Open Journal of Business and Management, 2026, 14(1), 654-680
https://www.scirp.org/journal/ojbm
ISSN Online: 2329-3292
ISSN Print: 2329-3284

The Role of Mathematical Modeling and Optimization in Achieving Sustainable Energy Transitioning Goals (SDG-7): A Systematic Literature Review of Ghana's Biofuel Transition Supply Chain

Gideon Fraser, Akyene Tetteh*

Department of Management Studies, University of Mines and Technology, Tarkwa, Ghana
Email: *atetteh@umat.edu.gh

How to cite this paper: Fraser, G., & Tetteh, A. (2026). The Role of Mathematical Modeling and Optimization in Achieving Sustainable Energy Transitioning Goals (SDG-7): A Systematic Literature Review of Ghana's Biofuel Transition Supply Chain. *Open Journal of Business and Management, 14,* 654-680.
https://doi.org/10.4236/ojbm.2026.141039

Received: November 11, 2025
Accepted: January 5, 2026
Published: January 21, 2026

Abstract

The universal access to clean and affordable energy goal (Sustainable Development Goal 7) is essential for sustainable development. For Ghana and several other developing countries, especially those within Sub-Saharan Africa, the transition to renewable energy is a non-negotiable approach to achieving sustainable development through energy security and promoting a green economy (GE). However, the transition to renewable energy presents several challenges, including supply chain uncertainties, which may significantly affect implementation and raise environmental, economic, and social concerns. Ghana, a case study in this research, has established ambitious targets for greenhouse gas emission reductions to achieve net zero CO_2 emissions by 2060. The targeted 10% integration of biofuels into national transportation energy for 2020 has not been achieved, and the 20% target for 2030 appears increasingly unlikely. This research aims to analyze the challenges associated with Ghana's biofuel transition supply chain, with a key objective of proposing how mathematical modeling and optimization can facilitate Ghana's sustainable energy transition. Bibliometric analysis was employed to assess the biofuel landscape in Ghana over the past decade (2014-2024) to understand the current state of research. The study results indicate a growing interest in biofuel research; however, applying mathematical modeling and optimization to address Ghana's specific transitioning challenges has been limited. The study recommends advancing technologies such as computer simulations and mathematical optimization models in research and expanding knowledge in these areas to enhance the likelihood of achieving sustainable biofuel transition goals in Ghana.

Keywords

Sustainable Development Goal 7, Mathematical Modeling and Optimization, Biofuel Transition Supply Chain, Sustainable Energy Transition, Ghana

1. Introduction

In 2015, the Sustainable Development Goal (SDG) was adopted by the United Nations (UN), pledging to balance the three pillars of sustainability, viz., economic, social, and environmental, represented by 17 objectives. The SDGs have become popular globally, especially the Global Sustainable Development Agenda for 2030, for their dedication to promoting economic growth while considering social interests and environmental preservation (Leal-Filho et al., 2019). Given the increasing effects of energy use on climate change, environmental degradation, and global health, the transition to sustainable energy for current and future generations is one of the 21st century's most urgent concerns (Hassan et al., 2024). Concerns regarding the sustainable management of energy resources have also been raised following the rapid expansion of global energy consumption. The recent analysis of global energy consumption indicates that Green Energy (Renewable Energy) is the most rapidly expanding energy resource despite receiving minimal attention (International Energy Agency, 2023). Green energy is projected to contribute to at least 15% of the global energy mix by 2040 and is expected to remain a primary power source thereafter (British Petroleum, 2019). This projected increase in green energy supply comes with an anticipation of propelling progress towards the Sustainable Development Goals (SDG) related to the theme of "Access to clean and affordable energy (SDG-7)", "Decent work and economic growth (SDG-8)", "Industrial and infrastructure development (SDG-9)" and "Climate action (SDG-13)" (United Nations, 2024; Tian et al., 2024; Hasan et al., 2023).

The primary aim of the paradigmatic shift to renewables as an innovative and more sustainable approach to SDG-7 is to reduce greenhouse gas (GHG) emissions while fostering economic development through clean energy technologies. For developing countries, the transition to green energy means energy security (especially in net-import energy-dependent countries) and job creation (Nyarko et al., 2024; International Energy Agency, 2023). The UN's SDG report has indicated significant progress through global efforts and collaboration toward achieving the indiscriminate, global access to clean and affordable energy (SDG-7). They further indicated that between 2020 and 2024, more than 273 million people worldwide gained access to electricity, while about 700 million have access to clean cooking fuels. However, despite the significant effort towards SDG-7, sub-Saharan African (SSA) nations continue to experience a decline in energy access and face significant challenges. Over one billion people in SSA will remain without access to clean and affordable energy by 2030 (United Nations, 2024). The region deserves attention to increase the likelihood of achieving the Universal Access to

Clean Energy Goal for 2030. Over the years, Africa's population and economy have increased rapidly, which has had significant regional and international ramifications for the continent's energy industry. Africa's GDP was valued at $7 trillion in 2018 and is expected to grow to $17 trillion by 2040 (International Energy Agency, 2023). Despite the economic growth, the local governments across SSA are unanimously facing challenges, including 1) lowering dependency on imported fossil fuels, which has a substantial impact on economic development; 2) maintaining consistent economic growth while lowering energy-related GHG emissions; and 3) generating employment through sustainable resource exploitation and management (Nyarko et al., 2024; Sparkman et al., 2023).

Furthermore, climate change has significantly affected the region, and its vulnerability is increasing because of its overreliance on natural resources. Nevertheless, Solar, wind, geothermal, hydro, ocean wave, nuclear, and biomass energy are among the region's abundantly available energy resources yet remain almost unexploited (Dahunsi et al., 2020; Afrane et al., 2021a). Amid these challenges, biofuels have emerged as a strategic opportunity for the region to exploit the enormous agricultural and waste resources to replace fossil fuels and support its economic development (Green Economy) (Asongu & Odhiambo, 2020; Sparkman et al., 2023). Biofuels transition can support several SDGs by lowering GHG emissions, thereby promoting good health (SDG-3), providing clean and affordable energy (SDG-7), promoting job creation and economic growth through agribusiness (SDG-8), promoting industrial and infrastructure development (SDG-9), and supporting climate mitigation actions by providing low-carbon energy resources (SDG-13) (Hasan et al., 2023; Nyarko et al., 2024). To direct investment into commercial biofuel production, several SSA governments, including South Africa, Nigeria, Mali, Ethiopia, and Ghana, have adopted various policies and incentives to support research, development, and deployment of biofuel to increase their production and use. Despite these efforts, only a handful have successfully transitioned to commercial usage (Sparkman et al., 2023). Several studies, including Sparkman et al. (2023), Ebadian et al. (2021) and Asongu & Odhiambo (2020), have suggested that there is a significant gap in renewable energy research and implementation, and there is an urgent need to investigate the causes of biofuel project failures despite growing interest in the field, particularly in SSA.

Globally, renewable energy projects confront several challenges, most notably supply chain uncertainty, which may impact implementation and sustainability. Mathematical modeling and optimization emerge as a practical approach for addressing a wide range of challenges in renewable energy transition, with applications in engineering, techno-economic analysis, supply chain management, and environmental management (Yue et al., 2024). Zahraee et al. (2020b) and Sun & Fan (2020) investigated the global bioenergy transition, asserting mathematical modeling and optimization's roles in supply chain logistics, specifically in enhancing bioenergy production at the operational, tactical, and strategic planning levels. The significance of mathematical modeling in sustainable energy transitions is becoming more important as bioenergy research expands globally. The transition to renewable energy may significantly impact the environment, the economy, and society along the energy supply chain; thus, careful consideration must be given to using mathematical modeling and optimization in research to support the sustainable transition to renewable energy (Zahraee et al., 2020b). This paper highlights the significance of mathematical modeling and optimization by bridging the gap between academic research and the implementation of energy policy, using Ghana's biofuel transition supply chain goals as a case study.

Statement of Problem and Objectives

As one of the fastest-developing alternatives to fossil fuels in transportation, biofuels represent a promising pathway toward achieving energy security and environmental sustainability by promoting the use of low-carbon energy. Biofuels can replace fossil fuels in automotive engines and machinery without necessarily changing the structure (overhaul) of the equipment, thereby supporting an economy-friendly transition (Morone & Cottoni, 2016). One of the most rapidly developing African countries, Ghana, relies heavily on imported energy, which accounts for 95% of fossil energy, while oil remains the widely used energy resource, as indicated in **Figure 1**. This exposes the country to supply chain market disruptions and global energy price volatility risks (Kamasa, 2020; National Petroleum Authority, 2023). Several empirical studies on Ghana's renewable energy landscape, including (Tetteh & Fraser, 2025; Nelson et al., 2021; Nyasapoh et al., 2022; Adusah-Poku & Takeuchi, 2019), highlight the abundance of resources like solar, wind, hydro, and biomass. These discoveries have also influenced the implementation of many renewable energy policies, ultimately aiming at a complete transition to renewables across all sectors in the country to promote energy access to the vast population without access to clean and affordable energy (Ahmed et al., 2017). The Ghana Energy Transition and Investment Plan (GET&IP) focus on transitioning to low-carbon renewable energy alternatives, such as biofuels, to replace fossil fuels across all sectors. The ultimate aim is to achieve the climate target of net zero carbon dioxide (CO_2) emissions by 2060. However, the Bioenergy Policy (BEP), which aims to integrate 10% biofuels into the national transportation energy mix by 2020, has not been met, while the 20% biofuels integration target for 2030 seems less optimistic (National Petroleum Authority, 2023; Energy Commission of Ghana, 2023; Ministry of Environment, Science, Technology and Innovation, 2023; Ministry of Energy, 2021; Energy Commission of Ghana, 2010).

Approximately 67% of Ghana's land area is used for agriculture, which employs many small-scale industries and can completely support biofuel production (Mawusi et al., 2023). Despite the abundant feedstock supply for biofuel production, Ghana still struggles upstream, with nearly one hundred biofuel projects collapsing within the first 5 years of operation (Ahmed et al., 2017). Several studies, including Ahmed et al. (2017), Ansah and Ansah (2022), and Kipkoech et al. (2022), described the challenge emanation predominantly from supply chain planning and resource management, citing 1) weak business planning 2) environmental and social impacts such as deforestation and food-energy nexus and 3) the lack of a domestic biofuel market or exports to other countries. The Energy Commission of Ghana (2023) reports that the projected SDG-7 objective of 38.1% integration is yet to be met, with just 6.4% achieved so far in 2023. Generally, the biomass-to-biofuel supply chain (BSC) is intrinsically complicated, with several interconnections between market dynamics, infrastructure, logistics, and feedstock availability (Yue et al., 2014). Balancing food security and land management imperatives and prioritizing the limited resources is critical to capitalize on the opportunities in biofuel production. To ensure the sustainable transition to biofuels, production must comply with policy and regulatory requirements, environmental sustainability, and market dynamics to ensure optimal environmental, economic and social outcomes while mathematical modeling and optimization hold a critical role (Kipkoech et al., 2022; You et al., 2022).

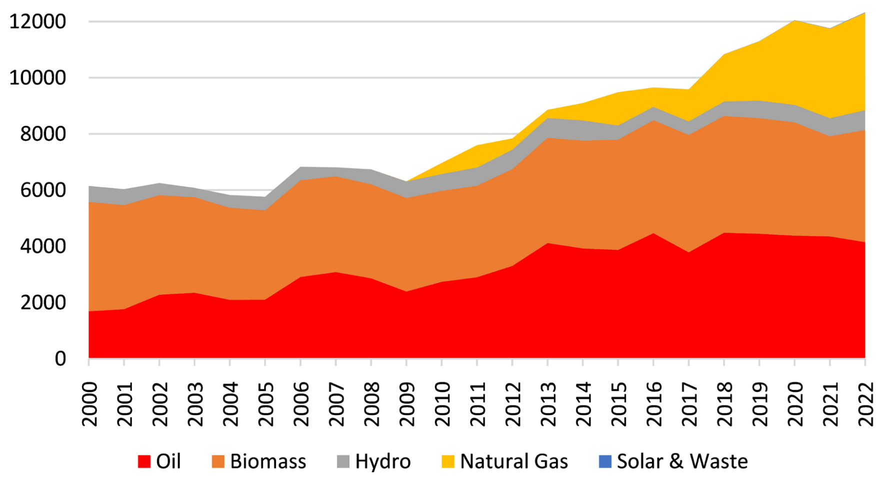

Figure 1. Energy supply mix in Ghana. Source: Energy Commission (2023).

According to Afrane et al. (2021a), renewable energy research has significantly intensified over the previous two decades, especially in Sub-Saharan Africa, while a review of Ghana's sustainable energy landscape reveals extensive empirical studies to support this transition. However, the findings of these studies remain disjointed, complicating the analysis, organization, and statistical quantification of the topic's trends and characteristics over an extended duration (Ahmed et al., 2017). To our knowledge, no studies have used bibliometric analysis and a comprehensive literature review to evaluate the role of mathematical modeling and optimization in facilitating a sustainable biofuel transition supply chain within the given geographic location, while their existence globally is few. This study was motivated by the growing use of mathematical modeling, simulation, and optimization techniques in addressing various global challenges in biofuel production. The study investigates the role of mathematical modeling, simulation, and optimization using Ghana's unique biofuel transition supply chain challenges as a case study, and recommends areas for further research. By endorsing the global initiative to enhance access to clean energy, the research identifies critical areas to strengthen renewable energy promotion while serving as a valuable guide for policy development and attaining SDG 7 for other developing countries with similar challenges.

This study aims to examine how mathematical modeling and optimization contribute to attaining Sustainable Development Goal 7 (SDG 7). By employing a systematic literature review (SLR) within a bibliometric analysis framework, the research thoroughly examines the distinctive role of mathematical modeling and optimization in the sustainable energy transition by concentrating on Ghana's biofuel transition. The study seeks to provide answers to the following questions:

1) What is the role of mathematical modeling and optimization in biofuel transition aligned with the Sustainable Development Goals (SDG 7)?

2) Which mathematical modeling and optimization trends are currently prevalent in the shift to sustainable energy?

3) What are the gaps in the body of current research?

4) What are the future research plans?

The remaining sections of the paper are arranged as follows: Section 2 presents a conceptual review that includes SDG-7 and the sustainable energy transition concept, an overview of Ghana's biofuel transition journey, and an overview of mathematical modeling and optimization in the energy transition. The research approach (methodology) is covered in section 3. The systematic literature review (SLR) within a comprehensive bibliometric analysis is conducted in this section to find answers to the research questions. Section 4 discusses the findings from the study and outlines the future research plan, while Section 6 presents the study's conclusions, implications, and recommendations to stakeholders.

2. Conceptual Review

2.1. SDG 7 and Sustainable Energy Transition Concept

Sustainable development is described by the World Commission on Environment and Development (WCED) in 1987 as a progressive attempt to integrate economic growth, environmental preservation, and social development to fulfill the present demands without sacrificing future generational needs. Energy is one of the primary aspects that must be included in discussions about sustainable development (Hassan et al., 2024). According to Nyasapoh et al. (2022), providing affordable energy services by increasing energy efficiency and deploying renewable energy is the aim of Sustainable Development Goal 7 (SDG-7). This approach can facilitate global environmental stewardship by minimizing the carbon footprints of energy use while promoting economic growth and addressing the energy poverty challenges in marginalized countries. The International Energy Agency (IEA) (2023) further affirms that for the world to attain sustainability, global efforts must be directed toward developing robust structures to promote renewable energy developments, especially in developing countries. Gunnarsdóttir et al. (2021) also established the Energy Indicators for Sustainable Development (EISD), which give indicators for assessing the sustainability of energy resources, including availability, cost, and social and environmental impacts. They defined a sustainable energy resource as one with little or no environmental effect, such as GHG emissions, over its entire life cycle, with the ability to protect public health and promote social development. To make energy systems more sustainable, energy sources must be diversified and localized, and the environmental effects of each energy source used must be minimized. Non-renewable energy supplies, such as fossil energy, contribute considerably to climate change, necessitating a shift to more sustainable renewable energy, such as geothermal energy, solar energy, wind energy, hydropower energy, and biomass, among the most popular alternatives. Additionally, the aggravating and prevalent climate change caused by prolonged fossil fuel use is becoming critical, and several organizations are committing to limiting carbon footprints and their associated impact. In this context, the Paris Agreement aims to hold the global warming temperature rise to 2˚C with a view to limiting it further to 1.5˚C in the future above the pre-industrial level (Adun et al., 2024; Malode et al., 2021). As a result, renewable energy resources with low carbon emissions present a potential alternative to traditional fossil fuels in achieving SDG-7 (International Energy Agency, 2023).

2.2. Overview of Ghana's Biofuel Transition Journey

Ghana's biofuel transition journey dates back to 2003, when the National Jatropha Project was developed through Anuanom Industries Limited. The goal was to use feedstock from local small-scale farmers and large-scale industries to grow up to one million hectares of jatropha plants in 53 districts. This effort aimed to generate foreign exchange and local job opportunities through exporting biofuels and local consumption. The government intended to invest in upstream biofuel production by supplying Jatropha seedlings and extension support to smallholder farmers and directly purchasing the produce, giving farmers a ready market. The next stage was to collaborate with Anuanom Industries Limited to build a biorefinery to refine the feedstock and produce biodiesel, which would be used to fuel state vehicles. In 2005, Ghana's Energy Commission issued the first biofuel policy, which called for a 20% biodiesel mix (B20) in all government vehicles. In addition to the policy draft, the Biofuel Implementation Group (BIG) was established to oversee implementation. In 2006, the National Jatropha Planning Committee revised the biofuel policy to introduce a 5% bioethanol (E5) by 2010 and adjusted the biodiesel target to 10% (B10) by 2015. These biofuel blends were expected to be attained using jatropha feedstock for biodiesel production and cassava or sugarcane for bioethanol.

In 2010, the Energy Commission of Ghana again revised the biofuel policy, which targeted 10% of biofuels (E10, B10) by 2020 and 20% of both bioethanol (E20) and biodiesel (B20) by 2030. The policy, which is still in effect today, also established goals for lowering GHG emissions, creating competitive markets and regulatory support, and removing institutional barriers. In the medium to long term, the policy sought to transform Ghana into a net exporter of biofuels, attracting investors who purchased approximately 950,131 hectares of land for biofuel projects between 2006 and 2011. In 2010, biofuel projects accounted for approximately 4% of the country's total land area, 7% of its agricultural land, and 12% of its land under cultivation. 520 ha were purchased for sugarcane, 401,050 ha for oil palm, 20,790 ha for soy, 1210 ha for maize, and 526,561 ha for jatropha. However, most biofuel initiatives described were never carried out after the discovery of crude oil in 2008, while the political interest in promoting biofuels was significantly diminished (Ahmed et al., 2017).

Ghana's energy landscape has experienced a shift over time in terms of final energy use. Before 2011, biomass dominated Ghana's energy supply until oil replaced biomass as the principal fuel (Energy Commission of Ghana, 2023). Biomass remains an essential part of Ghana's energy mix even after the transition to oil, accounting for 32.4% of the total energy supply by 2022. Biomass resources in Ghana cover about 20.8 million hectares of the nation's 23.8 million-hectare land mass. Ghana's vast arable land is suitable for cultivating varied crops and plants that can be converted into a wide range of biofuels. Large amounts of agricultural by-products/residues that can be used for energy production are generated from agricultural activities in the country. However, the local household consumes approximately 20 million tonnes of biomass fuel annually. Most of that supply comes from natural forests used as charcoal and firewood, contributing to GHG emissions (Energy Commission of Ghana, 2023). In 2023, the government of Ghana, through the Ministry of Environment, Science, Technology, and Innovation, established the Ghana Energy Transition and Investment Plan (GET&IP) policy, which aims to achieve a climate goal of net-zero CO_2 emissions by 2060. The primary goal is to eliminate and replace fossil fuels with low-carbon energy solutions such as biofuels across all government sectors (Ministry of Environment, Science, Technology and Innovation, 2023). Furthermore, the IEA (2023) predicts that global oil consumption and prices will fall between 2023 and 2050. These estimates show a decrease in oil consumption and prices, which can be attributed to the growing importance of renewable energy sources, particularly biofuels, improvements in transportation efficiency, and increased environmental awareness.

2.3. Mathematical Modeling and Optimization in Energy Transition

In recent years, several researchers have contributed to developing highly efficient energy systems, particularly in renewable energy. There is so much uncertainty in renewable energy production that precise methodologies must be developed to avoid overestimation, which wastes resources, or underestimation, which may impact not only customer preferences but also the overall well-being of the population (Yue & You, 2016). Furthermore, large-scale biofuels production could have implications on food prices and land competition, since the production of biofuels plays a role in dictating the amount of food available for consumption (Ansah &

Ansah, 2022). Hence, demand forecasting, multi-scale modeling and optimization can address the food-energy nexus by facilitating informed decision making on operations, process design, supply chain management, and sustainability assessment to help alleviate feedstock shortages over time (Yue et al., 2014). Mathematical modeling and optimization are important tools for solving complex biofuel production and integration problems, as they reflect real-world systems that use mathematical frameworks to analyze, forecast, and optimize results. These models allow researchers, policymakers and industry practitioners to investigate the implications of biofuel policies, optimize resource allocation, and simulate various scenarios, resulting in more effective and efficient decision-making toward energy sustainability goals. Energy systems are constrained by conditions such as thermodynamic, socio-economic, and environmental factors; hence, mathematical models are a critical tool in energy system optimization. The complexity of an energy model is heavily influenced by the various components of an energy system as well as the mathematical representation used. Zahraee et al. (2020b) divided mathematical modeling and optimization methodologies for addressing biomass-to-biofuel supply chain (BSC) challenges into five categories, namely: (1) static analysis and modeling; (2) simulation modeling; (3) mathematical programming; (4) sustainability optimization; and (5) financial and political policy analysis.

3. Methodology

This research employs a case study technique within a thorough literature review framework to examine the role of mathematical modeling and optimization in achieving sustainable energy transition goals (SDG-7). The study's quantitative method of examining Ghana's biofuel transition target offers extensive statistical data to substantiate the findings and enhance the validity and dependability of the conclusions (Sarstedt & Mooi, 2014). The first section focuses on a systematic literature review (SLR) using an extensive bibliometric search to evaluate existing research and analyze trends in Ghana's biofuel sector (Objectives 1 and 2). The subsequent part, Section 2, concentrates on identifying gaps in the research trend by examining current studies in the area (goal 3). The last part offers a pragmatic guide by presenting a future study direction linked with global sentiments to navigate the research gaps (Objective 4). This approach will enable the research to provide an effective tool that aligns with its primary objective of evaluating the role of mathematical modeling and optimization in Ghana's renewable energy transition by contributing to achieving SDG-7.

3.1. Systematic Literature Review (SLR)

The SLR involves the analysis of pertinent published papers to provide a complete framework of Ghana's biofuel landscape by assessing the extent of mathematical modeling and optimization applications in tackling sustainability concerns. A bibliometric analysis approach was employed, which involves assessing and interpreting accessible research papers related to the study concept from different electronic database systems within the field. SLR aids in developing significant insights based on a theoretical synthesis of previous research and identifies probable gaps in the literature (Creswell & Poth, 2018).

The bibliometric analysis is based on a literature search from key academic and peer-reviewed databases relevant to the research area. Research on biofuels in Ghana published in the last decade (2014 to 2024) was sourced via Google Scholar, Web of Science, Science Direct, and general internet searches for data samples. A total of 104 papers were discovered as output by utilizing the following keywords: "biofuel" OR "bioenergy" OR "biomass", "sustainable energy" OR "renewable energy" AND "Ghana" on 27th December 2024. The keyword search was executed using a pairwise query that individually evaluated one term from each category. All articles were initially filtered by manually analyzing the abstracts of the chosen papers to exclude publications extraneous to the study. In all, 104 peer-reviewed papers published in English were obtained and analyzed comprehensively in this study.

Data Analysis

This section uses a grounded theory approach to examine the relationships and patterns among the dataset's categories (Creswell & Poth, 2018). In the 104 scientific publications chosen for the review study, the objective is to evaluate key themes and identify gaps in the literature. The data was analyzed, categorized, and visualized using an Excel spreadsheet and VOSViewer software. This method will assist in finding trends, patterns, and frequencies in the vast quantity of data found in the bibliometric search. Six key themes, viz., Keyword analysis, Publication trend, Journal contributions, Research focus, Sustainability objective and Mathematical modeling and optimization application, were used to aggregate and evaluate the analysis based on the core areas gathered from the literature.

Keyword Analysis

The VOSviewer application assessed the keyword occurrences in titles, abstracts and the keywords list provided by authors' published works, as depicted in **Figure 2**. The purpose is to identify the major themes of the research topic, highlight gaps, and identify areas that require additional focus. From the results, 211 author keywords were found across the 104 publications dataset sample, with 69.4% occurring once, while the remaining appeared several times (twice or more), demonstrating a broad diversity of interest in study themes. **Figure 2** illustrates the discovered keywords as circles, while the size of the circles reflects the frequency of publications, and the line connecting the circles shows links between the keywords. The most frequently used keywords from the analysis were Ghana, bioenergy, biomass, sustainable development, and agricultural residue, with 78.3% occurrences across the data set.

Publication Trends

Figure 3 shows the biofuel research in Ghana distribution over time from 2014 to 2024. Over the last decade, Ghana's biofuel research has seen an increasing number of articles published annually, with few irregularities. The number of published papers increased steadily between 2014 and 2016, increasing from 4 to 6, while in 2017 reduced to 3, representing the lowest (2.9%) number of articles published on the subject. From them, the number of published papers increased gradually until it peaked in 2021, recording 18 published papers (17.5%). Although the number of published papers reduced to 11 in 2022, the publication trend was maintained, increasing at a constant rate to 2024, which recorded 16 published papers (2.4%). This growing trend indicates that biofuel production is increasingly recognized as essential to the transition to sustainable energy. The increase in research publications after 2020 can intrinsically be linked to the global drive to transition to renewable energy sources as a rapid response to climate change (International Energy Agency, 2023). This trend confirms the findings by Afrane et al. (2021a) and Sun and Fan (2020) on renewable energy research trends in Sub-Saharan Africa and the rest of the world respectively, emphasizing

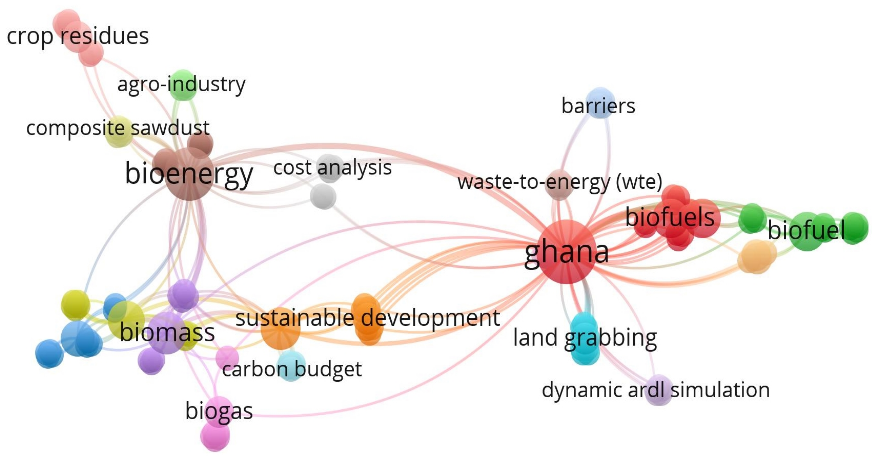

Figure 2. Thematic landscape of keyword occurrence. Source: Authors' Construct (2025).

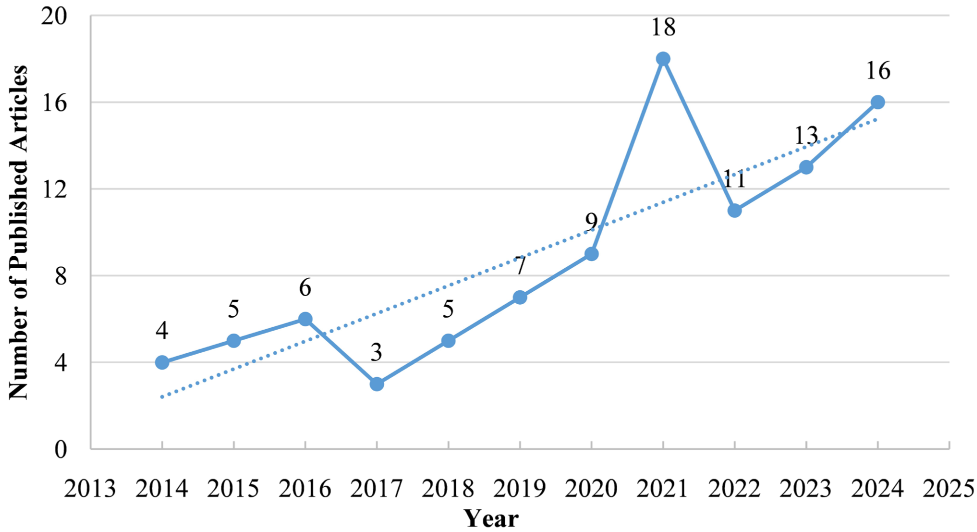

Figure 3. Review publication per year. Source: Authors' construct (2025).

that renewable energy is becoming increasingly recognized as a vital solution to the world's energy problems, especially in developing countries like Ghana.

Journal Contributions

The publication journal contributions were analyzed, summarized and presented in Figure 4. According to the study results, 33 journal publications contributed to this study of biofuels in Ghana. Renewable and Sustainable Energy Reviews became Ghana's premier source for biofuel research after publishing 19 papers (18.3%). The Journal of Cleaner Production is another prestigious publisher with 12 articles (11.5%) emphasizing sustainable industrial-process approaches. In demonstrating Ghana's contributions to the global discussion on biofuel production, Energies published 9 papers (8.7%), while Scientific African published 7 articles (6.7%), respectively. Overall, Ghana's biofuel research landscape is diverse and multi-disciplinary, as shown by the fact that a significant number of the articles (27.9%) are dispersed, with over 29 journals that only appeared once.

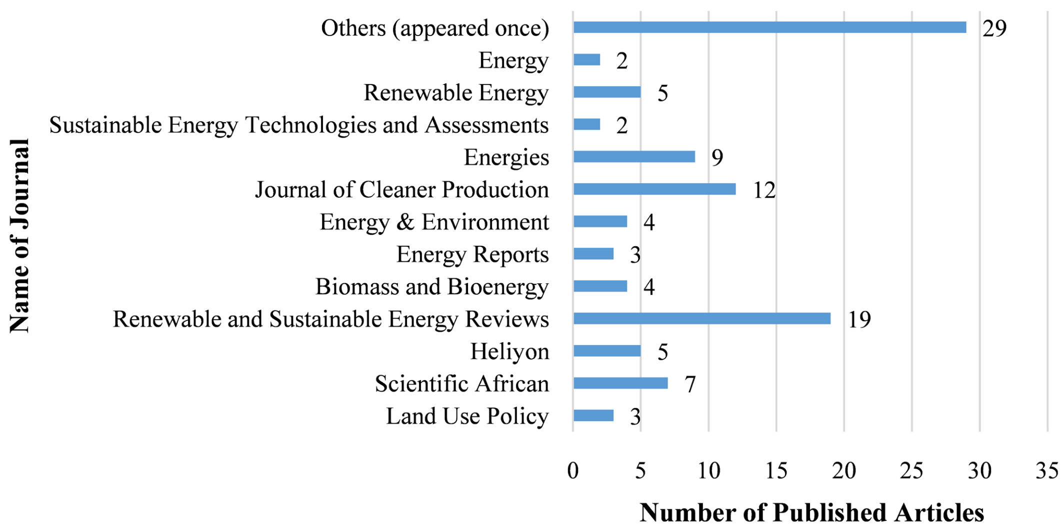

Figure 4. Reviewed journal contribution. Source: Authors Construct (2025).

Research Focus

The selected papers were categorized under the theme of Research Focus to identify prevalent subjects of interest among researchers and their interrelations with other renewable energy categories. This approach will facilitate identifying patterns and determining future research directions in Ghana's biofuel trajectory. The analysis of the study encompassed various topics; however, we organized them according to the most prominent discussion areas, as illustrated in Figure 5. Policy Analysis emerged as the predominant area of focus, encompassing 21 papers and accounting for 20.2% of the total. The researchers concentrated on the feasibility of attaining a 20% biofuel integration by 2030 and the Net-zero CO_2 emission goal by 2060, as outlined in the Bioenergy Policy (BEP) and the Ghana Energy Transition and Investment Plan (GET&IP), among other policies. Researchers emphasized the importance of strategic management and governance in developing resilient biofuel production systems. Feedstock Assessment was the second most prevalent subject of interest, comprising 12 papers (11.5%). In this area, scholars highlighted the importance of selecting a sustainable biofuel feedstock and stressed their availability in meeting the targeted 20% biofuel integration by 2030. Energy Use Assessment followed with 16 articles (15.4%), demonstrating interest in enhancing energy efficiency and lowering resource consumption. 11 publications (10.6%) were also evaluated from Experimental Studies. In this area, researchers demonstrated how biofuel technologies could be used in real-world settings by conducting laboratory experiments citing municipal wastes and agricultural residues across the country. Mathematical simulation and modeling appeared in 6 publications, representing 5.8%, while process optimization received 5 articles (4.8%). Despite being the most understudied topics, these areas are beneficial, especially as Ghana aims to establish an effective and sustainable biofuel industry. Finally, the analysis revealed that 27 publications (26.0%) addressed multi-focused/unspecific areas, which indicates a dispersed but multi-disciplinary approach to Ghanaian biofuel research.

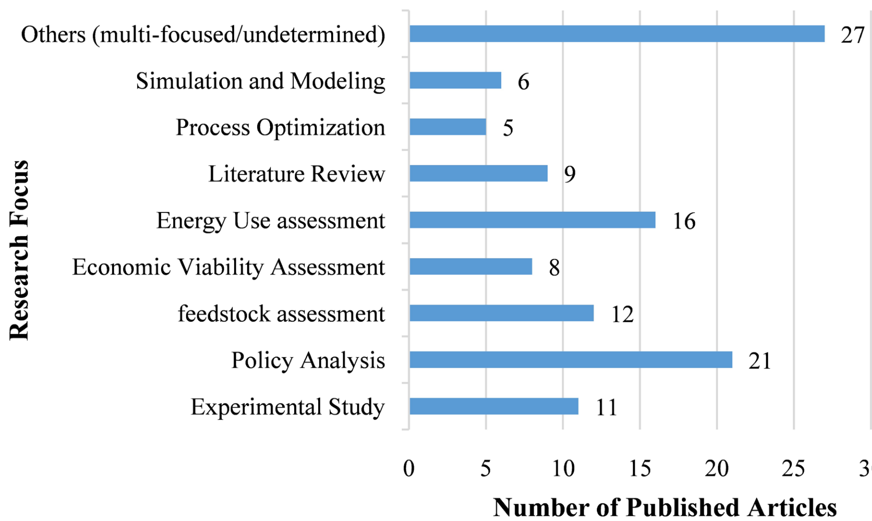

Figure 5. Review research focus. Source: Authors Construct (2024).

Sustainability Objective

Most authors were also very interested in the effects of biofuel production on sustainability. A large number of the qualifying articles connected the use of biofuel to one or more sustainability pillars, which are social, economic, and environmental. From the 104 reviewed papers, the mixed sustainability focus contributed most significantly, with 29 articles (47.5%) addressing various combinations of environmental, social, and economic dimensions. This emphasized the usefulness of integrated approaches to biofuel research, with specialization on sustainability considerations among the qualifying articles in Ghana, as shown in **Figure 6**. Specifically, the combined environmental and social sustainability focus represented the most research-interested area, with 36.1%. Environmental sustainability is the most emphasized individual pillar, appearing in 17 articles (27.9%), highlighting the priority placed on reducing carbon emissions and mitigating climate impacts using biofuels. The social and economic dimensions appear in 9 and 6 articles, respectively, while their combined interest revealed no publications in the area. Overall, 43 published papers analyzed within the study sample specified no sustainability objective, representing 41.3%, signalling a potential gap in addressing specific areas of specialization.

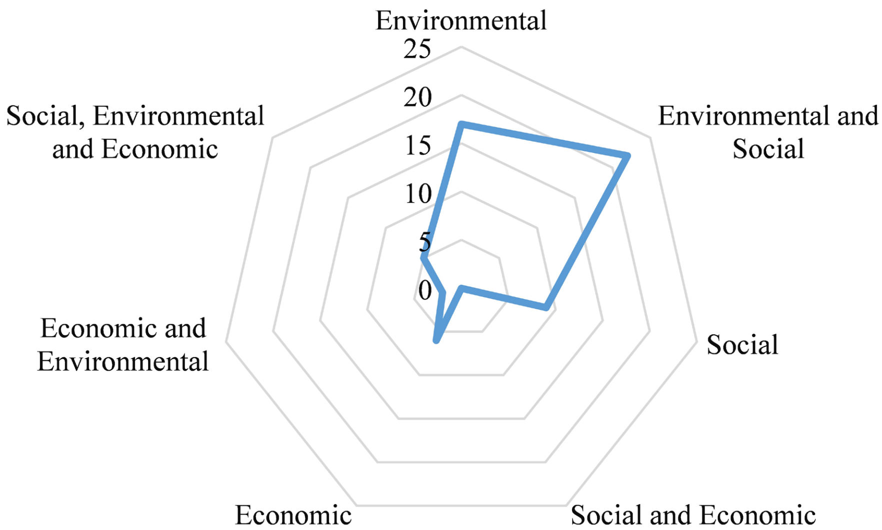

Figure 6. Sustainability focus. Source: Authors' Construct (2025).

Application of Mathematical Modeling and Optimization

As shown in **Figure 5**, comparatively fewer research papers (10.6%) of Ghana's biofuel research were devoted to mathematical simulation, modeling, and process optimization. **Table 1** lists the most research conducted on biofuel production using process optimization, modeling, and mathematical simulation. The classification used in **Table 1** was based on Zahraee et al. (2020b) theory of evaluating mathematical modeling in bioenergy and biofuel. The study applied categorizations such as financial and political policies in biomass supply and production systems, simulation modeling, mathematical programming, sustainability optimization, and static analysis and modeling. The application of these models covers comprehensively all the areas of the biomass-to-biofuel supply chain (BSC), which involves several operations from biomass cultivation, harvesting, pre-processing, transportation, handling, and storage (Ba et al., 2016). Overall, the most applied mathematical modeling and optimization tool was in Waste-to-Energy (WTE) technologies Analysis, which contributed widely to bioenergy research per the qualifying articles revealed in this study. The focus was on applying various mathematical optimization tools, such as multi-criteria decision-making (MCDM), in comparing the technologies and selecting optimal options for Ghana (Agbejule et al., 2021).

Table 1. Summary of publications with mathematical modeling and optimization.

Publication	Method Used	Focus Area	Key Findings
Akpahou et al., 2024	Optimization	Open-source energy modeling (OSeMOSYS tool)	The study proposed that renewable energy production in Ghana can account for over 50% of total electricity generation by 2070.
Adelesi et al., 2023	Simulation modeling	Economic model	Optimized resource allocation for smallholder mixed crop and livestock farming systems in Northern Ghana.
Afrane et al., 2022	Mathematical programming	Multi-criteria decision-making (MCDM)-integrated AHP-fuzzy TOPSIS	Anaerobic digestion was identified as the optimal waste-to-energy (WtE) technology for implementation in Ghana.
Ahmed et al., 2017	Simulations model	System dynamics model	Project the impact of large-scale biofuel feedstock cultivation on Ghana's food security.
Cudjoe et al., 2021	Static analysis	Demand forecasting and economic feasibility analysis.	Biogas from food waste is estimated to provide viable resources to achieve the 10% increase in renewable energy in the national electricity generation mix.
Bukari et al., 2021	Mathematical programming	Multi-criteria decision-making (MCDM)-AHP.	The ranking of renewable energy barriers in Ghana is categorized into political, economic, technical, social, and environmental dimensions.
Ossei-Bremang & Kamausuor, 2021	Mathematical programming	Multi-criteria decision-making (MCDM)-Fuzzy TOPSIS and AHP	The model identified animal manure as Ghana's most sustainable biomass resource for bioenergy production.
Agbejule et al., 2021	Mathematical programming	Multi-criteria decision-making (MCDM)-AHP	The study identified incineration as the most preferred waste-to-energy (WtE) technology in Ghana.
Afrane et al., 2021b	Mathematical programming	multi-criteria decision analysis (MCDA)-fuzzy TOPSIS	The model ranked gasification as Ghana's optimal waste-to-energy (WtE) technology option.
Agyenim et al., 2020	Mathematical programming	Multi-criteria decision-making (MCDM)	Assessed the feasibility of renewable energy technologies (RET) available in Ghana.
Okuley, 2019	Mathematical programming and statistical analysis	Multi-criteria decision-making (MCDM)-AHP and, TOPSIS, and GIS	The suitability of bioenergy crop production on marginal lands in Ghana was analyzed by choosing from several energy crops.
Singh et al., 2018	Static analysis	GIS-Based BSC Analysis	Techno-economic analysis was used to determine where Ghana's transportation sector's cellulosic ethanol production and distribution infrastructure should be located.
Iddrisu & Bhattacharyya, 2015	Simulation modeling	Econometric model	Forecasted demand for biofuel to achieve the targeted 20% transport fuel replacement in 2030
Kemausuor et al., 2015	Simulation modeling	Long-range energy alternatives planning (LEAP) model	The LEAP model assessed the impact of bioenergy on Ghana's energy mix from 2015 to 2030.

Source: Authors' Construct (2025).

4. Review Findings and Discussion

4.1. Interpretation of Findings

Minimizing anthropogenic greenhouse gas (GHG) emissions linked to fossil fuel use is essential due to their harmful impacts on human health and the environment, especially regarding climate change. Additionally, the urgent need for energy security demands immediate action. This has prompted numerous initiatives, including global research in renewable energy (Agyekum et al., 2021). Bioenergy research has seen a significant increase globally over the past few decades, as demonstrated by studies from Zubairu et al. (2024), Alizadeh et al. (2020), Sun & Fan (2020), and Hasan et al. (2023). The global pursuit of sustainable energy alternatives increases the demand for renewable energy research, focusing predominantly on solar, wind, hydro, and bioenergy. Biofuels specifically were given particular attention due to their potential as substitutes for fossil fuels in transportation. Afrane et al. (2021a) demonstrated that Sub-Saharan Africa has seen a rise in publications linked to the advancement of renewable energy projects and the UN's promotion of the Access to Clean Energy (SDG-7) initiative. Ghana is ranked among the top three countries with a significant interest in renewable energy, alongside South Africa, Nigeria, Algeria, Ethiopia, Morocco, Kenya, Egypt, Cameroon, and Tunisia, representing significant nations on the African continent. Consequently, Ghana's advancement in renewable energy transition significantly influences the region's energy landscape. Although Ghana's installed renewable energy capacity remains relatively low compared to leading nations such as South Africa, Nigeria, Egypt, Kenya, and Ethiopia, the country demonstrates strong performance in establishing policies and frameworks that promote incentives and support for renewable energy development. However, the studies on bioenergy present mixed feelings.

Even though bioenergy is a key renewable energy resource within Sub-Saharan Africa, it has received less attention in terms of publication than solar power, wind energy and hydropower (Afrane et al., 2021a). Despite the vast availability of biomass resources in the region, they are mainly used as firewood, raising questions about their production's sustainability and efficiency. The research landscape focuses more on converting biomass into other cleaner forms, particularly biofuel (Sparkman et al., 2023). Challenges with biofuels in Sub-Saharan Africa can be attributed to their production rather than research since their production demands tremendous effort in strategic decision-making within a technological and technical framework and financial investments (Tesfamichael et al., 2021). Conversely, researchers on biofuel studies globally focus on concepts directly related to sustainable development goals (SDGs) and driving development through the green economy. Large-scale biofuel production can effectively be harnessed if research focuses on the technology coupled with applying mathematical models, computer simulations and optimization models, especially when detailed operations and/or multi-period are considered (Ba et al., 2016).

This study specifically focuses on the role of mathematical modeling and optimization in propelling the progress toward the transition of renewable energy as a viable solution to the universal access to clean and affordable energy goal (SDG-7). The study focuses specifically on biofuels in Ghana and is consistent with the global trend of increasing renewable energy research over the past decade, as illustrated in **Figure 3**. Furthermore, it signifies an increased focus on biofuels as an essential component of Ghana's sustainable energy transition strategy to tackle the pressing challenges of climate change, energy security, and sustainable development. This study's increasing body of literature advocates for cleaner, greener energy options and is consistent with global trends. International and local policy initiatives, including the UN's Sustainable Development Goals, the Ghana Energy Transition and Investment Plan (GET&IP) and the Bioenergy Policy (BEP), are revealed in most studies as the primary drivers for this trend. In addition, these regulations further foster a conducive atmosphere for investment, research, and innovation, which helps develop biofuel technology.

A delve deeper into Ghana's biofuel research landscape shows diverse empirical studies focusing on themes including sustainable development, biomass feedstock assessment, agricultural residual value, waste-to-energy (WtE) feasibility studies and bioenergy experimental research. These studies, typically published in journals with international recognition (see **Figure 4**), show how actively Ghanaian experts tackle the global energy challenges. Overall, municipal solid waste (MSW), agricultural residues, and other second-generation biomass, representing a sustainable feedstock for biogas, bioethanol, and biodiesel have garnered considerable attention. Furthermore, bioenergy production in Ghana has been recognized throughout the research as a more sustainable alternative to achieving the Universal Access to Clean and Affordable Energy (SDG-7) goal, primarily due to its socio-economic and environmental benefits. Biofuel production, in particular, can boost Ghana's long-term development by creating jobs and income opportunities through agribusiness (social), reducing environmental pollution and municipal waste (environmental), and promoting rural economic growth (Nelson et al., 2021). This Study on Ghana's biofuel landscape also underscores the importance of advancing social equity, economic resilience, and environmental preservation. As shown in **Figure 5**, some key focus areas for researchers are policy analysis, feedstock assessment, energy use assessment, experimental study, simulation and modeling, and process optimization. Throughout the study, policy analysis research explicitly encompassing locally accessible and sustainable raw materials for biofuel production dominated. However, studies on application mathematical modeling and optimization revealed the least explored area of interest for scholars. This significant gap aligned with Ahmed et al. (2017) findings, which indicated weak business planning, the pre-existing socioeconomic challenges, such as food insecurity and land management, as major bottlenecks to biofuel development in Ghana, while they could be addressed effectively using mathematical modeling and optimization.

Mathematical modeling and optimization studies offered important insights into improving biofuel technology and strategies for integrating it into the nation's energy mix. Studies that addressed sustainability's economic, environmental, and social pillars used these approaches, albeit sparingly, as illustrated in **Fig-**

ure 6. Ghana's biofuel research landscape covers mathematical techniques such as demand forecasting, econometric modeling, location analysis utilizing GIS tools, and multi-criteria decision-making (MCDM). MCDM was used to determine the priorities for investments in feedstock and production technologies, econometric models evaluated the effect of biofuel regulations on energy market dynamics, and demand forecasting guarantees efficient resource management throughout the analysis. GIS-based location evaluations also help determine the best location for infrastructure to reduce costs and increase supply chain efficiency. In general, the use of mathematical modeling and optimization tools for biofuel research in Ghana's biofuel landscape was dominated by multi-criteria decision-making (MCDM) techniques such as fuzzy-TOPSIS, Analytic Hierarchy Process (AHP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

By bridging the gap between theoretical research and practical application, this bibliometric study of Ghana's biofuel landscape highlights how biofuel projects match Sustainable Development Goal (SDG) 7, which focuses on affordable and clean energy. It also emphasizes the need for mathematical modeling and optimization to achieve Ghana's energy transition objectives. Integrating sustainability concepts into quantitative frameworks offers these studies valuable insights to industry stakeholders and policymakers.

4.2. Research Gaps

A transition to renewable energy is necessary to meet the Sustainable Development Goals (SDGs), particularly SDG 7, which focuses on affordable and clean energy. During this transition, the three pillars of sustainability, viz., economic, environmental, and social, must be equally addressed in an integrated manner (International Energy Agency, 2023). There is a significant research gap, as 41.3% of biofuel research in Ghana deals with bioenergy without any specialization or targeted sustainability emphasis. This suggests that more thorough research is required to connect biofuel development to sustainability metrics and real-world challenges. Additionally, there is a need for more focus on mathematical simulation, modeling, and process optimization, especially as this review has flagged their underutilization, covering only 10.6% of Ghana's biofuel research. There is a wide range of unexplored mathematical modeling and optimization techniques that can help address the various challenges identified in Ghana's biofuel integration journey. Although multi-criteria decision-making (MCDM) techniques were used in Ghana's biofuel landscape, their application was limited only to TOPSIS, AHP, and fuzzy-TOPSIS in addressing waste-to-energy (WtE) technology assessment, leaving gaps for their alternative applications within the biomass-to-biofuel supply chain (BSC), including transportation and logistics optimization, optimal facility location analysis, technology and process analysis, and sustainability focus.

Furthermore, mathematical models and optimization methodologies can help Ghana's biofuel industry address sustainability challenges at multiple scale planning levels, including strategic, tactical, and operational planning. These holistic approaches can help to make accurate decisions throughout the BSC's planning stages. This includes upstream, midstream, and downstream production levels such as biomass feedstock production, pre-processing, biorefinery, storage, and distribution (Yue et al., 2014). To navigate the economic challenge of biofuel infrastructure's capital-intensive nature within a developing country's framework, it would be critical to consider integrating the existing petroleum supply chain into the network design in Ghana's BSC strategic planning (Tesfamichael et al., 2021). Although several studies have highlighted Ghana's abundance of first-generation feedstocks for biofuel production, there is a need to focus on unconventional feedstocks, while optimizing land use for feedstock production can address food-energy nexus issues. In the collection and transportation of feedstock for biofuel production, logistics sustainability modeling, such as multi-objective optimization modeling combined with life cycle assessment (LCA), can reduce GHG emissions while increasing cost-effectiveness. In developing biorefineries for biomass and waste processing, process optimization models can effectively improve the energy efficiency of biofuel production facilities, promoting climate action (SDG 13). Economically, cost analysis models may help inform policy decisions by assessing the subsidies or incentives required to increase biofuel use (Sun & Fan, 2020; Zahraee et al., 2020b). These areas demonstrate how mathematical modeling and optimization can accelerate Ghana's transition to renewable energy by bridging the gap between research and real-world applications.

4.3. Proposed Framework for Future Research

Several challenges limit the large-scale use of biofuels in Sub-Saharan Africa, including limited infrastructure, financial constraints, food-energy nexus, land-use disputes, and the novelty of biofuel systems in developing countries. Designing hybrid networks that integrate biofuel supply chains with existing fossil fuel infrastructures necessitates an innovative approach that considers the application of mathematical modeling and optimization (Tesfamichael et al., 2021). Future research in Ghana's biofuel industry could strategically target the following key areas to research gaps and promote a sustainable energy transition.

4.3.1. Analysis of Biomass-to-Biofuel Supply Chain (BSC)

The biomass-to-biofuel supply chain (BSC) is an integrated whole that must be thoroughly examined, even if one component overlaps another (Sun & Fan, 2020). A thorough analysis of the entire BSC is critical, and it involves biomass harvesting, storage, pre-processing, transportation, biorefinery, and final biofuel use. At each stage of the supply chain, it is necessary to effectively evaluate the application of mathematical models that can optimize in a way consistent with the country's overall strategic plan. A BSC must also be designed to be cost-effective, environmentally sustainable, and meet local energy regulations (Yue et al., 2014).

4.3.2. Planning Decisions for Biomass-to-Biofuel

Future research may focus on strategic, tactical, and operational planning decisions made along the biofuel supply chain. Strategic-level models may handle long-term decisions like feedstock selection, network design and biorefinery site selection and technology, transportation modes used, and long-term supply contracts. Tactical-level models may optimize medium-term planning, such as procurement strategies and seasonal harvesting plans. At the operational level, real-time models could streamline repetitive processes like managing biorefineries and scheduling transportation routes. To enhance decision-making across several planning horizons, mathematical optimization modeling techniques such as mixed-integer linear programming (MILP), linear programming (LP), nonlinear programming (NLP), heuristic and metaheuristics, and stochastic optimization may be applied. Simulation modeling can also be applied to various BSC planning decisions on process analysis and economic calculations to evaluate costs, energy consumption and GHG emissions. A wide range of simulation models including the Integrated Biomass Supply Analysis and Logistics (IBSAL), Biomass Logistics Computer Simulation (BIOLOGICS), Straw Handling Model (SHAM), Long-range Energy Alternative Planning System (LEAP), Biomass Logistics and Environmental Impact Model (BLEM), Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET), BioScope, BeWhere and are also efficient, widely used for large and complex supply chains can be modeling allowing the opportunity for dynamics appraisal (Zahraee et al., 2020b; Ba et al., 2016). Zahraee et al. (2020a) applied GREET to develop a combined life cycle and dynamic simulation model to investigate water-energy nexus under uncertainties, as well as estimation of GHG and particulate matter emissions of the BSC in Malaysia, with practical application in Ghana's case.

4.3.3. Sustainability Metrics Modeling

Sustainability modeling is crucial for evaluating and improving biofuel systems' economic, social, and environmental aspects. Future research may employ lifecycle assessment (LCA) models to quantify the carbon footprint associated with biofuel production and analyze the socio-economic status of smallholder farmers in BSC. Multi-objective optimization models may be used to balance trade-offs between cost, emissions reduction, and the creation of rural jobs to guarantee that biofuel projects offer a comprehensive contribution to sustainable development (Sun & Fan, 2020).

4.3.4. Modeling for Performance Evaluation

Future studies can focus on assessing biofuel systems in various supply chain and operations management scenarios, utilizing various performance evaluation methods. The theory of industrial performance measurement and management systems (PMM) may provide a comprehensive framework that can enhance decision systems' effectiveness and resilience. Key Activity Indicators (KAI) specific to bioenergy industrial and research sectors would need to be added to the PMM. Key Activity Indicators (KAIs) and Lean Manufacturing, as well as the Toyota Production System (TPS), are popular methods for achieving operational excellence

(Fantozzi et al., 2022). Other performance assessment methodologies include data envelopment analysis (DEA), which may be used to measure the efficiency of various biorefineries while finding best practices and areas for development. Stochastic simulation models can evaluate supply chain performance under uncertain conditions, such as fluctuating market demand or feedstock availability (Yue et al., 2014). Future studies should also make space for uncertainties in other model variables, such as biomass quality, product demand, equipment failure and repair times, and prices. To obtain this, the probability distribution functions for uncertain factors could be predicted and incorporated into the models (Zahraee et al., 2020b).

4.3.5. Emerging Fields of Study

Beyond these areas of emphasis, future studies may investigate cutting-edge subjects like combining biofuels with the current conventional petroleum infrastructure and other renewable energy sources, like wind or solar, to provide hybrid energy solutions. Artificial intelligence (AI) and machine learning (ML) algorithms may also improve decision-making at all supply chain levels, forecast feedstock availability, and optimize manufacturing procedures. The effects of trade restrictions, carbon taxes, and subsidies on the competitiveness of biofuels may also be examined using policy modeling.

5. Conclusion, Research Significance and Recommendations

5.1. Conclusion

Renewable energy technologies have their challenges and opportunities. Bioenergy presents a unique opportunity to combat climate change caused by greenhouse gas emissions associated with prolonged fossil fuel use. Biofuel, in particular, can reduce reliance on fossil fuels in transportation without replacing the engine or machinery, making it a preferred and sustainable energy resource. The transition to biofuels can support the Sustainable Development Goals by providing a clean energy resource with minimal GHG emissions, promoting public health and climate change mitigation actions (SDG 7, 3 and 13, respectively). For developing countries, their contribution to fostering rural infrastructural development and employment to reduce poverty (SDG 9,8 and 1, respectively) are added advantage. However, the rapid expansion of biofuel production may result in a food-energy nexus over land usage, leading to high food prices and hunger, which contradicts SDG-2 (Zero hunger). Large-scale biofuel production confronts challenges, such as limited resources, land management, supply chain disruptions, high initial capital expenditures, and inadequacies in the legal and technical frameworks. Mathematical modeling and optimization have wide applications in addressing challenges related to supply chain optimization, performance assessment, and sustainability modeling and these challenges. Their application in multi-level planning and support biofuel supply chain planning on tactical, strategic, and operational levels and addressing a wide range of challenges.

This study applies bibliometric analysis to survey Ghana's biofuel research landscape and revealed limited use of mathematical modelling and optimization to address these challenges, resulting in a significant gap in biofuel implementation in the country. Using decision-support tools like demand forecasting, multi-criteria decision-making, and econometric modeling, policymakers and stakeholders may make well-informed choices that optimize biofuels' economic, environmental, and social benefits. Biofuels can significantly transform Ghana's energy landscape and contribute to developing a more resilient and sustainable energy system. However, realizing this potential requires a concerted effort to address current problems, invest in research and capacity-building, and implement comprehensive policies. This study lays the groundwork for future research and strategic planning while highlighting mathematical modeling and optimization's critical role in the growth of Ghana's biofuel economy. Ghana can transform its sustainable energy environment and promote economic growth and environmental stewardship by incorporating these principles into its national energy strategy.

5.2. Significance of the Study

Biofuels have real economic, social and environmental implications. The in-depth bibliometric analysis of the sustainable biofuel landscape of Ghana revealed gaps in biofuel production in Ghana. This study provides up-to-date, consistent and reliable data to achieve its objective. The study's results confirm that Ghana's key to sustainable energy transition is contingent on the smooth transition to biofuels, which can address the challenges with fossil fuel use. While several policies and innovative experimental research have been developed over the past decade, the country still lacks the unique application of mathematical modeling and optimization in addressing the challenges with biofuel production and sustainable energy transition. This study has far-reaching implications by providing valuable information for academics, industry players, and government officials seeking to promote biofuel development in Ghana. The paper strongly emphasizes the importance of mathematical modeling and optimization in improving resource allocation, supply chain efficiency, sustainability, and the potential for biofuels to support SDG 7 and other interconnected SDGs, such as SDGs 8, 9, and 13. More investment in cutting-edge technology, capacity building through training, and legislative frameworks are required to realize biofuels' potential fully. The study emphasizes the importance of a multi-level planning strategy that includes strategic, tactical, and operational decisions to overcome challenges such as resource constraints, significant initial investment, and infrastructure issues. The outcome of this study can offer a reliable pathway to inform Ghana's national energy policy development, especially support biofuel integration, and establish them as a significant force behind the nation's socio-economic growth and sustainable energy transition.

5.3. Recommendations

To propel the shift to renewable energy (RE), this study highlights the pressing need for cleaner, more sustainable energy supply chains. The study result offers a strategic framework for practitioners and policymakers to maximize the performance of the biofuel supply chain by recognizing biofuels as a feasible renewable energy source for Ghana. The analysis in this study identifies important elements that significantly influence the uptake and effectiveness of biofuel systems, including infrastructure, land availability, subsidies, technical developments, policy and regulatory assistance, and more. These underlying challenges either facilitate or impede the development of renewable energy; thus, careful consideration is recommended to enable the sustainable implementation of biofuel projects. Furthermore, we recommend investing in cutting-edge biofuel technology, particularly researcher training in computer simulations, mathematical modeling, and optimization, which should be explicitly tailored to Ghana's resource availability and geographic setting. A comprehensive planning strategy that includes operational, tactical, and strategic decision-making levels is recommended to address current challenges in biomass sourcing, processing, and distribution.

Although the study focuses on Ghana's biofuel industry, other Sub-Saharan African countries with comparable energy and sustainability requirements may generally benefit from its conclusions, and it is recommended that they align with their specific needs. Global energy stakeholders may use this study as a roadmap to optimize biofuel production systems, which will eventually help create a cleaner, more sustainable energy future. The study also lays a strong foundation for other renewable energy resources by recommending cutting-edge mathematical modeling and optimization technologies that can effectively support the clean energy transition in areas such as fuel cells, hydrogen, and carbon capture and storage. Countries all across the globe may increase the economic, social, and environmental advantages of RE systems by using the suggested future research framework recommended in this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Adelesi, O. O., Kim, Y., Webber, H., Zander, P., Schuler, J., Hosseini-Yekani, S. et al. (2023). Accounting for Weather Variability in Farm Management Resource Allocation in Northern Ghana: An Integrated Modeling Approach. *Sustainability, 15,* Article No. 7386. https://doi.org/10.3390/su15097386

Adun, H., Ampah, J. D., Bamisile, O., & Hu, Y. (2024). The Synergistic Role of Carbon Dioxide Removal and Emission Reductions in Achieving the Paris Agreement Goal. *Sustainable Production and Consumption, 45,* 386-407. https://doi.org/10.1016/j.spc.2024.01.004

Adusah-Poku, F., & Takeuchi, K. (2019). Energy Poverty in Ghana: Any Progress So Far? *Renewable and Sustainable Energy Reviews, 112,* 853-864. https://doi.org/10.1016/j.rser.2019.06.038

Afrane, S., Ampah, J. D., & Aboagye, E. M. (2021a). Investigating Evolutionary Trends and Characteristics of Renewable Energy Research in Africa: A Bibliometric Analysis from 1999 to 2021. *Environmental Science and Pollution Research, 29,* 59328-59362.

https://doi.org/10.1007/s11356-022-20125-0

Afrane, S., Ampah, J. D., Agyekum, E. B., Amoh, P. O., Yusuf, A. A., Fattah, I. M. R. et al. (2022). Integrated AHP-TOPSIS under a Fuzzy Environment for the Selection of Waste-to-Energy Technologies in Ghana: A Performance Analysis and Socio-Enviro-Economic Feasibility Study. *International Journal of Environmental Research and Public Health, 19,* Article No. 8428. https://doi.org/10.3390/ijerph19148428

Afrane, S., Ampah, J. D., Jin, C., Liu, H., & Aboagye, E. M. (2021b). Techno-Economic Feasibility of Waste-to-Energy Technologies for Investment in Ghana: A Multicriteria Assessment Based on Fuzzy TOPSIS Approach. *Journal of Cleaner Production, 318,* Article ID: 128515. https://doi.org/10.1016/j.jclepro.2021.128515

Agbejule, A., Shamsuzzoha, A., Lotchi, K., & Rutledge, K. (2021). Application of Multi-Criteria Decision-Making Process to Select Waste-to-Energy Technology in Developing Countries: The Case of Ghana. *Sustainability, 13,* Article No. 12863. https://doi.org/10.3390/su132212863

Agyekum, E. B., Amjad, F., Mohsin, M., & Ansah, M. N. S. (2021). A Bird's Eye View of Ghana's Renewable Energy Sector Environment: A Multi-Criteria Decision-Making Approach. *Utilities Policy, 70,* Article ID: 101219. https://doi.org/10.1016/j.jup.2021.101219

Agyenim, F. B., Dzamboe, P. D., Mohammed, M., Bawakyillenuo, S., Okrofu, R., Decker, E. et al. (2020). Powering Communities Using Hybrid Solar-Biogas in Ghana, a Feasibility Study. *Environmental Technology & Innovation, 19,* Article ID: 100837. https://doi.org/10.1016/j.eti.2020.100837

Ahmed, A., Campion, B. B., & Gasparatos, A. (2017). Biofuel Development in Ghana: Policies of Expansion and Drivers of Failure in the Jatropha Sector. *Renewable and Sustainable Energy Reviews, 70,* 133-149. https://doi.org/10.1016/j.rser.2016.11.216

Akpahou, R., Johson, J.E., Aboagye, E., & Plazas-Niño, F.A. (2024). *Long-Term Energy System Modelling in Developing Countries: An Open-Source Optimization Approach for Energy Transition Analysis in Ghana*.

Alizadeh, R., Lund, P. D., & Soltanisehat, L. (2020). Outlook on Biofuels in Future Studies: A Systematic Literature Review. *Renewable and Sustainable Energy Reviews, 134,* Article ID: 110326. https://doi.org/10.1016/j.rser.2020.110326

Ansah, I., & Ansah, J.P. (2022). Evaluating the Impact of Large-Scale Cultivation of Biofuel Feedstock on Food Security in Ghana: A Modelling Study. *Journal of Agriculture and Food Sciences, 6,* 1-19.

Asongu, S. A., & Odhiambo, N. M. (2020). Economic Development Thresholds for a Green Economy in Sub-Saharan Africa. *Energy Exploration & Exploitation, 38,* 3-17. https://doi.org/10.1177/0144598719835591

Ba, B. H., Prins, C., & Prodhon, C. (2016). Models for Optimization and Performance Evaluation of Biomass Supply Chains: An Operations Research Perspective. *Renewable Energy, 87,* 977-989. https://doi.org/10.1016/j.renene.2015.07.045

British Petroleum (BP) (2019). *BP Energy Outlook*. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf

Bukari, D., Kemausuor, F., Quansah, D. A., & Adaramola, M. S. (2021). Towards Accelerating the Deployment of Decentralised Renewable Energy Mini-Grids in Ghana: Review and Analysis of Barriers. *Renewable and Sustainable Energy Reviews, 135,* Article ID: 110408. https://doi.org/10.1016/j.rser.2020.110408

Creswell, J. W., & Poth, C. N. (2018). *Research Design: Qualitative and Quantitative Approaches* (4th ed.). Sage.

Cudjoe, D., Nketiah, E., Obuobi, B., Adu-Gyamfi, G., Adjei, M., & Zhu, B. (2021). Forecasting the Potential and Economic Feasibility of Power Generation Using Biogas from Food Waste in Ghana: Evidence from Accra and Kumasi. *Energy, 226,* Article ID: 120342. https://doi.org/10.1016/j.energy.2021.120342

Dahunsi, S. O., Fagbiele, O. O., & Yusuf, E. O. (2020). Bioenergy Technologies Adoption in Africa: A Review of Past and Current Status. *Journal of Cleaner Production, 264,* Article ID: 121683. https://doi.org/10.1016/j.jclepro.2020.121683

Ebadian, M., McMillan, J., & Saddler, J. (2021). *Commercializing Conventional and Advanced Transport Biofuels from Biomass and Other Renewable Feedstocks.*

Energy Commission of Ghana (2010). *Ghana Bioenergy Policy Draft.* (61 p.).

Energy Commission of Ghana (2023). *2024 Energy (Supply and Demand) Outlook for Ghana* (95 p.). Annual Report.

Fantozzi, I. C., Di Luozzo, S., & Schiraldi, M. M. (2022). Industrial Performance Measurement Systems Coherence: A Comparative Analysis of Current Methodologies, Validation and Introduction to Key Activity Indicators. *Applied Sciences, 13,* Article No. 235. https://doi.org/10.3390/app13010235

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., & Sigurgeirsdottir, S. (2021). It Is Best to Ask: Designing a Stakeholder-Centric Approach to Selecting Sustainable Energy Development Indicators. *Energy Research & Social Science, 74,* Article ID: 101968. https://doi.org/10.1016/j.erss.2021.101968

Hasan, M., Abedin, M. Z., Amin, M. B., Nekmahmud, M., & Oláh, J. (2023). Sustainable Biofuel Economy: A Mapping through Bibliometric Research. *Journal of Environmental Management, 336,* Article ID: 117644. https://doi.org/10.1016/j.jenvman.2023.117644

Hassan, Q., Viktor, P., J. Al-Musawi, T., Mahmood Ali, B., Algburi, S., Alzoubi, H. M. et al. (2024). The Renewable Energy Role in the Global Energy Transformations. *Renewable Energy Focus, 48,* Article ID: 100545. https://doi.org/10.1016/j.ref.2024.100545

Iddrisu, I., & Bhattacharyya, S. C. (2015). Ghana's Bioenergy Policy: Is 20% Biofuel Integration Achievable by 2030? *Renewable and Sustainable Energy Reviews, 43,* 32-39. https://doi.org/10.1016/j.rser.2014.10.066

International Energy Agency (IEA) (2023). *World Energy Outlook* (355 p.). OECD Publishing.

Kamasa, K. (2020). Do Crude Oil Price Changes Affect Economic Welfare? Empirical Evidence from Ghana. *Ghana Mining Journal, 20,* 51-58. https://doi.org/10.4314/gm.v20i1.6

Kemausuor, F., Nygaard, I., & Mackenzie, G. (2015). Prospects for Bioenergy Use in Ghana Using Long-Range Energy Alternatives Planning Model. *Energy, 93,* 672-682. https://doi.org/10.1016/j.energy.2015.08.104

Kipkoech, R., Takase, M., & Amankwa Afrifa, E. K. (2022). Renewable Energies in Ghana in Relation to Market Condition, the Environment, and Food Security. *Journal of Renewable Energy, 2022,* Article ID: 8243904. https://doi.org/10.1155/2022/8243904

Leal Filho, W., Tripathi, S. K., Andrade Guerra, J. B. S. O. D., Giné-Garriga, R., Orlovic Lovren, V., & Willats, J. (2019). Using the Sustainable Development Goals towards a Better Understanding of Sustainability Challenges. *International Journal of Sustainable Development & World Ecology, 26,* 179-190. https://doi.org/10.1080/13504509.2018.1505674

Malode, S. J., Prabhu, K. K., Mascarenhas, R. J., Shetti, N. P., & Aminabhavi, T. M. (2021). Recent Advances and Viability in Biofuel Production. *Energy Conversion and Management: X, 10,* Article ID: 100070. https://doi.org/10.1016/j.ecmx.2020.100070

Mawusi, S. K., Shrestha, P., Xue, C., & Liu, G. (2023). A Comprehensive Review of the

Production, Adoption and Sustained Use of Biomass Pellets in Ghana. *Heliyon, 9,* e16416. https://doi.org/10.1016/j.heliyon.2023.e16416

Ministry of Energy (2021). *National Energy Policy* (144 p.).

Ministry of Environment, Science, Technology and Innovation (MESTI) (2023). *Ghana Energy Transition and Investment Plan* (44 p.).

Morone, P., & Cottoni, L. (2016). Biofuels: Technology, Economics, and Policy Issues. In R. Luque, C. S. K. Lin, K. Wilson, & J. Clark (Eds.), *Handbook of Biofuels Production Processes and Technologies* (2nd ed.). Elsevier.

National Petroleum Authority of Ghana (NPA) (2023). *Downstream Petroleum Industry Report-Third Quarter, 2023* (20 p.). Research Department of NPA.

Nelson, N., Darkwa, J., Calautit, J., Worall, M., Mokaya, R., Adjei, E. et al. (2021). Potential of Bioenergy in Rural Ghana. *Sustainability, 13,* Article No. 381. https://doi.org/10.3390/su13010381

Nyarko, I., Nwaogu, C., Diagi, B. E., & Hájek, M. (2024). The Dynamics and Potential of Carbon Stocks as an Indicator of Sustainable Development for Forest Bioeconomy in Ghana. *Forests, 15,* Article No. 256. https://doi.org/10.3390/f15020256

Nyasapoh, M. A., Elorm, M. D., & Derkyi, N. S. A. (2022). The Role of Renewable Energies in Sustainable Development of Ghana. *Scientific African, 16,* e01199. https://doi.org/10.1016/j.sciaf.2022.e01199

Okuley, A. (2019). *Assessment of Biofuel Potential on Marginal Lands and from Waste Vegetable Oil Resources in a Ghana*. Master's Thesis, PAUWES.

Ossei-Bremang, R. N., & Kemausuor, F. (2021). A Decision Support System for the Selection of Sustainable Biomass Resources for Bioenergy Production. *Environment Systems and Decisions, 41,* 437-454. https://doi.org/10.1007/s10669-021-09810-6

Sarstedt, M., & Mooi, E. (2014). *A Concise Guide to Market Research: The Process, Data, and Methods Using IBM SPSS Statistics* (2nd ed., 347 p.). Springer.

Singh, R., Kemausuor, F., & Wooldridge, M. (2018). Locational Analysis of Cellulosic Ethanol Production and Distribution Infrastructure for the Transportation Sector in Ghana. *Renewable and Sustainable Energy Reviews, 98,* 393-406. https://doi.org/10.1016/j.rser.2018.09.017

Sparkman, M., Tobin, W., & Zandi, M. (2023). *Policy Sprint: Building a Biofuels Industry in Africa* (12 p.). The Atlantic Council.

Sun, O., & Fan, N. (2020). A Review on Optimization Methods for Biomass Supply Chain: Models and Algorithms, Sustainable Issues, and Challenges and Opportunities. *Process Integration and Optimization for Sustainability, 4,* 203-226. https://doi.org/10.1007/s41660-020-00108-9

Tesfamichael, B., Montastruc, L., Negny, S., & Yimam, A. (2021). Designing and Planning of Ethiopia's Biomass-to-Biofuel Supply Chain through Integrated Strategic-Tactical Optimization Model Considering Economic Dimension. *Computers & Chemical Engineering, 153,* Article ID: 107425. https://doi.org/10.1016/j.compchemeng.2021.107425

Tetteh, A., & Fraser, G. (2025). Using Mixed Integer Linear Programming to Integrate Biofuel into Ghana's Petroleum Supply Chain for Sustainable Energy Transition. *International Journal of Engineering Business Management, 17.* https://doi.org/10.1177/18479790251343931

Tian, J., Culley, S. A., Maier, H. R., & Zecchin, A. C. (2024). Is Renewable Energy Sustainable? Potential Relationships between Renewable Energy Production and the Sustainable Development Goals. *NPJ Climate Action, 3,* Article No. 35. https://doi.org/10.1038/s44168-024-00120-6

United Nations (UN) (2024). *The Sustainable Development Goals Report-2024* (51 p). https://unstats.un.org/sdgs/report/2024/

You, F., Tao, L., Graziano, D. J., & Snyder, S. W. (2022). Optimal Design of Sustainable Cellulosic Biofuel Supply Chains: Multiobjective Optimization Coupled with Life Cycle Assessment and Input-Output Analysis. *AIChE Journal, 58,* 1157-1180. https://doi.org/10.1002/aic.12637

Yue, D., & You, F. (2016). Biomass and Biofuel Supply Chain Modeling and Optimization. In J. B. Holm-Nielsen, & E. A. Ehimen (Eds.), *Biomass Supply Chains for Bioenergy and Biorefining* (pp. 149-166). Woodhead Publishing. https://doi.org/10.1016/b978-1-78242-366-9.00007-1

Yue, D., You, F., & Snyder, S. W. (2014). Biomass-to-Bioenergy and Biofuel Supply Chain Optimization: Overview, Key Issues and Challenges. *Computers & Chemical Engineering, 66,* 36-56. https://doi.org/10.1016/j.compchemeng.2013.11.016

Zahraee, S. M., Golroudbary, S. R., Shiwakoti, N., Stasinopoulos, P., & Kraslawski, A. (2020a). Water-Energy Nexus and Greenhouse Gas-Sulfur Oxides Embodied Emissions of Biomass Supply and Production System: A Large Scale Analysis Using Combined Life Cycle and Dynamic Simulation Approach. *Energy Conversion and Management, 220,* Article ID: 113113. https://doi.org/10.1016/j.enconman.2020.113113

Zahraee, S. M., Shiwakoti, N., & Stasinopoulos, P. (2020b). Biomass Supply Chain Environmental and Socio-Economic Analysis: 40-Years Comprehensive Review of Methods, Decision Issues, Sustainability Challenges, and the Way Forward. *Biomass and Bioenergy, 142,* Article ID: 105777. https://doi.org/10.1016/j.biombioe.2020.105777

Zubairu, N., Mohammed, A., & Zohny, Z. (2024). Navigating the Path to Sustainable Energy Transition in Oman: A Systematic Literature Review and Future Research Opportunities. *Management of Environmental Quality: An International Journal, 35,* 1744-1772. https://doi.org/10.1108/meq-01-2024-0021