regarding cassava and sugarcane, alongside environmental concerns requiring life-cycle assessment and sustainable land-use planning (Deenanath et al., 2012).

South Africa

South Africa has achieved notable bioethanol progress using locally available feedstocks, including sugarcane, sugar beet, and maize. The 2007 Biofuels Industrial Strategy set blending targets and promoted investment in large-scale production facilities, focusing on surplus crops to avoid food security risks and support rural development (Department of Minerals and Energy, 2007; Mvelase & Ferrer, 2024).

The AlcoNCP biorefinery, Africa's largest fermentation distillery, produces 85 ML of ethanol annually, originally from molasses and maize. Due to food security concerns, maize is now prioritized for high-quality neutral ethanol for food, beverage, and pharmaceutical industries, while bioethanol fuel production focuses on sugarcane and sugar (AlcoNCP, 2021; Department of Minerals and Energy, 2007).

Challenges include land-use conflicts, fluctuating commodity prices, water availability constraints, low policy implementation, and delayed establishment of a biofuel pricing framework, all of which have hindered consistent output and discouraged private investment (Mvelase & Ferrer, 2024; Department of Minerals and Energy, 2007).

3.1.4.2 Comparative Analysis and Multiplication

Ghana's bioethanol feedstock landscape demonstrates both notable strengths and limitations compared to regional and continental counterparts. Its diversified portfolio, centred on cassava peels, sweet sorghum, and other agricultural residues, provides resilience against climate and market variability (Adebayo, 2023; Santos et al., 2025). Cassava yields of 22–38 t/ha and ethanol conversion rates of 280–320 L/t from peels give Ghana a competitive advantage, with a theoretical capacity of 200 ML of bioethanol annually from residues alone (Martinez et al., 2018; Oppong-Ansah, 2025a). However, only 5% of this potential is currently harnessed due to underdeveloped residue collection and processing infrastructure, reflecting broader West African constraints (Obayelu, 2014).

Nigeria, Africa's largest cassava producer, achieves an annual yield of 50 Mt and substantial residue output, theoretically supporting 7.56 billion litres of bioethanol per year (Awoyale & Lokhat, 2019; FAO, 2023a). Unlike Ghana, Nigeria has implemented a structured policy framework—including the National Biofuels Policy, the Presidential Cassava Initiative, and region-specific programmes such as the Jigawa sugarcane bioethanol project—which integrates high-yield, disease-resistant feedstocks, localized ecological planning, and smallholder engagement (Munonye et al., 2023; NNPC, 2007). Nigeria has also advanced into second-generation biofuels, such as bio-gel from sawdust and water hyacinth (African Development Bank, 2013), innovations Ghana has yet to implement. Nevertheless, Nigeria's bioethanol sector faces challenges in infrastructure, policy consistency, and food-versus-fuel conflicts from first-generation feedstock use (Sekoai & Yoro, 2016).

Mali offers a contrasting model that prioritizes biodiesel from jatropha rather than large-scale bioethanol. Its decentralized, community-based approach, exemplified by the Garalo

"Bagani Courant" project, used jatropha oil to electrify rural areas and generate carbon credits (Favretto et al., 2014; Jumbe et al., 2009). Ghana's exploration of sweet sorghum as a non-staple crop could benefit from Mali's approach in engaging out-growers while avoiding food-fuel conflicts. However, Mali faced setbacks from low yields, overestimated land-use potential, and weak environmental monitoring.

Similarly, Burkina Faso adopted jatropha-based models, integrating hedgerows, degraded-land cultivation, and multi-stakeholder collaboration, notably through the BioStar project. This approach increased smallholder adoption by 40%, demonstrating the value of local manufacturing and sustainable agro-waste utilization, such as cashew shell bioenergy systems (Cirad, 2023). Ghana could emulate such stakeholder coordination and local technology deployment to improve its 5% feedstock utilization rate.

Kenya's strategy focuses on molasses and cassava grown on marginal land, aligning with Ghana's goal of avoiding food-crop displacement. Projects like Giraffe Bioenergy, alongside regulatory tools such as VAT waivers and W10 blending mandates, have increased bioethanol production for clean cooking (Giraffe Bioenergy, 2025; World Bank Group, 2024). While Ghana struggles with underutilized capacity, Kenya has implemented structured out-grower schemes and circular economy models that repurpose residues like bagasse and molasses (Mbothu et al., 2021).

Mozambique provides another instructive model. It's revised 2023 Biofuels Strategy and public-private initiatives such as Project Gaia have established community-scale bioethanol production using cassava peels and sugarcane residues (Project Gaia, 2025; Sixpene, 2025). Blending mandates and farmer inclusion mechanisms have enabled scale, although policy immaturity and food-versus-fuel debates highlight limitations Ghana must navigate.

South Africa's industrial-scale strategy, guided by the 2007 Biofuels Industrial Strategy, utilizes surplus sugar beet, sugarcane, and maize to mitigate food security risks while promoting rural development (Department of Minerals and Energy, 2007). Despite infrastructural and regulatory challenges, government incentives and large-scale blending targets provide lessons for Ghana on economic scaling.

Overall, Ghana's bioethanol sector demonstrates strengths in feedstock diversity and climate resilience. Unlocking its full production potential requires integrating lessons from regional peers, particularly Nigeria's policy planning, Kenya's decentralized models, Mozambique's clean cooking scale-ups, and Burkina Faso's community engagement frameworks. Addressing constraints in logistics, infrastructure, and stakeholder management will be critical to translating Ghana's theoretical capacity into tangible energy and economic benefits.

3.1.4.3 Policy Frameworks and Implementation Mandates

3.1.4.3.1 Ghana's Policy Development

Ghana's policy development on bioethanol unfolded over more than a decade, starting with early energy planning and ending in current efforts to establish a binding regulatory framework that supports blending mandates, feedstock diversification, rural development, and clean cooking goals. Ghana's Energy Sector Strategy and Development Plan in 2010 (Energy Commission, 2010), set out a target to integrate biofuels into its energy mix, envisioning a 10% bioethanol blend by 2020 and increasing to 20% of total transport fuels by 2030 through a combination of bioethanol and biodiesel, outlined in national projections of fuel demand and mixing scenarios (Kipkoech et al., 2024). This strategy was reinforced by the Renewable Energy Act 2011 (Renewable Energy Act, 2011), which provided fiscal incentives for private sector investment, tasked the National Petroleum Authority with pricing biofuel blends, and laid out a formal institutional structure for biofuel regulation.

Despite these policy frameworks, implementation remained largely aspirational as renewable energy laws and master plans launched in 2019 affirmed the need to reduce fossil fuel dependency and encourage bioethanol use (Energy Commission, 2019). However, enforcement mechanisms were weak, and bioethanol development was limited to small industrial niches rather than widespread blending or household use (Kasoa et al., 2025). Leading experts pointed to the absence of a clear bioethanol mandate, unstable market indications, a lack of regulatory authority, such as a dedicated Biofuel Development Authority, and insufficient fiscal measures, particularly tax incentives or concessional finance to drive investments.

3.1.4.3.2 ECOWAS Regional Policy Context

The Economic Community of West African States (ECOWAS) has taken significant steps toward developing a comprehensive policy framework for bioethanol as part of its broader strategy for renewable energy and sustainable development. Identifying the region's reliance on imported fossil fuels and the environmental degradation caused by traditional biomass use, ECOWAS, through its specialised energy agency, the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) has spearheaded efforts to harness bioethanol as a clean and locally available alternative. In 2018, ECREEE, in collaboration with the United Nations Industrial Development Organisation (UNIDO) and the Global Environment Facility (GEF), launched the West African Clean Cooking Alliance (WACCA), which included bioethanol as a significant component in promoting clean cooking solutions and reducing GHG in the region (ECREEE, 2018). Moreover, ECOWAS developed the Bioenergy Policy and Strategy Framework to promote sustainable bioenergy production, including bioethanol by encouraging national governments to adopt coherent standards, sustainability criteria, and regional investment incentives (ECREEE, 2013). The policy highlights the use of agricultural residues and non-food feedstocks to prevent competition with food security, in alignment with international sustainability standards. It aimed to integrate gender and socio-economic dimensions, ensuring that bioethanol development contributed to poverty reduction and rural employment (ECREEE, 2013; UNIDO, 2022). While implementation varies across member states, countries like Ghana and Nigeria have initiated pilot projects and feasibility studies to develop domestic bioethanol production capacities. ECOWAS's policy development efforts thus reflect a regional commitment to diversifying energy sources, mitigating climate change, and achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 on affordable and clean energy and SDG 13 on climate action.

3.1.4.4 Other Successful Africa Implementation Models

3.1.4.4.1 Malawi's Blending Mandate

Malawi's bioethanol blending mandate, launched in 1982, aimed to reduce petroleum imports by incorporating 10% ethanol (E10) from sugarcane molasses into petrol. Its success relied on consistent policies, public-private partnerships, tax incentives, infrastructure investment, and technical capacity building (Deenanath et al., 2012; Odetoye et al., 2019). Key measures included Cabinet directives, ethanol-driven vehicle programs, storage and distribution via the National Oil Company, and international partnerships for research and technician training (National Commission for Science and Technology, 2011; Caryanga, 2024). Challenges included limited ethanol-compatible vehicles, seasonal feedstock shortages, and high upfront investment.

Ghana's Renewable Energy Act sets similar 10–20% blending targets, but successful adoption will require strong policy enforcement, adaptive pricing, diversified feedstocks, and improved institutional coordination. Constraints such as land tenure issues, food security concerns, governance gaps, and financing barriers could hinder replication of Malawi's model.

3.1.4.4.2 Ethiopia's Blending Mandate

The absence of strategic execution blending mandates in Ghana sharply contrasts with Ethiopia's successful E10 blending implementation, Ethiopia is one of Africa's earliest adopters of bioethanol, with production dating back to the 1950s (Miftah & Mutta, 2024). The country's sugar factories, such as Kenana Sugar Factory, have produced bioethanol as a byproduct historically, reaching 65 ML annually in 2009, with exports to the European market (Benti et al., 2021). Ethiopia's E10 blending programme from 2009 to 2013 showed bioethanol works as a transport fuel with about 38.54 ML of bioethanol blended, saving GH₵335 million on fossil fuel imports in the country (Miftah & Mutta, 2024).

However, the programme was discontinued due to the competing demand from the beverage industry, indicating a critical challenge, the lack of policies to prioritise energy over other bioethanol uses. Unlike Ghana, which is exploring non staple food crops particularly sweet sorghum, Ethiopia's reliance on sugarcane – a crop also used for sugar production, has resulted in supply fluctuations (Miftah & Mutta, 2024).

3.1.4.5 Policy Lessons for Ghana

Ghana's bioethanol policy pathway offers several important lessons, particularly when viewed against successful African implementation models such as Malawi and Ethiopia, as well as the broader regional efforts by ECOWAS. Despite the country's early commitment to integrating biofuels into its energy mix through the 2010 Energy Sector Strategy and Development Plan, which targeted a 10% bioethanol blend by 2020 and 20% by 2030 yet implementation has remained largely aspirational (Energy Commission, 2010). The Renewable Energy Act of 2011 provided initial regulatory support, including fiscal incentives and pricing mechanisms via the National Petroleum Authority (Renewable Energy Act, 2011), but lacked a clear and enforceable bioethanol blending mandate. This deficiency, coupled with weak enforcement, unstable market signals, and the absence of a dedicated regulatory authority such as a Biofuel Development Authority, has significantly impeded progress. However, Malawi's success based on consistent policy backed by a Cabinet directive, strong public-private partnerships, and tax incentives that supported the bioethanol blending mandate of 10-20%, implemented through collaboration with firms like EthCo and technical institutions such as the National Commission for Science and Technology (Caryanga, 2024; National Commission for Science and Technology, 2011). Ethiopia similarly demonstrated the benefits of leveraging sugar industry byproducts for bioethanol production, blending 38.54 ML between 2009 and 2013 and saving GH₵335M on fossil fuel imports (Miftah & Mutta, 2024). However, Ethiopia's experience also highlights risks tied to feedstock competition from other industries, underlining the importance of policies that prioritise energy security. ECOWAS's regional strategy further underscores the necessity of consistent sustainability standards, gender-inclusive policy frameworks, and incentives for feedstock diversification using non-food crops such as sweet sorghum, currently under exploration in Ghana. Therefore, Ghana must strengthen its institutional coordination, establish enforceable mandates, introduce adaptive pricing and fiscal incentives, and ensure sustainable feedstock supply chains to move from aspirational policy to actionable implementation.

Table 16 provides a SWOT analysis of Ghana's bioethanol market, highlighting its key strengths, weaknesses, opportunities, and threats.

Table 16: SWOT analysis of the Ghanaian bioethanol market

STRENGTHS	WEAKNESSES
• Comprehensive policy framework. • Emerging expertise in sorghum processing. • Existing rail network for biomass transport. • Growing domestic energy demand. • GHG reduction potential (40-80%).	• Lack of binding blending mandates. • Limited large-scale biorefinery capacity. • Diverse agro-residues feedstock base. • Poor road networks and storage facilities. • Deforestation risks from biomass collection.
OPPORTUNITIES	**THREATS**
• Potential to produce 2300M L/yr from lignocellulosic. • ECOWAS biofuel cooperation potential. • Second-generation bioethanol potential. • Mobile pre-processing unit adoption. • E10 blending market potential. • Circular economy applications.	• Food-fuel competition risks. • Policy inconsistency and implementation gaps. • Dependence on imported technologies. • High transport costs. • Competition from fossil fuel subsidies. • Climate change impacts on feedstock.

Addressing the weaknesses and leveraging strengths could enhance Ghana's bioethanol industry, improve sustainability and energy independence while compete regionally.

Table 17 provides a comparative analysis of West African countries and select other African nations, highlighting transferable best practices applicable to Ghana. This analysis identifies successful strategies and policies implemented in these countries that can be adapted to Ghana's context to enhance the development of its bioethanol sector and promote sustainable energy practices across the region.

Table 17: Key advantages of bioethanol production in the West African regional context

Country	Key Advantages	Transferable Practices for Ghana
Nigeria	High cassava production (50Mtons/year). Existing medium-scale cassava bioethanol facilities. Fuel distribution networks.	Scale up cassava residue utilisation for bioethanol to avoid food-fuel conflict. Improve infrastructure integration (e.g., blending urban fuel networks).
Mali	Successful decentralized jatropha biodiesel projects. Strong NGO partnerships and community engagement models.	Adopt decentralised bioethanol pre-processing units for rural electrification. Integrate women's cooperatives into feedstock supply chains.
Burkina Faso	EU-supported biofuel initiatives. Biogas-to-fertiliser models for circular economy. Government investment initiatives.	Leverage international partnerships for funding and investments. Explore aquatic weeds (e.g., water hyacinth) for bioethanol + fertiliser.
Ethiopia	Successful E10 blending mandates (saved GH₵335M in fuel imports). Sugar factory byproduct utilisation.	Enforce blending mandates with clear timelines. Develop byproduct synergies.
Malawi	Long-standing E10 policy (since 1982) with smallholder outgrower schemes. Stable policy framework.	Implement enforceable blending targets. Link bioethanol production to agricultural programs (e.g., Planting for Food and Jobs).
Kenya	Drought-resistant cassava for bioethanol on marginal lands. VAT waivers for bioethanol stoves.	Incentivise household bioethanol adoption via tax breaks. Promote non-food feedstock cultivation in northern Ghana.
Mozambique	National Biofuels Policy (2009) prioritizes residues (cassava peels, bagasse). Eni partnership for export-oriented production.	Expand agricultural residue collection infrastructure. Partner with international firms for technology transfer.
South Africa	Large-scale biorefinery (AlcoNCP) with maize-to-bioethanol.	Avoid maize for fuel; focus on sweet sorghum/cassava residues.

		Develop high-value ethanol for pharmaceuticals.
ECOWAS Policy	Regional collaboration on bioenergy standards & infrastructure.	Advocate for harmonised West African bioethanol policies. Position Ghana as a regional hub for R&D.

3.1.5 Strategies for Enhancing Bioethanol Supply Chain Management in Ghana

Ghana's bioethanol sector holds strong potential to reduce fossil fuel imports, enhance energy security, and boost rural economies. Yet, underdeveloped supply chains, policy gaps, logistical inefficiencies, and weak stakeholder coordination limit growth. This study identifies strategies to strengthen Ghana's bioethanol supply chain, drawing on global best practices and local evidence. It evaluates interventions across four dimensions—feedstock optimisation, infrastructure development, policy enforcement, and technological innovation—offering a practical roadmap for policymakers, investors, and industry stakeholders.

3.1.5.1 Feedstock Optimisation and Regional Concentration

A major challenge in Ghana's bioethanol supply chain is scattered and seasonal feedstock availability. Key residues, cassava, maize, sugarcane, yam, and sorghum, offer high ethanol yields (cassava peels: 280–320 L/t; sorghum straw: 300–340 L/t) but compete with livestock feed (13%) and soil preservation (7%) (G. Osei et al., 2013b; Afedzi et al., 2025).

GIS mapping can optimise regional feedstock allocation: northern Ghana suits sorghum, while Bono, Ahafo, and Eastern regions support maize stover hubs (Tulashie et al., 2023). Mobile pre-processing units at farm gates can cut transport costs by 30% through residue densification (Wang et al., 2024). Prioritising non-food feedstocks like sweet sorghum and agricultural residues ensures supply resilience, reduces transport dependency, and mitigates food-security concerns.

3.1.5.2 Logistical and Infrastructure Improvements

Ghana's poor rural road networks and lack of storage facilities increase supply chain costs. Research shows that integrating rail transport for bulk residue movement may cut feedstock transportation costs by GH₵ 0.88 per ton-kilometre compared to road haulage (Wang et al., 2024). Decentralised storage solutions, such as hermetic silos, are significant for mitigating post-harvest losses, which exceed 30% for maize stover during rainy seasons (Tulashie et al., 2023).

Ghana could adopt Brazil's success by adopting a hub-and-spoke distribution model, following Brazil's proven success in optimising efficiency and scalability. By establishing aggregation centres in agroecological zones (e.g. Volta Region for cassava), inefficiencies associated with transportation could be minimised (Wang et al., 2024). Also, blockchain-based traceability enhances transaction transparency in residue supply chains, ensuring fair pricing for farmers and reducing middlemen exploitation (Kim et al., 2023). Infrastructure gaps are major limitations in Ghana's bioethanol supply chain. Thus, strategies such as rail integration reduce dependency on unreliable road networks, while decentralised storage prevents spoilage. Blockchain technology, as proven in Brazil's ethanol supply chain, improves accountability and reduces cheating, promoting trust among stakeholders.

3.1.5.3 Policy and Regulatory Interventions

Ghana's biofuel policy framework, including the Renewable Energy Act (2011) and National Bioenergy Policy (2010), lacks enforceable mandates. Unlike Malawi's mandatory E10 blending policy, which stabilized bioethanol demand, Ghana's blending policies remain aspirational. Implementing a 10% ethanol blending mandate (E10) could stimulate market demand, following Nigeria's success where similar policies boosted production by 38% within five years (NNPC, 2025). The implementations of tax exemptions for biorefineries using agricultural residues to improve financial viability and developing a national biofuel data system to track feedstock volumes, biorefinery capacity, and distribution networks (Iddrisu & Bhattacharyya, 2015). Policy inconsistency is a recurring issue in Ghana's energy sector, with obligatory blending mandates, as seen in Malawi and Nigeria, creating stable demand, attracting private investment. Tax incentives offset high capital costs for biorefineries, while a centralised data system ensures real-time monitoring and adaptive policymaking.

3.1.5.4 Technological and Financial Innovations

Advanced pretreatment technologies, including microwave-assisted and enzymatic hydrolysis, can boost bioethanol yields by 15–20% while lowering energy use (Kim et al., 2023). Kenya's Giraffe Bioenergy model demonstrates the feasibility of decentralised cassava-to-bioethanol biorefineries, a model adaptable to rural Ghana.

Financial mechanisms are key for scaling. Green financing initiatives, such as low-interest loans similar to Brazil's PROINFA program, can attract private investment, while public-private partnerships (PPPs) mitigate risks and expand sustainable production. Pilot projects like the Volta Region cassava-bioethanol plant show the potential for scaling.

Technological challenges, low yields and high processing costs, can be addressed through advanced pretreatment. Incorporating carbon capture and utilisation further reduces environmental impacts and creates additional commercial opportunities, making the sector more attractive for investors and sustainable in the long term.

3.1.5.5 Stakeholder Collaboration and Circular Economy Integration

The circular economy offers significant potential for Ghana's bioethanol sector. Mozambique's partnership with Eni demonstrates how agricultural residues can generate revenue for export (Eni, 2022). In Ghana, lignin byproducts could be repurposed as fertilisers to offset costs. Stakeholder workshops involving MoFA, the Energy Commission, and NPA are crucial to align policies and resolve land tenure issues. Farmer cooperatives, modelled on Kenya's out-grower schemes, can stabilise feedstock supply and ensure equitable income (Deenanath et al., 2012; Tulashie et al., 2023).

Applying circular economy principles enhances resource efficiency and supports sustainable growth. Lessons from Brazil highlight the importance of participatory stakeholder processes and policy management to overcome adoption barriers.

Ghana's bioethanol supply chain can be strengthened through integrated strategies: enforce E10 blending mandates to stimulate demand, invest in rail and mobile pre-processing infrastructure to lower logistics costs, apply circular economy approaches to valorise waste, and empower farmer cooperatives for feedstock stability. These evidence-based measures provide a roadmap for policymakers, investors, and the agricultural sector to develop a viable, sustainable bioethanol industry.

3.1.6 Effective Marketing Strategies

This study reviewed strategies to increase domestic and export demand for bioethanol in Ghana. Effective marketing relies on five interlinked approaches: consumer awareness and rebranding, regulatory blending mandates, export-oriented sustainability positioning, public-private partnerships (PPPs), and price stabilization frameworks.

Consumer Awareness: Ghanaian households and institutions remain largely unaware of bioethanol's advantages over LPG, charcoal, or petrol. Public education campaigns—via radio, community workshops, and school curricula—can foster adoption, as demonstrated by Brazil's Proálcool programme (Goldemberg et al., 2008; Oppong-Ansah, 2025b).

Blending Mandates: Mandatory ethanol blending (e.g., E10), proven in Malawi and India, can create consistent domestic demand and stable offtake channels (IEA, 2019; UNIDO, 2022). Ghana currently lacks such mandates, despite technical feasibility (ECREEE, 2022). Implementing mandates with quality assurance and refinery incentives would secure the domestic market.

Export Positioning: Ghana can target premium markets by producing low-carbon fuels from crop residues and adopting sustainability certifications like Bonsucro or ISCC, complemented by blockchain traceability (FAO, 2022; Bonsucro, 2023; ISCC, 2025). Highlighting green branding, transparent supply chains, and socio-economic benefits strengthens international appeal (IRENA, 2020).

Public-Private Partnerships: PPPs can build infrastructure, facilitate logistics, and co-finance market expansion. Partnerships between the Ghana Oil Company, NPA, and local producers could supply state fleets and institutions, creating visible demand anchors that validate the market (IEA, 2019; Ministry of Energy, 2023).

Price Stability: Dual pricing mechanisms, forward contracts, buffer stocks, and insurance can stabilize producer and consumer prices, mitigating seasonal and regulatory risks (MOFA, 2023; World Bank, 2011).

In summary, Ghana's bioethanol market can expand through integrated strategies combining awareness, mandates, certification, PPPs, and price stabilization. Implementing these approaches within coordinated policy and institutional frameworks is essential to address demand-side barriers and ensure sustained market growth.

3.2 Discussion

3.2.1 A Critical Perspective on Ghana's Bioethanol Sector

Ghana's bioethanol sector holds significant potential but remains underdeveloped. Despite abundant feedstocks like cassava and sweet sorghum, favourable climate, and growing demand for sustainable energy, bioethanol contributes minimally to Ghana's energy mix (Ofosu-Peasah et al., 2024; David et al., 2025). Household use is only 0.04%, and no infrastructure currently supports the E10 transport fuel mandate (Boakye & Ofori, 2022; Kelly et al., 2025).

Feedstocks and Technology: First-generation crops and agricultural residues remain underutilized. Prioritizing non-food or dual-purpose crops like sweet sorghum, alongside cassava peels and maize stalks, can reduce food-fuel conflicts and valorize agricultural waste. Second-generation feedstocks require technical capacity and logistics improvements, which could be addressed through decentralized modular biorefineries, phased implementation, PPPs, and international technology transfer, following models from India and Brazil (IRENA, 2022; Mawusi et al., 2023).

Policy and Institutional Gaps: Existing frameworks (Renewable Energy Act 2011, National Energy Transition Framework) lack enforceable mandates and dedicated oversight. Establishing a Bioethanol Development Authority is recommended to coordinate research, investment, and implementation. Enforcing the E10 blending mandate requires robust production, distribution, and fiscal incentives such as tax breaks and subsidies.

Residential Energy: Bioethanol stoves provide health and environmental benefits, but affordability and access are barriers. A Bioethanol Stove Subsidy Programme, supported by carbon finance or donors, with targeted household registration and digital tracking, can drive adoption while preventing misallocation (Accenture, 2012; Global Alliance for Clean Cookstoves, 2017).

Rural Industrialization: Linking small-scale ethanol refineries to cassava or sorghum cooperatives under the 1D1F initiative can create rural jobs, empower women and youth, and support NDC climate targets by potentially displacing 150 ML of petrol annually (Singh et al., 2018). Multi-stakeholder governance boards can mitigate risks from political influence, weak cooperative management, and low local demand (Mensah et al., 2021).

R&D and Digital Tools: Investment in a Biofuel Research and Innovation Fund and digital monitoring tools can optimize feedstock yields, refining efficiency, and emissions tracking.

Phased Roadmap:

- ✓ Short-term (2025): Launch National Biofuel Policy, public education campaigns, tax breaks for small producers.
- ✓ Medium-term (2030): Enforce blending mandates; establish 1D1F-linked biorefineries in 20 districts; replace 10% of petrol with ethanol.
- ✓ Long-term (2040): Expand ethanol to aviation fuel; transition 30% of households to ethanol cookstoves.

Monitoring & Evaluation: KPIs should track production, stove adoption, blending compliance, and reductions in wood fuel use and deforestation, coordinated by the Bioethanol Development Authority, Energy Commission, Ghana Statistical Service, and academic partners.

Table 18 outlines the various key stakeholders and their respective responsibilities within Ghana's bioethanol sector.

Digital tools – like mobile apps for stove tracking and GIS for feedstock mapping will improve data collection and transparency. Progress should be reviewed regularly against targets set in Ghana's National Energy Transition Framework (Energy Commission of Ghana, 2022). Effective implementation of these interventions will require strong multi-institutional collaboration.

In conclusion, while Ghana's bioethanol market is still in its infancy, it holds immense potential for energy diversification, rural development, and climate resilience. Strategic interventions – ranging from feedstock diversification, infrastructure investments, policy reform, and public awareness, will be required to unlock this potential. With a coordinated, inclusive, and forward-looking implementation strategy, Ghana can position itself as a regional leader in sustainable bioenergy.

Table 18: Key stakeholders and their role in Ghana's bioethanol sector

Stakeholder	Role/Responsibility
Ministry of Energy	Lead policy formulation, enforce blending mandates, and coordinate national energy diversification strategies.
Energy Commission	Technical regulation, data monitoring, and oversight of bioethanol integration in national energy planning.
Ministry of Food and Agriculture (MOFA)	Coordinate feedstock zoning, support farmer training, and develop agricultural extension services related to energy crops.
Environmental Protection Agency (EPA)	Monitor and regulate environmental impacts of bioethanol production, including emissions and water use.
Forestry Commission	Monitor and report on deforestation trends linked to bioenergy transitions; support sustainable land use.
Proposed Bioethanol Development Authority (BDA)	Central coordinating institution for bioethanol policy, research, implementation, and inter-agency collaboration.
Private Sector (producers, blenders, distributors)	Invest in and operate ethanol refineries, blending facilities, transport logistics, and stove manufacturing.
Donor Agencies and Climate Finance Institutions	Provide funding support for infrastructure, R&D, and subsidy programmes (e.g., GCF, GEF, AfDB).
Civil Society Organisations (CSOs) and NGOs	Conduct public education campaigns, ensure community engagement, and monitor local-level implementation.
Academic and Research Institutions	Conduct R&D on feedstocks, pre-treatment technologies, and bioethanol efficiency; support policy design with evidence.

3.2.2 Comparative Analysis of Ghana's Bioethanol Sector in the Regional Context

Ghana's bioethanol potential is well-established in the literature (Kelly et al., 2025; Pelizan, 2019) and affirmed in this comparative review. However, the country remains behind peer nations such as Nigeria, Kenya, Mozambique, and Malawi in translating this potential into a sustained and scaled production model. This discussion critically analyses the findings through a comparative lens and offers context-specific proposals for Ghana, particularly focusing on policy coherence, technological implementation, feedstock strategy, and institutional alignment.

3.2.2.1 Feedstock Utilisation and Technological Gaps

Ghana's feedstock portfolio reflects a favourable mix of cassava peels, sweet sorghum, yam straw, sugarcane bagasse, and maize stalks. These agricultural residues demonstrate theoretical annual bioethanol yields of up to 200 ML, enough to meet clean cooking needs for five million households (Oppong-Ansah, 2025b). However, only 5% of this potential is being exploited, a clear reminder of logistical, technological, and institutional limitations (Obayelu, 2014).

Comparatively, Nigeria's vast cassava production (50 Mt annually) and multi-feedstock strategy present a more structured and industrialised model (Awoyale & Lokhat, 2019; FAO, 2023b). While Ghana explores drought-tolerant sweet sorghum to avoid food crop displacement (Liu, 2024), it lacks Nigeria's investment in second-generation technologies such as bio-gel derived from sawdust and water hyacinth (African Development Bank, 2013). This points to a critical implementation gap in Ghana's technological roadmap.

Ghana can draw inspiration from Burkina Faso's BioStar project and the use of agro-waste like cashew shells in rural processing facilities (Cirad, 2023). Such localised innovations align with Ghana's biomass residue abundance and could offer smallholder income while solving waste management problems. Ghana should invest in decentralised biorefinery models that combine low-cost conversion technology with community-managed feedstock supply chains. Incentivising research into crop residues sorghum straw and establishing public-private partnerships for small-scale bioethanol distillation can enhance rural income and improve clean cooking fuel availability.

3.2.2.2 Policy Frameworks: From Aspirations to Action

Ghana's Renewable Energy Act (2011) and Energy Sector Strategy (2010) provide a foundational policy framework, targeting a 10% bioethanol blend by 2020 and 20% by 2030 (Energy Commission, 2010; Renewable Energy Act, 2011). Despite these commitments, implementation has remained aspirational. The absence of a legally binding blending mandate, a dedicated biofuel development authority, and fiscal incentives has hindered private sector investment and long-term planning (Kasoa et al., 2025)

Malawi offers a practical model, having maintained a 10% bioethanol blending mandate since 1982 through cabinet directives, tax incentives, and a collaborative partnership with EthCo (Deenanath et al., 2012; Caryanga, 2024). Ethiopia's blending success (38.54 ML of bioethanol between 2009 and 2013) shows that bioethanol can be a cost-effective substitute for imported fossil fuels (Miftah & Mutta, 2024). However, Ethiopia's failure to safeguard bioethanol supplies from industrial competition such as the beverage production underlines a key risk for Ghana's strategy.

Ghana should legislate a mandatory E10 blend and establish a bioethanol Development Authority under the Energy Commission with legal powers to enforce blending targets, oversee licensing, and coordinate cross-sector implementation. Fiscal tools such as VAT exemptions on bioethanol stoves and concessional finance for bioethanol producers –following Kenya’s model should be prioritised (WORLD BANK GROUP, 2024).

3.2.2.3 Socioeconomic Integration and Community Participation

Mali and Burkina Faso demonstrate the value of community-driven models. The Garalo Bagani Courant project in Mali and hedgerow jatropha cultivation in Burkina Faso both decentralised energy production while improving local incomes (Baumert et al., 2018; Favretto et al., 2014). Similarly, Mozambique’s Project Gaia successfully linked smallholder cassava supply chains with household-scale bioethanol stoves (Project Gaia, 2025)

While Ghana's sweet sorghum initiatives reflect an intent to avoid food-fuel conflicts, the sector lacks effective farmer integration mechanisms. Smallholders, particularly women and youth, are often excluded from pilot project ownership, limiting the socio-economic benefits that bioethanol could offer.

Ghana should introduce an Out-Grower bioethanol Scheme to support the cultivation of non-food feedstocks such as sweet sorghum. Organising cooperatives, especially targeting women and youth, can create rural jobs while enhancing feedstock consistency. Lessons from Kenya’s Giraffe Bioenergy project and farmer cooperatives (David et al., 2025) should guide implementation.

3.2.2.4 Institutional Synergy and Regional Alignment

At the regional level, ECOWAS through ECREEE and WACCA has established frameworks that promote non-food feedstocks and gender-inclusive bioenergy development (ECREEE, 2013, 2018). However, uptake among member states has been uneven. Ghana has engaged with these initiatives primarily at the policy study level but lacks a robust institutional mechanism to localise ECOWAS targets.

Nigeria’s Presidential Cassava Initiative and Kenya’s National Clean Cooking Strategy show that synergy between national plans and regional goals fosters coherence and investment confidence (Giritusugar, 2023; NNPC, 2007)

Ghana should align its Renewable Energy Master Plan with ECOWAS’s Bioenergy Strategy by incorporating measurable indicators for bioethanol blending, clean cooking access, and rural employment. Regional funding mechanisms, such as ECOWAS's research and innovation funds, could be leveraged to support technical upgrades and pilot projects.

3.2.2.5 Proposed Ghana-Specific Implementation Strategy

The proposed Ghana-specific strategy for bioethanol development takes a holistic approach. Key elements include:

- ✓ Policy Enforcement: Implement a statutory E10 blending mandate by 2027 and establish a Bioethanol Development Authority for sector oversight.
- ✓ Feedstock Innovation: Promote drought-resistant sweet sorghum and a National Agricultural Residue Collection Program to ensure sustainable, locally sourced feedstock.

- ✓ Technological Infrastructure: Support SMEs producing stoves and local distillation units, and incentivize research into second-generation bioethanol technologies like lignocellulosic conversion.
- ✓ Institutional Coordination: Create a multi-agency Bioethanol Implementation Task Force and align efforts with ECOWAS policies and SDGs for coherent execution.
- ✓ Community Empowerment: Launch a National Out-Grower Scheme and train rural cooperatives in agronomy and bioethanol entrepreneurship to build capacity, employment, and supply chain resilience.
- ✓ Financing and Incentives: Offer VAT exemptions, tax holidays, and collaborate with international donors to fund pilot projects and bioethanol hubs.

Ghana's transition requires moving from fragmented pilots to an integrated national strategy grounded in policy enforcement, institutional accountability, and socioeconomic inclusion. Learning from Nigeria, Mozambique, and Malawi offers guidance, but local adaptation is essential. By emphasizing feedstock resilience, decentralized innovation, and inclusive participation, Ghana can unlock the environmental and socioeconomic benefits of bioethanol at scale.

Drawing from comparative analysis, the following comprehensive implementation strategy is proposed for Ghana:

a) **Policy Enforcement:**
   - Pass a statutory blending mandate (E10 by 2027).
   - Establish a Bioethanol Development Authority.

b) **Feedstock Innovation:**
   - Promote drought-resistant sweet sorghum cultivation.
   - Establish a National Agricultural Residue Collection Program, backed by logistics and processing infrastructure.

c) **Technological Infrastructure:**
   - Support SMEs in bioethanol stove production and local distillation.
   - Incentivise second-generation bioethanol research (e.g., lignocellulosic conversion).

d) **Institutional Coordination:**
   - Form a multi-agency Bioethanol Implementation Task Force.
   - Align national strategy with ECOWAS Bioenergy Policy and SDG targets.

e) **Community Empowerment:**
   - Launch a National Out-Grower Scheme.
   - Train rural cooperatives in agronomy and bioethanol entrepreneurship.

f) **Financing and Incentives:**
   - Offer VAT exemptions and tax holidays for bioethanol firms.
   - Collaborate with donors (e.g., UNDP, World Bank) to fund pilot bioethanol hubs.

3.2.2.6 Quantitative cost-benefit analysis of the proposed interventions, Systematic Risk Assessment and Mitigation Strategies, and Implementation Timeline

This subsection outlines a strategy to expand bioethanol in Ghana, covering policy enforcement, feedstock innovation, technology, institutional coordination, community empowerment, and financial incentives. Key actions include enforcing an E10 mandate, promoting drought-resistant feedstocks, supporting SMEs, creating a multi-agency task force, and empowering rural communities. Risks like political delays and logistical challenges are addressed, with a quarterly 2025–2027 timeline for legislation, pilot projects, and capacity building to boost domestic bioethanol use, reduce imports, and support rural livelihoods.

The meaning of the quarterly (Q) denotations of the implementation timelines of the proposed interventions is described as follows:

Q1→	First Quarter (January–March)
Q2→	Second Quarter of 2025 (April–June)
Q3→	Third Quarter (July–September)
Q4→	Fourth Quarter (October–December)

Table 19 shows the different timelines based on milestones and indicators.

Table 19: Timelines with milestones and indicators

Phase	Milestone	Indicators
	Policy enforcement strategies	
2025 Q4	Draft bill submitted	Draft gazetted
2026 Q2	Authority established	Staff recruited for office operation
2027 Q1	E10 mandate enforced	Regulatory compliance reports
	Feedstock innovation strategies	
2025 Q3	NARCP launched in 5 regions	50 cooperatives registered
2026 Q2	Sorghum out-growers on boarded	10,000 ha under cultivation
2027 Q1	Residue-to-bioethanol pilot starts	10ML produced from residues
	Technological infrastructure strategies	
2025 Q2	R&D calls launched	3 projects funded
2026 Q1	SME incentive scheme rolled out	50 stoves SMEs supported
2027 Q3	First local 2G pilot commissioned	1 pilot plant operational
	Institutional coordination strategies	
2025 Q2	Task Force inaugurated	Monthly meetings held
2025 Q4	National plan updated	ECOWAS alignment certified
2026 Q2	Annual M&E framework operational	Progress reports published
	Community empowerment strategies	
2025 Q3	Training starts in 3 regions	3,000 trained
2026 Q1	Cooperatives begin feedstock supply	30 cooperatives active
2027 Q1	20% of feedstock sourced via the scheme	Verified supply contracts
	Financing and incentives strategies	
2025 Q1	Fiscal policy proposal ready	Cabinet memo approved

2026 Q2	3 donor agreements signed	GH₵111.1M committed
2027 Q2	Pilot hubs operational	5 hubs producing ethanol

Summary of phased timeline

Year	**Key Outputs**
2025	Legal reforms initiated, NARCP launched, R&D and training started
2026	Authority operational, feedstock and SME rollout, donor finance secured
2027	E10 blending starts, pilots producing ethanol, community model scaling up

A. Policy Enforcement

Actions:

- Pass a statutory E10 blending mandate by 2027.
- Establish a Bioethanol Development Authority under the Energy Commission.

Cost-Benefit:

- Cost: ~ GH₵ 33.3 M (legal drafting, public consultations, regulatory setup).
- Benefit: Annual fuel import savings of ~ GH₵227.7M by replacing 10% petrol with domestic bioethanol (based on 200ML local potential at GH₵ 0.56/L vs. GH₵11.1/L imported petrol).

Risk & Mitigation:

- Political delay: Engage Parliament through policy briefs and media advocacy.
- Private sector apathy: Link mandate to fiscal incentives and financing schemes.

B. Feedstock Innovation

Actions:

- Promote drought-resistant sweet sorghum and residues (cassava peels, bagasse).
- Launch National Agricultural Residue Collection Program (NARCP).

Cost-Benefit:

- Cost: GH₵166.6M (training, logistics hubs, collection centres).
- Benefit: 100ML/year ethanol from waste; GH₵111.1M in rural income; reduction in field burning and waste disposal costs (~GH₵22.2M annually).

Risk & Mitigation:

- Farmer disengagement: Provide purchase guarantees and input subsidies.
- Logistics failure: Use GIS to map residues and optimize collection.

C. Technological Infrastructure

Actions:

- Support SMEs in stove manufacturing and distillation.
- Incentivise 2G ethanol research (e.g., lignocellulosic tech).

Cost-Benefit:

- Cost: GH₵222.2M (equipment grants, R&D, SME support).

- Benefit: GH₵88.8M annual SME revenue; 1,000 jobs; reduced reliance on imported LPG.

Risk & Mitigation:

- Tech failure: Partner with institutions like CSIR, KNUST.
- Market mismatch: Run awareness campaigns on ethanol stove benefits.

D. Institutional Coordination

Actions:

- Establish a multi-agency Bioethanol Implementation Task Force.
- Align RE Master Plan with ECOWAS targets.

Cost-Benefit:

- Cost: GH₵16.6M (task force setup, inter-ministerial coordination).
- Benefit: Improved implementation efficiency (~30% reduction in project delays); alignment opens access to ~ GH₵55.5M in regional funding.

Risk & Mitigation:

- Bureaucratic fragmentation: Mandate reporting to Office of the Vice President.
- Donor fatigue: Deliver regular monitoring reports.

E. Community Empowerment

Actions:

- Launch National Out-Grower Scheme for non-food feedstocks.
- Train women/youth cooperatives.

Cost-Benefit:

- Cost: GH₵133.3M (extension services, training centres, start-up kits).
- Benefit: 50,000 rural jobs; increase rural household incomes by 20–30%; empowerment of 15,000 women/youth.

Risk & Mitigation:

- Elite capture: Use quota systems for marginalised groups.
- Low participation: Provide financial incentives and land tenure support.

F. Financing and Incentives

Actions:

- Offer VAT/tax holidays for bioethanol and stoves.
- Leverage donor funding for pilot hubs.

Cost-Benefit:

- Cost: ~ GH₵88.8M in foregone taxes.
- Benefit: ~ GH₵666.6M investment mobilised from private and donor sectors; reduced biofuel price volatility.

Risk & Mitigation:

- Fiscal pushback: Demonstrate medium-term public savings (reduced fuel imports, health costs).
- Donor delays: Align with SDG-7 and climate finance frameworks.

The ECOWAS Renewable Energy Policy enables cooperation on bioenergy standards and infrastructure (African Union, 2019). Ghana could leverage this framework to become West Africa's hub for advanced bioethanol technology and expertise. Also, Ghana can reduce energy gender inequalities by adopting Mali's approach by requiring gender impact assessments and women's participation in its revised biofuel policies.

By combining these regional best practices while addressing gender and environmental dimensions, Ghana can accomplish its potential as a regional bioethanol leader while contributing to extensive sustainable development goals. Future Research and development (R&D) should emphasise on optimising second-generation technologies, measuring gender impacts, and developing climate-resilient feedstock varieties adapted to West African weather conditions.

3.2.3 Strategic Framework for Enhancing Ghana's Bioethanol Supply Chain: Insights, Opportunities, and Challenges

This study set out to examine strategic approaches for strengthening Ghana's underdeveloped bioethanol supply chain, drawing from global best practices while critically considering the socio-economic and logistical realities in the Ghanaian context. Four broad dimensions guided the analysis: feedstock optimisation, infrastructure development, policy frameworks, and technology innovation. The insights drawn reveal opportunities, tensions, and contextual challenges that shape the path forward for Ghana's bioethanol sector.

3.2.3.1 Feedstock Optimisation and Regional Concentration

Feedstock availability in Ghana is scattered and seasonal, with cassava, maize, sugarcane, and sorghum residues identified as viable sources (Osei et al., 2013a). Competing uses, livestock feed (13%) and soil replenishment (7%), limit residues for bioethanol (Afedzi et al., 2025). Regional concentration—sorghum in northern Ghana, cassava in Volta and Eastern regions—faces challenges from fragmented land ownership, weak cooperatives, and limited farmer incentives (Tulashie et al., 2023).

GIS-MCDM tools could guide regional zoning in high-yield areas like Bono and Eastern regions, simplified for local extension officers (Wang et al., 2024). Mobile pre-processing units, as tested in China, can cut transport costs by up to 30% and could be adapted locally using low-tech biomass densifiers fabricated by technical universities.

Prioritizing non-food residues, such as sweet sorghum and cassava peels, is critical to avoid food-fuel competition. Designating sweet sorghum as a biofuel crop, coupled with a residue buy-back program, would stabilize supply, encourage adoption, and align bioethanol development with circular bioeconomy principles.

3.2.3.2 Infrastructure and Logistics

Ghana's agricultural logistics face major gaps. Post-harvest losses for maize stover exceed 30% during the rainy season due to inadequate storage (Tulashie et al., 2023), while poor rural roads and reliance on costly transport raise further challenges (Wang et al., 2024). Rail transport could cut costs by GH₵0.88 per ton-kilometre, but limited rural networks make this aspirational. Targeting rail corridors between regional hubs, like Techiman to Kumasi, via public-private investment could improve efficiency.

Decentralized storage, such as hermetic silos, is low-cost and scalable and should be prioritized under government programs like "Planting for Food and Jobs." Pilot silos linked to community biorefineries could demonstrate feasibility.

Brazil's hub-and-spoke model (Kim et al., 2023) offers a useful template, but success in Ghana depends on stronger coordination among MoFA, NPA, and private actors. While blockchain could enhance traceability, mobile-based farmer data systems—similar to those in the cocoa sector—may be a more practical solution given rural digital limitations (Stoop et al., 2021).

3.2.3.3 Practical Policy and Regulatory Approach

Ghana's bioenergy policies, including the Renewable Energy Act (2011) and National Bioenergy Policy (2010), lack enforceable mechanisms. Unlike Malawi's E10 mandate or Nigeria's bioethanol incentives (NNPC, 2025), Ghana's blending targets remain aspirational, limiting private sector engagement.

A mandatory E10 policy could boost demand, but bottlenecks—limited refining capacity, inconsistent feedstock, and petroleum sector resistance—must be addressed. A phased rollout, starting with government fleets, and tax exemptions for residue-based refineries would reduce risks and costs (Iddrisu & Bhattacharyya, 2015).

A national biofuel monitoring database, managed by the Ghana Statistical Service and Energy Commission, is essential for tracking production and enabling evidence-based policymaking, similar to Ghana's National Forest Monitoring System (Forestry Commission, 2018).

3.2.3.4 Technological and Financial Innovation

Technologies like microwave-assisted and enzymatic hydrolysis can boost bioethanol yields by 15–20% and lower energy use (Kim et al., 2023), but they are expensive for most small-scale Ghanaian producers. A gradual "technology ladder" approach is recommended—starting with low-cost pre-treatments like lime soaking and biomass chipping, then moving to advanced methods through donor or PPP-funded pilot centres.

Giraffe Bioenergy's decentralized cassava model in Kenya shows how village-scale refineries, supported by community out-grower schemes, can provide both energy and income. A cassava-bioethanol pilot in Ghana's Volta Region already demonstrates local feasibility. Scaling this model will require green financing tools such as low-interest loans, carbon credits, and biorefinery risk guarantees, taking cues from Brazil's PROINFA programme (Kim et al., 2023).

Since Ghana's financial sector is cautious with renewable energy risks, public-private partnerships are key to de-risking early investments. Establishing a Green Bioenergy Investment Facility under the Ministry of Finance, backed by international climate funds like the Green Climate Fund, is recommended.

3.2.3.5 Stakeholder Collaboration and the Circular Bioeconomy

The Mozambique-Eni partnership (Eni, 2022) shows the value of turning agricultural waste into export products. Ghana could do the same by using ethanol byproducts like lignin as soil amendments or biochar. This requires coordination among stakeholders—MoFA, the Energy Commission, NPA, and traditional authorities—to align land use policies and organize out-grower schemes. The Kenyan model, where farmers keep land rights but supply feedstock, could work well in Ghana.

Circular economy strategies, reusing waste, producing biogas, or converting lignin to fertilizer, can lower costs and boost sustainability. Future plans should include circularity audits and environmental assessments at each production stage.

Table 20 shows a SWOT analysis of Ghana's bioethanol supply chain, highlighting strengths and challenges. Table 21 compares global strategies, like GIS feedstock zoning, mobile pre-processing, rail integration, decentralized storage, blockchain traceability, hub-and-spoke aggregation, blending mandates, tax incentives, and advanced enzyme processing. These can improve logistics, reduce costs, and increase demand, but success depends on addressing infrastructure, technical skills, investment, digital literacy, and policy challenges.

These challenges span across various stages, from the sourcing of feedstock to the distribution of bioethanol, and are interconnected across critical areas such as infrastructure, policy frameworks, technological capacity, and stakeholder coordination. Addressing these bottlenecks requires a comprehensive approach that integrates improvements in infrastructure development, policy support, technological upgrades, and enhanced coordination among stakeholders to ensure a more efficient and sustainable bioethanol sector in Ghana.

This study establishes that while global models offer rich insights, Ghana's success in bioethanol supply chain development depends on context-specific adaptation. Regional feedstock specialisation, decentralised infrastructure, enforceable policy frameworks, and practical technological transitions form the cornerstones of a viable bioethanol roadmap. However, institutional inaction, infrastructural limitations, and financial conservatism pose significant implementation challenges.

Table 20: SWOT analysis of strategic supply chain enhancement

Strengths	Weaknesses
• Abundant agricultural residues. • Existing policy framework. • Strong rural agricultural base and decentralised farming culture. • Pilot projects already exist (e.g., Volta Region cassava-bioethanol plant) • Government interest in energy diversification and import reduction	• Poor rural infrastructure (roads, storage, transport networks). • Weak enforcement of existing biofuel policies. • Fragmented feedstocks supply due to seasonal variability and competing uses. • Lack of real-time data for planning and monitoring. • Low technical capacity for advanced processing and GIS tools. • Limited stakeholder coordination.
Opportunities	**Threats**
• Regional zoning and GIS-guided feedstock allocation. • Adoption of decentralised mobile processing and storage. • Phased E10 blending policy to create stable demand. • PPP and green financing for biorefinery investment • Circular economy integration (lignin for fertiliser). • Digital solutions for supply chain traceability and pricing fairness.	• Land tenure conflicts and food-fuel trade-offs. • Political instability or inconsistent regulatory support. • High capital costs for technology acquisition and infrastructure. • Resistance from petroleum sector stakeholders. • Climate variability affecting crop residues. • Low public awareness and acceptance of ethanol fuel.

Table 21: Comparative Analysis of Strategies

Strategy	**Global Best Practice**	**Applicability in Ghana**	**Expected Impact**	**Potential Challenges**
Regional Feedstock Zoning using GIS-MCDM	China: GIS-MCDM used to match feedstock with regions	High: Bono, Eastern, Northern, Volta Regions show potential	Efficient feedstock allocation, reduced transport costs	Requires technical capacity; may need donor support for GIS tools
Mobile Pre-processing Units at Farm Gates	China: Reduced transport costs by 30%	Moderate: Can be adapted using local tech	Lower logistics costs, residue compression	Upfront cost, farmer training, maintenance issues
Rail Integration for Bulk Transport	Brazil & China: Rail used for bioethanol supply chains	Low to Moderate: Limited rural rail coverage	Reduced transport cost per ton	Infrastructure investment is high; network coverage limited

Decentralised Storage (Hermetic Silos)	Sub-Saharan Africa – Used to reduce post-harvest losses	High – Existing agricultural projects can integrate	Reduced spoilage (30% loss in maize stover), year-round availability	Maintenance, farmer education
Blockchain Traceability Systems	Brazil: Used for residue pricing and supply chain transparency	Moderate: Mobile-based versions can be adapted	Fair pricing, farmer trust, data traceability	Limited rural internet coverage; digital literacy
Hub-and-Spoke Model for Feedstock Aggregation	Brazil: Efficient bioethanol logistics model	High: Regional agroecological hubs like Volta for cassava	Aggregation improves scale, reduces per-unit cost	Coordination across districts, initial setup costs
Mandatory E10 Blending Policy	Malawi: Demand creation via mandate	Moderate: Can start with public fleet vehicles	Market stability, investor confidence	Political resistance, blending capacity limits
Tax Exemptions	Nigeria: Policy supports increased output by 38%	High: Helps attract PPPs in Ghana	Makes residue use financially viable	Requires legislative change, fiscal planning
Enzymatic & Microwave Hydrolysis	Thailand, South Korea – Yield improvements of 15–20%	Low: High CAPEX; long-term viability only	Higher yield, lower energy input	Technology cost, skilled labour requirement
Decentralised Biorefineries (e.g. Giraffe Bioenergy)	Kenya: Rural cassava-based bioethanol	High: Suits Ghana's rural context	Empowers communities, job creation, low logistics	Requires investment and community coordination
Green Financing (e.g. Brazil's PROINFA)	Brazil: Incentivised private sector with low-interest loans	Moderate: Requires new financing models	Mobilises capital, mitigates risks	Conservative local banks; requires guarantees
Circular Economy Integration (Waste Valorisation)	Mozambique & EU: Export of residues; Brazil: use of lignin for fertiliser	High: Lignin can be used locally	Resource efficiency, cost recovery	Market creation for by-products needed
Out-grower Schemes and Stakeholder Workshops	Kenya: Farmer cooperatives improve feedstock flow	High: Aligns with Ghanaian cooperative structures	Stable supply, rural income equity	Requires strong coordination; land tenure issues

Figure 10 provides a visual summary of the bottlenecks affecting Ghana's bioethanol supply chain. Ultimately, Ghana's bioethanol sector can be transformed, but not through technology alone. It requires institutional coordination, political will, and a reimagining of rural value chains under the bioeconomy paradigm. By leveraging local strengths and learning from global missteps and successes, Ghana can build a resilient, inclusive, and sustainable bioethanol future.

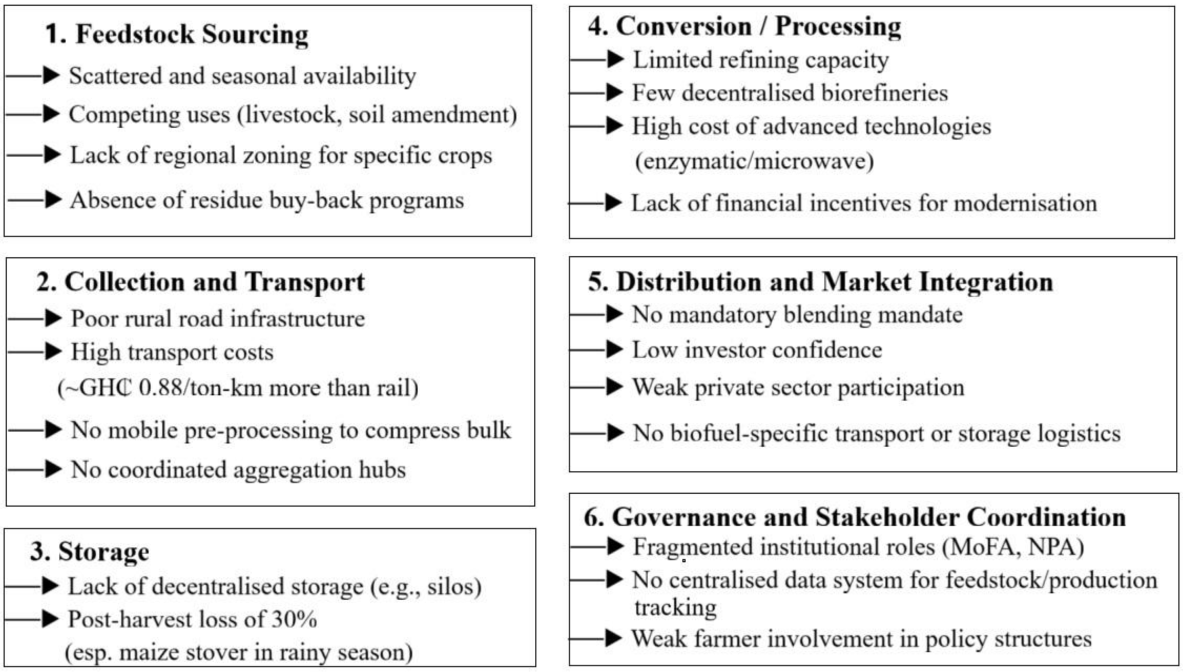

Figure 10: Challenges and Bottlenecks in Ghana's Bioethanol Supply Chain

3.2.4 Critical Analysis of Marketing Strategies to Boost Domestic and Export Demand for Bioethanol in Ghana

The objective of this study was to critically assess effective marketing strategies that can increase both domestic and export demand for bioethanol in Ghana. The findings of this systematic research indicate that a multifaceted marketing approach, grounded in consumer awareness and rebranding, regulatory blending mandates, sustainable export certification, public-private partnerships (PPPs), and price stabilisation, offers a robust pathway for demand creation in Ghana's emerging bioethanol industry. However, to transform these theoretical strategies into real-world results, they must be examined as part of an integrated and context-specific framework. This section provides a critical discussion of these results, explores collaborations among the strategies, and presents feasible implementation pathways tailored to Ghana's socio-economic and policy environment.

3.2.4.1 How the Marketing Strategies Work Together

Each proposed strategy addresses a specific demand-side challenge in Ghana's bioethanol market but is most effective when linked with others. For example, consumer education and rebranding can only create lasting behavioural change if supported by price stability and strong market anchors such as public procurement and blending mandates. Likewise, export market development—though valuable for foreign exchange and demand stability—depends on certification systems, traceable supply chains, and sustainable feedstock production driven by local investment and public-private collaboration.

An effective marketing framework should therefore operate as a mutually reinforcing system. Institutional procurement, such as government transport fleets, can act both as a promotional tool and a stable market for producers. Public-private partnerships can further lower infrastructure and distribution costs, improving price competitiveness. When coordinated with consumer awareness campaigns, especially in peri-urban areas, these efforts can boost acceptance and adoption of bioethanol products (Oppong-Ansah, 2025b). The key is not to apply these strategies in isolation but to integrate them within a cohesive, synergistic framework.

3.2.4.2 Consumer Education and Demonstration Projects

Based on the research findings, the first step toward implementation should be public education and institutional demonstration. According to the Energy Commission of Ghana (2022), many households and institutions are still unaware of bioethanol's benefits. Drawing lessons from Brazil's Proálcool programme (Goldemberg et al., 2008), Ghana could start with community-based demonstrations and media campaigns in peri-urban and off-grid areas.

Given Ghana's diverse and digitally expanding communication landscape, outreach should combine local-language radio, social media, school programmes, and community energy forums, especially in charcoal-dependent regions (Oppong-Ansah, 2025b). Partnerships with schools, faith-based groups, and women's organizations can build trust and encourage behavioural change.

Collaboration with NGOs and district assemblies to deploy mobile energy education centres, an approach that has proven effective in East Africa (Corvaglia et al., 2023), could also raise awareness. However, challenges such as cultural resistance, limited funding, and language barriers may affect impact. Complementary strategies like fixed community hubs, media outreach, and engagement of local leaders can help overcome these issues. With adequate support and partnerships, mobile education could reach tens of thousands of households and more than 10,000 individuals (Kommers et al., 2021).

3.2.4.3 Short- to Medium-Term Priority: Bioethanol Blending Mandates

Following initial awareness efforts, a policy push through fuel blending mandates would create the regulatory certainty needed to scale demand. Examples such as Malawi's E10 and India's Bioethanol Blending Programme show that binding targets drive investment and market growth (IEA, 2019; UNIDO, 2022). While Ghana currently lacks blending mandates, ECREEE (2022) studies confirm the feasibility of an E5 or E10 policy. A phased rollout could begin with an E5 pilot in major cities like Accra and Kumasi, supported by duty waivers for blending equipment and guaranteed offtake agreements under NPA oversight.

Challenges include limited infrastructure, supply disruptions, and potential fuel quality issues that may erode consumer confidence. Political resistance and weak enforcement could further slow adoption. The Ministry of Energy, Parliament, Energy Commission, and NPA must lead coordinated infrastructure investments—such as blending terminals and testing labs—to ensure success. Effective implementation depends on clear regulation, robust monitoring, and targeted incentives (David et al., 2025).

3.2.4.4 Mid-Term Objective: Sustainable Export Certification and Market Access

Positioning Ghana's bioethanol for export to Europe and other premium markets requires early investment in sustainability certification. Premium markets target high-quality or differentiated products that justify higher prices. In fuel markets, this includes enhanced attributes such as higher octane ratings, better performance, or additives that improve efficiency (Carlos & Pinto, 2022). The EU Renewable Energy Directive II (REDII) enforces strict sustainability and traceability standards (FAO, 2022), achievable through certifications like ISCC and Bonsucro (Bonsucro, 2023; ISCC, 2025). However, certification costs remain prohibitive for small producers. A national certification support scheme—funded by the Ministry of Energy or climate finance programs—could alleviate this burden. Additionally, blockchain-based traceability systems could enhance transparency and trust in Ghana's bioethanol value chain (IRENA, 2016). Key challenges include high costs, technical barriers, weak digital infrastructure, and stakeholder resistance, evolving regulations, and fragmented supply chains. Addressing these issues is crucial to strengthen investor confidence and secure sustainable market access.

3.2.4.5 Long-Term Investment: Public-Private Partnerships and Infrastructure

Public-Private Partnerships (PPPs) combine government and private sector resources to share risks and accelerate bioethanol market development (Global Biofuel Alliance, 2023). They can address logistical and financing gaps, as seen in India's Ethanol Blending Programme, where collaboration among sugar mills, petroleum firms, and the government enabled coordinated investment and offtake agreements (IEA, 2019).

In Ghana, similar partnerships between domestic producers, GOIL, and public fleet operators (e.g., STC, Metro Mass Transit) could drive adoption. Supplying schools, hospitals, and prisons with bioethanol would create stable demand and boost investor confidence. PPPs could also support co-financed storage and distribution infrastructure, particularly in rural areas. However, success depends on aligned priorities, clear contracts, and strong governance to overcome financial and bureaucratic barriers and ensure sustainable growth.

The proposed marketing strategies for Ghana's bioethanol sector are promising; however, several challenges may impede their successful implementation as detailed in table 22. Key challenges include low public awareness, infrastructure deficits, producer constraints, and institutional resistance. Limited consumer understanding and behavioural inertia can hinder adoption; thus, community engagement through trusted networks and culturally tailored messaging is vital.

Table 22: Potential challenges and mitigation strategies

Challenge	Mitigation Strategy
Inadequate public awareness and behaviour inertia	Community engagement through trusted local networks, culturally sensitive messaging.
Infrastructure gaps (blending, storage, distribution)	Leverage PPPs, phased capital investment, rural depot prioritisation.
Certification cost burdens for small producers	National sustainability certification support scheme, donor-backed subsidies.
Political resistance or lack of coordination	Inter-ministerial taskforce, stakeholder advocacy, parliamentary briefing sessions.
Market resistance from petroleum sector	Incentive alignment (e.g., tax waivers, offtake guarantees), blended fuel branding.
Volatile feedstock supply and pricing	Buffer stock schemes, agricultural risk management tools, and forward contracts.

Infrastructure gaps in blending, storage, and distribution should be addressed through public-private partnerships (PPPs), phased investments, and rural depot prioritisation to enable gradual market integration.

For small producers, high certification costs restrict participation; a national certification support scheme and donor-backed subsidies can ease this burden. Political resistance and weak coordination require an inter-ministerial task force, stakeholder advocacy, and parliamentary briefings to ensure alignment. Market resistance from the petroleum sector can be mitigated by tax incentives, offtake guarantees, and branding of blended fuels to promote acceptance. Finally, feedstock volatility demands buffer stocks, risk management tools, and forward contracts to stabilise supply and pricing.

Together, these measures target key barriers to enable a smooth and sustainable rollout of Ghana’s bioethanol market.

3.2.4.6 Price Stabilisation and Risk Management

Volatility in bioethanol prices, driven by seasonal feedstock changes and logistical inefficiencies, poses a major threat to demand growth (MOFA, 2023). Table 23 outlines key stakeholders, their interests, and influence levels. Ghana should implement a dual pricing mechanism, like South Africa’s model, which guarantees a minimum producer price while capping consumer prices relative to global benchmarks (The World Bank, 2011). In addition, forward contracts and feedstock buffer stocks should be established to stabilise supply and pricing. An Agricultural Risk Management Fund, administered through the Ministry of Food and Agriculture, could offer weather-indexed insurance products to protect bioethanol feedstock growers from climatic shocks, thus strengthening supply chain resilience.

Table 23: Stakeholder mapping and influence analysis

Stakeholders	Primary Interest	Level of Influence
Ministry of Energy	Policy direction, energy security, decarbonisation.	High
National Petroleum Authority (NPA)	Regulatory oversight, fuel quality, and blending compliance.	High
Energy Commission	Technical standards, public education, M&E.	High
Ministry of Food and Agriculture	Feedstock supply chain resilience.	High
Private Bioethanol Producers	Profitability, market access, and production scalability.	High
NGOs and Civil Society	Community acceptance, transparency, and sustainability.	Medium
Development Partners (e.g. UNIDO, GIZ)	Technical assistance, capacity building, and funding.	Medium-High
Local Assemblies and Traditional Authorities	Community trust, and local governance	Medium
Faith-based and Women's Groups	Public trust, and grassroots mobilisation	Medium
End Consumers (urban & rural)	Affordability, health/safety, and energy reliability	Low (individually)

Successful implementation depends on coordinated efforts among public agencies, private actors, and local communities.

3.2.4.7 Implementation Prioritisation

Implementation prioritisation ensures that bioethanol initiatives are deployed strategically, efficiently, and sustainably. A phased approach allows for optimal resource use, risk reduction, and adaptive learning, enhancing long-term success.

- ✓ Phase I focuses on awareness and market preparation through consumer education and pilot projects—low-cost, low-risk actions that build trust and pave the way for future scale-up.
- ✓ Phase II institutionalises demand via mandatory blending in major cities, public-private partnerships, and sustainability certifications. These measures stabilise supply chains, attract investment, and demonstrate viability for national expansion.
- ✓ Phase III scales the system nationally with an E10 blending mandate, price-stabilisation mechanisms, and export market development. Export certification and risk-sharing tools address volatility and encourage large-scale investment, ensuring competitiveness.

This structured approach enables gradual, adaptive growth, where each phase builds on previous successes, strengthens capacity, and refines policy for sustainable industry development.

A phased implementation roadmap would optimise resource use and allow for policy learning:

1. Phase I (0–1 year):

    - Consumer education campaigns and pilot cooking fuel projects.
    - Institutional demand pilots in public schools and hospitals.

Early consumer education and pilot projects will raise awareness and build initial demand, engaging thousands of households and public institutions. Although production impact is minimal, this phase establishes critical market foundations, enabling smoother adoption in subsequent phases.

2. Phase II (1–3 years):

    - Introduction of a mandatory E5 blending policy in major cities.
    - Development of PPP frameworks and incentives for private investment.
    - Establishment of sustainability certification support units.

The E5 blending mandate in major cities and PPP development will drive modest bioethanol demand, potentially replacing 5–7% of petrol/gasoline consumption in urban areas. Sustainability certification supports market credibility. Private investment incentives and institutional demand pilots foster supply chain growth, laying the groundwork for scale-up.

3. Phase III (3–5 years):

    - National rollout of blending mandates (E10).
    - Full price stabilisation mechanism with risk-sharing instruments.
    - Export certification to access premium EU markets.

National E10 rollout combined with price stabilisation and export certification will significantly expand bioethanol market share, aiming to replace 10% or more of national petrol demand. Risk-sharing mechanisms will reduce market volatility, encourage investments, and open premium export markets, contributing substantial foreign exchange savings and rural economic benefits.

3.2.4.8 Monitoring and Evaluation Mechanisms

This section outlines the Monitoring and evaluation (M&E) mechanisms essential for assessing the progress and effectiveness of bioethanol policy implementation. It emphasizes the importance of tracking key indicators such as household usage, fuel blending volumes, export shipments, and public-private partnership projects through various tools like progress reports, audits, digital platforms, and community feedback. The section also identifies the Energy Commission as the leading agency responsible for M&E, supported by other key institutions, ensuring that the findings inform ongoing policy reviews and adjustments. Overall, these mechanisms are critical for ensuring transparency, accountability, and continuous improvement in Ghana's biofuel initiatives.

Monitoring and evaluation are essential for tracking implementation progress, identifying bottlenecks, and enabling adaptive policy learning. A robust M&E system should include:

a) **Key Performance Indicators (KPIs):**

- Number of households/institutions using bioethanol
- Volume of E5/E10 fuel blended nationally
- Number of certified export shipments
- Number of new PPP infrastructure projects established

b) **Monitoring Tools:**

- Annual progress reports by the Energy Commission
- Independent third-party audits
- Digital data collection platforms (e.g., mobile dashboards)
- Community-based feedback mechanisms

c) **Institutional Responsibility:**

- **Lead agency:** Energy Commission
- **Supporting actors:** NPA, MoFA, district assemblies, EPA
- M&E reporting should be integrated into national energy and climate policy reviews.

This section describes the use of scenario planning to project different outcomes for the bioethanol market development. Three scenarios are outlined: the best case involves full implementation of E10 blending and widespread use, leading to rural growth and energy security; the most likely case suggests a gradual adoption with moderate infrastructure development and export growth; and the worst-case entails delays and resistance, resulting in missed economic opportunities and continued dependence on fossil fuel imports. These scenarios help in understanding potential risks and guiding strategic planning.

This study proposes three implementation scenarios as shown in table 24.

Table 24: Bioethanol market development scenarios

Scenario	Description	Implications
Best Case	Full rollout of E10 blending, widespread adoption of bioethanol for cooking, and sustainable exports to the EU.	Strong rural development, improved energy security, and significant forex savings and climate gains.

Most Likely	E5 mandate implemented in major cities, moderate adoption in peri-urban areas, and slow but growing exports.	Gradual scale-up of infrastructure and private investment, limited but positive market traction.
Worst Case	Delays in blending policy, weak coordination, and resistance from fuel marketers and consumers.	Missed economic opportunities, underutilised capacity, and continued reliance on imported fossil fuels.

3.2.4.9 Policy Recommendations

Based on the study findings and discussed strategies, the following policy recommendations are proposed to guide the phased implementation of Ghana's bioethanol marketing roadmap:

a) Develop a National Bioethanol Strategy integrating marketing, regulation, and infrastructure under a single policy framework led by the Ministry of Energy.
b) Initiate targeted consumer education campaigns in peri-urban and charcoal-dependent areas, with support from local leaders, schools, and media.
c) Pilot institutional demand anchors in schools, prisons, hospitals, and public transport fleets to demonstrate early benefits and market viability.
d) Adopt an E5 blending mandate in urban centres, accompanied by duty exemptions, blending infrastructure upgrades, and off-take contracts.
e) Establish a sustainability certification support mechanism for domestic producers to facilitate access to premium export markets.
f) Design a PPP framework to attract private investment in blending depots, storage, and last-mile distribution, particularly for off-grid areas.
g) Implement a price stabilisation scheme using minimum price guarantees, forward contracts, and agricultural insurance tools to mitigate supply chain risks.
h) Institutionalise Monitoring and Evaluation (M&E) with annual reporting, mobile feedback platforms, and periodic policy reviews.

These recommendations should be implemented in a sequenced, flexible manner, accompanied by strong governance and continuous stakeholder engagement to ensure policy durability and market responsiveness.

Chapter 3 analysed Ghana's bioethanol sector, showing strong potential based on abundant residues from cassava, maize, sorghum, sugarcane, and yams. Optimising regional processing, improving transport and storage, and establishing supply hubs can cut costs and boost output. Comparisons with other African countries highlight the need for strong policies, coordination, and circular economy practices. Yet, fragmented feedstock supply, weak infrastructure, and policy gaps limit progress, with only about 5% of potential capacity used. Addressing these challenges through blending mandates, regional specialisation, and investment can help Ghana build a sustainable and resilient bioethanol industry.

Conclusion and Perspectives

This study provides a comprehensive analysis of Ghana's bioethanol sector, highlighting both its opportunities and challenges for sustainable development. Ghana has abundant feedstock resources, including agricultural residues such as cassava peels, maize, and sorghum stalks, with significant potential for lignocellulosic bioethanol production. Spatial analysis and supply chain modelling indicate that up to 2,788 million litres of bioethanol could be produced annually from cassava residues alone under optimal conditions, if logistical, infrastructural, and technological constraints are addressed. Currently, inadequate feedstock collection, poor transport networks, and limited storage facilities hinder scaling from pilot projects to a fully operational industry.

The lack of a coherent national biofuel policy – such as clear blending mandates, investment incentives, and quality standards – further limits investor confidence and market growth. Lessons from other West African countries suggest that supportive regulatory frameworks, regional cooperation, and incentive schemes are critical to unlocking Ghana's bioethanol potential. ECOWAS bioenergy strategies offer additional opportunities for regional market integration and export development.

Environmental and socio-economic analyses show substantial benefits: bioethanol blending could reduce greenhouse gas emissions by up to 70%, while the sector could generate around 50,000 jobs, particularly in rural areas, contributing to poverty reduction and economic development. Using second-generation feedstocks and agricultural residues could enhances sustainability and mitigates competition with food crops.

Advancing lignocellulosic bioethanol technologies requires targeted investments in research, pilot projects, capacity-building, and infrastructure. A coherent national policy, private sector participation, and regional collaboration are essential to overcome current barriers. By integrating supply chain strategies, technological innovation, and circular economy principles, Ghana can establish a sustainable bioethanol industry, supporting energy diversification, climate goals, and socio-economic growth.

Future research should focus on pilot implementations, monitoring technological innovations, and refining supply chain models to respond to evolving market and infrastructural conditions.

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