Tailoring Climate-Smart Biofuel Crop Production Options for Ghana: A Comprehensive Review

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Abstract

As countries increasingly adopt low-carbon energy strategies, bioenergy, especially biofuels, presents significant opportunities for sustainable growth. Biofuel production offers a range of benefits, including atmospheric carbon sequestration, job creation, foreign revenue, sustainable land management, biodiversity conservation, renewable energy, ecosystem stability, and land degradation mitigation. This study aims to enhance Ghana's biofuel policies and climate-smart agricultural strategies by identifying suitable biofuel species for integration into current frameworks. Through a review of seven critical criteria, carbon balance with perennial crops, suitability for marginal lands, minimal impact on food prices, water footprint, fertilizer and/or pesticide needs, sustainable nitrogen management, and prioritization of native species, this study highlights promising indigenous biofuel perennials for agroforestry models in Ghana. Native species such as shea (*Vitellaria paradoxa*), baobab (*Adansonia digitata*), *Allanblackia parviflora*, *Khaya senegalensis*, oil palm (*Elaeis guineensis*), and elephant grass (*Pennisetum purpureum*) show strong resilience and adaptability for sustainable local cultivation. Furthermore, several non-native species with favourable agronomic traits and adaptability to marginal lands were identified as potential biofuel crops, contingent on prior ecological assessments to ensure environmental compatibility. These species include *Calotropis procera*, castor bean (*Ricinus communis*), *Jatropha curcas*, neem (*Azadirachta indica*), moringa (*Moringa oleifera*) and cassava (*Manihot esculenta*). Additionally, Ghana's established export crops such as cocoa (*Theobroma cacao*), rubber (*Hevea brasiliensis*), cotton (*Gossypium hirsutum*) and tobacco (*Nicotiana tabacum*) offer further biofuel potential by converting underutilized by-products, such as non-edible seeds and husks, into biofuels. The study underscores a critical need for additional research on bioenergy yields, biofuel properties, and alignment with local energy systems to inform policy and investment decisions. A shortage of empirical data, particularly life-cycle and cost-benefit analyses, was identified. Consequently, emphasizing the need for rigorous research to equip farmers, policymakers, and investors with the knowledge needed for sustainable biofuel development in Ghana.

Keywords: Climate resilience, Climate-smart crop production, biofuel sustainability, biofuel crops selection

Global Shift toward Biofuels: A Sustainable Energy Alternative

The urgency of addressing climate change, primarily driven by excessive greenhouse gas emissions (Demirbas, 2008; Joshi *et al*., 2017), has brought biofuels into focus as a sustainable energy solution. Biofuels reduce reliance on finite oil reserves, enhancing energy security and reducing vulnerability to the economic impacts of oil market fluctuations (van Eijck *et al*., 2014; Su *et al*., 2015; Azadi *et al*., 2017; Rodionova *et al*., 2017; Correa *et al*., 2019; Dunn, 2019; Mahapatra *et al*., 2021), without the limitations seen in other renewables (Azarpour *et al.*, 2013).

With the global economy's expansion comes an increasing demand for transportation fuels, a sector that consumes roughly 60% of the world's energy, more than 80% of which is derived from fossil fuels (Joshi *et al*., 2017). Developed nations are thus investing heavily in biofuel research and development to meet both domestic and global demands (Joshi *et al*., 2017). Policy initiatives in countries like the U.S., EU, China, Brazil, and South Korea support biofuel production, helping establish biofuels as a major industry (Dunn, 2019; The Government of the Republic of Korea, 2020). Currently, the U.S., Brazil, and the EU lead in biofuel production, using feedstocks such as maize, wheat, rapeseed, soybean, and sugarcane (Correa *et al*., 2019).

Developing nations, such as Ghana, are particularly well-positioned to benefit from biofuel production, thanks to favourable climates and vast underutilized land areas that keep biomass production costs low (United Nations, 2008; van Eijck *et al*., 2014). By engaging in biofuel production, Ghana can create substantial rural employment, where job opportunities are most needed, while also accessing global markets. Additionally, biofuel initiatives offer environmental benefits, including carbon removal credit opportunities that could provide a revenue stream for Ghana as it contributes to global climate mitigation efforts (United Nations, 2008).

Ghana's Biofuel Policies, Strategies, and Environmental Conservation Efforts

Ghana has established several policy objectives and actions focused on energy, climate change, and natural resource management. Hafner *et al*. (2018) expressed confidence that with continued commitment to these policies, Ghana could exceed its domestic biofuel demand by 2050. This optimistic outlook suggests that the country's efforts in the biomass energy sector could not only fulfil its own energy needs but also generate surplus biofuels for export, thereby boosting the economy and contributing to global sustainability goals. The success of Ghana's cocoa industry, which supplies premium cocoa beans to international markets (Amankwah-Amoah *et al*., 2018), exemplifies how such initiatives could succeed.

Ghana's pursuit of biomass energy, as outlined by Hafner *et al*. (2018) and Kipkoech *et al*. (2022), is driven by a blend of environmental, economic, and sustainability objectives. By prioritizing sustainable biofuel production, addressing institutional barriers, and promoting competitive markets, the country has the potential to establish itself as a leader in the biofuel industry while simultaneously addressing significant environmental and energy challenges.

However, the global collapse of the jatropha biofuel initiative, including its failure in Ghana, serves as a cautionary tale about the dangers of launching such ventures without solid scientific research (Sanderson, 2009; Kumar *et al*., 2012; Axelsson *et al*., 2012; Edrisi *et al*., 2015; Dogbevi, 2015; Abubakari *et al*., 2017; Nygaard & Bolwig, 2018; Tufa *et al*., 2018; Antwi-Bediako *et al*., 2019). Moreover, there is no comprehensive, scientifically validated portfolio of biofuel production options for Ghanaian farmers and investors. This highlights the need for the development of tailored biofuel crop options that are specifically suited to the country's environmental, economic, and agricultural conditions.

Methodology for Tailoring Climate-Smart Biofuel Crop Production Options for Ghana

To develop customized climate-smart biofuel crop production options for Ghana, a comprehensive literature review was conducted. This review involved extracting relevant information from journal articles, scientific reports, and book chapters using the

Google Scholar, Scopus, and Web of Science databases. Keywords such as "climate change," "climate-smart crop production," "biofuel criteria," "biofuel crops," and "Ghana" were used in combination with the Boolean operator "AND" to refine search results.

The collected literature underwent a thorough critical analysis, with key findings, discrepancies, conclusions, and recommendations identified through comparison and synthesis. The most recent empirical evidence, trends, and criteria were used as a foundation for constructing the narrative review. This process led to the identification of several sub-themes, which contributed to the preliminary development of climate-smart biofuel crop production options tailored to Ghana's evolving environmental and agricultural conditions.

Criteria for Selecting Sustainable Biofuel Feedstocks

As the world confronts climate change and the need to transition to more sustainable energy sources, the detailed analysis of biofuels and bioproducts becomes central to informing policy and decision-making in this critical sector. The potential of biofuels to mitigate greenhouse gas emissions depends on several key factors, including the amount of fossil fuel inputs required for biofuel production, the carbon intensity of these inputs, and the fossil fuels that biofuels are intended to replace (United Nations, 2008). A commonly used approach to evaluate the sustainability of biofuels and bioproducts is life cycle analysis (LCA) (Rosen, 2018; Dunn, 2019). Life cycle analysis entails a thorough examination of the material and energy inputs and outputs at each stage of a product's life cycle, resulting in the quantification of energy use and environmental impacts.

While biofuel and bioproduct LCAs often emphasize greenhouse gas emissions due to regulatory and certification requirements, they also account for other critical factors such as water consumption, air pollution, and broader environmental considerations (Dunn, 2019). This comprehensive assessment method enhances understanding of the wider sustainability implications of biofuel production and helps establish essential criteria for selecting appropriate feedstocks.

In this study, seven primary criteria have been identified as essential for selecting a sustainable, climate-smart biofuel crop option for Ghana. However, it is important to recognize that additional social, economic, and environmental factors, as discussed by Markevičius *et al*. (2010), are equally important and must be considered before final implementation.

Primary Criteria for Sustainable Biofuel Feedstock Production in Ghana

Amid the escalating global climate change crisis, it is increasingly evident that prioritizing environmental and social advantages over the purely economic considerations of biofuel production is crucial. Research into sustainable biofuel feedstocks in Ghana underscores the importance of assessing crops using several key criteria to ensure long-term sustainability and alignment with climate goals. Seven primary criteria have been identified as essential for selecting climate-smart biofuel crops: carbon balance with perennial crops, exotic species applications, marginal land fitness, vulnerability to food price fluctuations, water footprint, fertilizer and pesticide requirements and sustainable nitrogen management.

Transitioning from annual biofuel crops, such as maize and soybean, to perennial crops can significantly reduce carbon dioxide emissions. Perennials sequester carbon in the soil and require fewer fertilizers and pesticides, which in turn diminishes environmental pollution. Native perennials, well adapted to local ecosystems, are essential as they help sustain biodiversity while minimizing competition with food crops, which can enhance food security. By promoting perennial crops for biofuels, a favourable carbon balance can be achieved, ensuring a more sustainable energy source (Correa *et al*., 2019; United Nations, 2008).

The use of exotic species in biofuel production must be approached with caution. Many studies have erroneously recommended invasive species like *Eucalyptus camaldulensis* and *Leucaena leucocephala* for biofuel cultivation in Ghana without fully understanding the ecological risks. Invasive species can damage local ecosystems and threaten biodiversity. To mitigate such risks, guidelines for proper screening and invasive species assessments must be adhered to. Introducing non-native species must involve a comprehensive ecological risk assessment to ensure their environmental suitability and prevent potential long-term harm (Davis *et al*., 2010; Richardson & Rejmánek, 2011).

The conversion of agricultural land to biofuel crop production has raised concerns over food security, as it competes with food crop cultivation. To address this issue, the study advocates for cultivating biofuel crops on marginal or degraded lands. This would prevent the displacement of food crops while maximizing underutilized land for biofuel production. However, the environmental and social impacts of using such land must be rigorously assessed to ensure that such practices do not lead to negative consequences (Joshi *et al*., 2017; Correa *et al*., 2019).

The widespread use of food crops such as sugarcane and maize for biofuel production exacerbates the "food versus fuel" debate, as it links biofuel prices to food market fluctuations. Over 90% of biodiesel worldwide is derived from vegetable oils, which directly affects food prices. To mitigate these issues, research must prioritize non-food feedstocks like algae, waste materials, and non-food crops. Shifting to alternative sources will reduce pressure on food crops and contribute to a more resilient and secure global food supply (Correa *et al*., 2019; Joshi *et al*., 2017).

Water scarcity is a growing concern, especially in regions where water resources are already strained. The cultivation of biofuel crops can exacerbate these challenges, making the selection of drought-tolerant species essential. Focusing on biofuel feedstocks that are naturally adapted to arid conditions can significantly reduce water consumption. These crops can also promote water conservation, ensuring that water resources remain available for food production. As climate change intensifies, selecting water-efficient biofuel crops is paramount to ensuring the sustainability of both energy and food production (United Nations, 2008; Correa *et al*., 2019).

The environmental impact of fertilizers and pesticides used in biofuel crop cultivation is considerable, contributing to greenhouse gas emissions and soil degradation. To mitigate these effects, the research advocates for the use of energy perennials that have lower nutrient requirements and greater resistance to pests and diseases. By focusing on these crops, it is possible to reduce the environmental impact of biofuel production, particularly in terms of fertilizer and pesticide application, thereby promoting more sustainable farming practices (Correa *et al*., 2019; United Nations Environment Programme, 2023).

Nitrous oxide, a potent greenhouse gas, is emitted from agricultural practices, particularly through the use of nitrogen fertilizers, and through the planting of nitrogen-fixing plants, which may actually offset climate change mitigation efforts (Crutzen *et al*., 2007; Kou-Giesbrecht & Menge, 2021). The over-application of nitrogen can also result in air pollution and eutrophication. Therefore, sustainable nitrogen management practices are critical in biofuel production. Light-feeding crops that require minimal nitrogen, such as grasses and certain woody plants, should be prioritized as biofuel feedstocks. These crops are not only more environmentally friendly but also contribute to reduced nitrous oxide emissions, ensuring that biofuel production aligns with global climate goals (Ogle *et al.*, 2008; United Nations Environment Programme, 2023).

Selecting appropriate biofuel feedstocks for Ghana requires a comprehensive evaluation of environmental, social, and economic criteria. By prioritizing sustainability in biofuel feedstock production, it is possible to create a system that supports climate resilience, promotes biodiversity, and contributes to food security. A shift towards perennial crops, responsible land use, and water-efficient species, coupled with innovative nitrogen, pesticide and fertilizer management, will be crucial to achieving a sustainable biofuel industry in Ghana that benefits both the environment and society.

Recommendations for Developing Climate-Smart Biofuel Crop Industries in Ghana

The importance of ecological and environmental factors in biofuel production is often overlooked, yet they are crucial for ensuring sustainability, as highlighted by Raghu *et al.* (2011). To optimize biofuel production, it is essential to select feedstocks that are tailored to the specific bio-geophysical conditions of a region, as emphasized by the United Nations (2008). This is especially pertinent in Ghana, a country with diverse agroecological zones, ranging from the semi-arid north to the forested and coastal regions in the south. The vast ecological variation makes it critical to choose plant species that are well-suited to each zone's unique conditions.

Studies by Karmakar *et al*. (2010), Atabani *et al*. (2013) and Yang *et al*. (2014) identified several plant species suitable for commercial biofuel production in tropical regions. Subsequent studies by Nelson *et al*. (2021) and Takase *et al*. (2023) tailored these recommendations specifically for Ghana. However, many of the species suggested were either important food crops unsuitable for marginal land or were native to Asia and America, raising concerns about their invasiveness. As a result, these species were excluded from consideration. Additionally, some species, though of African origin, were not native to West Africa. Research by IUCN/PACO (2013), Ansong *et al*. (2019), and Uyi *et al*. (2021) has shown that plants from other African regions can become invasive in West Africa. Therefore, non-West African species were also excluded from this analysis.

The biofuel species that remain suitable for consideration in Ghana, which are native to West Africa, include shea (*Vitellaria paradoxa*), baobab (*Adansonia digitata*), *Allanblackia parviflora*, *Khaya senegalensis*, oil palm (*Elaeis guineensis*) and elephant grass (*Pennisetum purpureum*).

This review focused on the potential for commercializing specific biofuel plant species in Ghana, emphasizing their suitability based on environmental, ecological, and socio-economic criteria. These include factors such as non-invasiveness, suitability for marginal land, non-food status, potential for restoring degraded lands, providing ecosystem services, and contributing to biodiversity conservation. It is important to note that this review did not consider other critical factors, such as feedstock yield, production costs, the stage of conversion technology development, biofuel quality, and engine performance. While these factors were outside the scope of this review, they are essential for a comprehensive assessment and should be explored further in future research, as they could play a pivotal role in determining the viability of different biofuel options.

To ensure the sustainability and success of biofuel crop industries in Ghana, it is essential to conduct life cycle and cost-benefit analyses tailored to the local context. These analyses should evaluate each stage of a feedstock's life cycle, from cultivation and processing to transportation and final use. Such comprehensive assessments will provide valuable insights into the environmental impacts, resource consumption, and overall sustainability of biofuel production in Ghana.

A detailed cost-benefit analysis will also enable a thorough understanding of the economic viability of different biofuel feedstocks. This analysis should consider factors such as initial investments, operational costs, and potential financial returns, as well as the broader benefits, including reduced greenhouse gas emissions, enhanced energy security, economic development, job creation, community development, and long-term environmental sustainability. By integrating these economic and ecological considerations, Ghana can develop a climate-smart biofuel industry that supports both national energy needs and environmental conservation.

Native Energy Perennials in Ghana and Their Biofuel Potential

After an extensive review of multiple scientific articles, it has been determined that only six energy plant species can be confirmed as indigenous to West Africa. These species are shea (*Vitellaria paradoxa*) (Bello & Mamman, 2015; Tulashie *et al.*, 2018; Iddrisu *et al.*, 2020; Yau *et al.*, 2020; Danlami *et al.*, 2022; Ogunlade *et al.*, 2022), baobab (*Adansonia digitata*) (Buhari *et al.*, 2014; Modiba *et al.*, 2014; Chilabade *et al.*, 2021), *Allanblackia parviflora* (Kyereh *et al.*, 2021; Takase *et al.*, 2021), *Khaya senegalensis* (Olagbende *et al.*, 2021; Adewuyi & Oderinde, 2022; Usman *et al.*, 2022), oil palm (*Elaeis guineensis*) (Kareem *et al.*, 2017; El-Araby *et al.*, 2018; Meijide *et al.*, 2020; Wahyono *et al.*, 2022), and elephant grass (*Pennisetum purpureum*) (Aiyejagbara *et al.*, 2016; Stanley *et al.*, 2017; Campos *et al.*, 2019; Kolo *et al.*, 2020; Osman *et al.*, 2020; Safaat *et al.*, 2022). Although all these species exhibit potential for biofuel production, except for *Khaya senegalensis* and *Pennisetum purpureum*, they do not fully satisfy the critical sustainability criteria of non-edible biofuel sources.

Elephant Grass Biofuel Potential in Ghana

Elephant grass (*Pennisetum purpureum*) offers significant agricultural and environmental benefits in northern Ghana, where livestock farming is integral to livelihoods. It provides high-quality forage that complements livestock fodder, improving both animal and caretaker well-being. By producing silage for farmers to sell to herdsmen during the dry season, it can help ease tensions between crop farmers and herders. Additionally, utilizing livestock dung as fertilizer promotes sustainable farming. Elephant grass also aids in reforestation, stabilizing degraded lands, combating desertification, and enhancing ecological health, making it a valuable tool for both socio-economic and environmental improvement.

Oil Palm Biodiesel Potential in Ghana

Producing biodiesel from oil palm offers a dual advantage by utilizing both palm oil and palm kernel oil, each with distinct benefits (Kareem *et al*., 2017). However, in Ghana, where palm oil is a dietary staple, shifting towards biofuel production could lead to competition for this valuable resource, raising prices and creating shortages for food uses. This may divert agricultural land from food crops, affecting food security. Additionally, oil palm cultivation in Ghana is linked to deforestation, threatening biodiversity and contributing to environmental degradation and climate change (Meijide *et al*., 2020; Wahyono *et al*., 2022). Commercial oil palm farming also has a high water and nutrient footprint (Wahyono *et al*., 2022). Given these challenges, it is essential for Ghana to balance oil palm expansion for biofuel with ecosystem preservation and sustainable food production to ensure the well-being of its people and environment.

Khaya senegalensis Biofuel Potential in Ghana

Khaya senegalensis, or African mahogany, is crucial for timber production in Ghana, meeting both domestic and international demands (Usman *et al*., 2022). Its cultivation supports sustainable forestry and conserves natural forests. Additionally, the seeds of *Khaya senegalensis* can be used for biofuel production, reducing waste and contributing to Ghana's bioenergy sector (Adewuyi & Oderinde, 2022). This dual-purpose tree promotes sustainable practices and aligns with eco-friendly energy goals.

Shea, baobab, and *Allanblackia parviflora* Biofuel Potential in Ghana

Shea (*Vitellaria paradoxa*), baobab (*Adansonia digitata*) and *Allanblackia parviflora* are slow-growing species, presenting challenges for local farmers in Ghana, as it can take years to reap the benefits. Shea trees begin fruit production after 15 to 30 years (Iddrisu *et al*., 2020), and allanblackia after 8 years (Balogun *et al*., 2019). To encourage cultivation, strategies such as offering carbon credits (Dimobe *et al*., 2019) can incentivize farmers.

Currently, many farmers gather edible parts of these trees from the wild due to limited domestication efforts (Iddrisu *et al*., 2020; Kyereh *et al*., 2021). This underutilization reflects a gap in commercial cultivation for these valuable crops. Unlike conventional biofuel crops like maize and soybean, which are annuals, these native West African trees offer perennial growth, providing a unique opportunity for biofuel production while sequestering carbon dioxide. Baobab and shea's drought resistance makes them ideal for Ghana's semi-arid regions (Modiba *et al*., 2014; Iddrisu *et al*., 2020). However, shea's vulnerability to flooding (Iddrisu *et al*., 2020) may limit its potential with climate change. To integrate these species into biofuel production, long-term viability practices and partnerships between governments, research institutions, and local communities are essential for sustainable cultivation and maximizing economic potential.

Consideration of Fuel Crop Species for Biofuel Production

Identifying ideal biofuel plant species that meet both sustainability and agronomic criteria remains a challenge, as no single species fulfils all requirements. This review does not dismiss species that do not fully align with these criteria, as many still offer potential for biofuel production in Ghana. Given the complexity of biofuel crop selection, it is important to maintain an open perspective and explore species with promising qualities in specific contexts. Ongoing research and experimentation are essential to discover the most suitable and sustainable biofuel crop solutions for the future.

Exploring the Biofuel Potential of Exotic Export Crops in Ghana

In Ghana, there is a unique opportunity for sustainable biofuel production by utilizing crop species cultivated primarily for export, such as cocoa (*Theobroma cacao*), rubber (*Hevea brasiliensis*), cotton (*Gossypium hirsutum*), and tobacco (*Nicotiana tabacum*). These crops are economically viable for biofuel production, making them promising candidates for economic diversification.

Many by-products from these crops, including seeds, pods, and husks, are underutilized, often discarded as waste (Adewuyi & Oderinde, 2022). This waste poses environmental challenges, highlighting the need for alternative uses. One potential solution is converting non-edible oils from these seeds into biodiesel or cocoa husks into bioethanol (Nelson *et al.*, 2021), turning waste into valuable biofuel and promoting environmental sustainability. Additionally, utilizing these by-products for biofuel production could create employment opportunities, fostering economic growth and stability in local communities. However, before implementing large-scale commercial biofuel production, conducting cost-benefit analyses is essential to assess the viability of each feedstock for biofuel conversion.

Exotic Biofuel Crops with Potential for Marginal Lands

Certain agronomic traits, such as high tolerance to low soil fertility, resilience to environmental variations, pest resistance, rapid growth, low water usage, and abundant seed production, are essential for successful biofuel feedstock production (Barney & DiTomaso, 2008). These characteristics align with the goals of biomass producers, aiming to meet growing energy demands while minimizing the impact on food production and reducing the need for chemical inputs. Such traits also support sustainability by enhancing crop adaptability to climate challenges and reducing reliance on fertilizers and pesticides.

Several exotic species introduced to Ghana, including *Calotropis procera*, castor bean (*Ricinus communis*), *Jatropha curcas*, neem (*Azadirachta indica*), cassava (*Manihot esculenta*), and moringa (*Moringa oleifera*), exhibit strong adaptability to local conditions. These crops can thrive in nutrient-poor soils, withstand drought, and resist pests and grazing animals. However, some of these species, such as *Azadirachta indica*, *Calotropis procera*, *Ricinus communis* and *Jatropha curcas*, have become invasive in parts of West Africa, posing ecological risks by outcompeting native plants and disrupting local ecosystems (Richardson & Rejmánek, 2011; IUCN/PACO, 2013; Ansong *et al*., 2019).

To mitigate these risks, it is crucial to develop strategies that balance biofuel production with environmental preservation. This includes implementing biosecurity measures, practicing responsible land management, and conducting research on sustainable farming methods. Additionally, ecological risk assessments are necessary to prevent further invasions and ecological damage. While cassava is a staple food crop in Ghana, the other species are not fully domesticated, and lessons from the failure of jatropha biofuel cultivation highlight the importance of conducting growth and yield studies. These studies will help assess the feasibility of these exotic species for commercial biofuel production, ensuring that biofuel development is both sustainable and economically viable.

Conclusions and Recommendations

The establishment of a biomass industry in Ghana offers numerous advantages, including carbon sequestration, job creation, foreign revenue inflows, sustainable land management, biodiversity conservation, and the production of renewable, carbon-neutral energy. Additionally, it supports agroecological stability, mitigates land degradation, and helps prevent deforestation. Given the urgency of addressing the global climate change crisis, concerns about the affordability and reliability of biofuels compared to fossil fuels have proven to be largely unfounded. This study emphasizes the need to prioritize the environmental and social benefits of biofuels over the lower production costs typically associated with fossil fuels.

For Ghana to successfully develop a sustainable biofuel industry, biofuel crop options must be assessed based on key criteria, including their carbon balance, the use of exotic species, suitability for marginal lands, resilience to fluctuations in food prices, water footprint, and the requirements for fertilizers, pesticides, and nitrogen management. These factors are essential to ensure that biofuel crops are not only viable but also climate-resilient and environmentally sustainable. Among the most promising strategies is the cultivation of indigenous biofuel perennials within an agroforestry framework. Species such as shea, baobab, *Allanblackia parviflora*, *Khaya senegalensis*, oil palm, and elephant grass have the potential to support agroforestry, reforestation, and land reclamation while preserving Ghana’s biodiversity. However, many of these species are not fully domesticated, requiring extensive research to assess their suitability as biofuel feedstocks for different agroecological zones in Ghana.

In addition to indigenous species, several exotic species, including *Calotropis procera*, castor bean, *Jatropha curcas*, neem, moringa, and cassava, have been identified as potentially suitable for biofuel production on marginal lands. However, to ensure their successful integration into a biofuel industry, rigorous ecological risk assessments, and growth and yield studies must be conducted. Since these species are already present in Ghana, they provide a valuable opportunity to conduct empirical studies and develop appropriate biosecurity measures. Additionally, export crops such as cocoa, rubber, cotton, and tobacco, which are already commercially grown in Ghana, offer the potential for biomass production through underutilized by-products like oil seeds and husks. A thorough cost-benefit analysis is essential to assess their feasibility for biofuel production on a larger scale.

While this study contributes to enhancing Ghana's biofuel, climate-smart agriculture, and environmental conservation policies, it is important to acknowledge that no single biofuel crop currently meets all the ideal criteria. There is a critical gap in empirical data, particularly life cycle and cost-benefit analyses, which are essential for providing farmers, policymakers, and investors with the information necessary to make informed decisions. Therefore, it is recommended that extensive empirical research and field studies be undertaken before making final recommendations and implementing large-scale biofuel production strategies.

To move forward, it is crucial to prioritize the domestication and research of indigenous biofuel species, conduct ecological and yield assessments of exotic species, and evaluate the cost-effectiveness of utilizing underutilized agricultural by-products. Collaboration between policymakers, stakeholders, and the global community will also be key to establishing a sustainable biofuel industry in Ghana, helping to mitigate climate change and promote environmental and economic sustainability.

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