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An Evaluation of the Land Available for Sustainable Sugarcane Cultivation and Potential for Producing Ethanol and Bioelectricity in Angola

Adilson João Matias [1], Luiz Augusto Horta Nogueira [2,*] and Eric Alberto Ocampo Batlle [2]

1 Energy Engineering, Federal University of Itajubá—UNIFEI, Av. BPS 1303, Itajubá 37500-903, Brazil; adilsonjoaomatias@gmail.com

2 Institute of Electrical Systems and Energy, Federal University of Itajubá—UNIFEI, Av. BPS 1303, Itajubá 37500-903, Brazil; ericocampo@unifei.edu.br

* Correspondence: horta@unifei.edu.br

Abstract: With a predominantly humid tropical climate and a large area for expanding agricultural activities, Angola has in principle favorable conditions for bioenergy production. The focus of this study was to evaluate the availability of suitable land for producing sugarcane. This crop is highly efficient in converting solar energy into biomass for energy purposes in Angola. To this end, this paper outlines a method for data collection, processing, and analysis divided into three sections. The first section uses the GAEZ (Global Agroecological Zones) database and QGIS (Quantum GIS) software (version 3.22.5) to assess land availability for sugarcane cultivation in Angola, classifying the regions' suitability into four levels. The second section supplements this with data from the FAOSTAT database, systematically excluding areas with restrictions, such as protected zones, land already used for other crops, and regions unsuitable for sugarcane. Finally, the third section employs an agricultural yield model to estimate the potential yield of sugarcane based on climatic parameters and the amount of bioenergy (ethanol and bioelectricity) able to be produced in the available land. Under these criteria, this study identified the existence of 6.3 Mha in lands of good agricultural suitability, with water resources, corresponding to 5% of the Angolan territory, distributed in seven provinces of the country, especially in the provinces of Cuando Cubango and Cunene, where 85% of the very suitable land under irrigation is located. Adopting a model of agricultural productivity, assuming irrigation and adequate agricultural practices, such area could produce approximately 956 million tons of sugarcane annually, which is significantly higher than the current production in this country. This amount of feedstock processed using current technology could potentially produce 81.3 GL of ethanol and 176.9 TWh of electricity with low GHG emissions per year, which is able to mitigate, as a whole, circa 60.3 $MtCO_2$-eq/year by displacing gasoline in light vehicles and diesel and natural gas consumed in power generation.

Keywords: Angola; sugarcane; sustainable land use; ethanol; bioelectricity

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1. Introduction

The consumption of sustainable bioenergy has been increasing worldwide, driving it to be one of the best alternatives to promote the energy transition and decarbonization of the global energy matrix. In this sense, the IEA (International Energy Agency) projections for the evolution of global energy consumption for transport indicate that biofuels, which currently account for 4% of demand, could reach around 30% in 2050 [1], while IRENA (International Renewable Energy Agency) states that the share of biofuels is expected to grow threefold by 2030 [2].

Bioenergy can supply different energy uses, emitting little fossil carbon, and is considered one of the most feasible types of renewable energy [3]. Liquid biofuels are replacing fossil fuels in transportation in several countries [4], with ethanol being particularly important and burned in blends with gasoline or pure in more than 90 countries, in which consumption increased from 32.5 to 127.3 billion liters from 2002 to 2022 [5]. FAO (Food and Agriculture Organization of the United Nations) expects global ethanol fuel consumption will reach 132.4 trillion liters in 2030 [6].

Several crops have been adopted for bioethanol production by fermenting sugars or starches from plants such as sugarcane, maize, wheat, sugar beet, cassava, and others [7]. However, sugarcane, containing 9.8% fermentable sugars in its juice [8], for several key reasons is the most cost-effective source of bioenergy (bioethanol and bioelectricity) and bioproducts (Figure 1) [9]. First, sugarcane presents high efficiency in converting solar energy into chemical energy [10]; thus, it requires relatively less area and offers flexibility and diversity that improves the competitiveness of farmers and rural areas [11]. Second, in the context of a developing country, sugarcane agro-industries can be implemented in regions with limited electricity infrastructure since they can provide their own energy through readily available and cost-effective agricultural residues [12,13]. Finally, sugarcane agro-industrial and agro-energy investments establish economic connections among numerous small businesses, suppliers, and end-users [14]. These connections serve as catalysts for local and regional growth and development. For these key reasons, this culture can promote human development and meet strict sustainability indicators, reducing greenhouse gas (GHG) emissions by approximately 80% compared to gasoline [15].

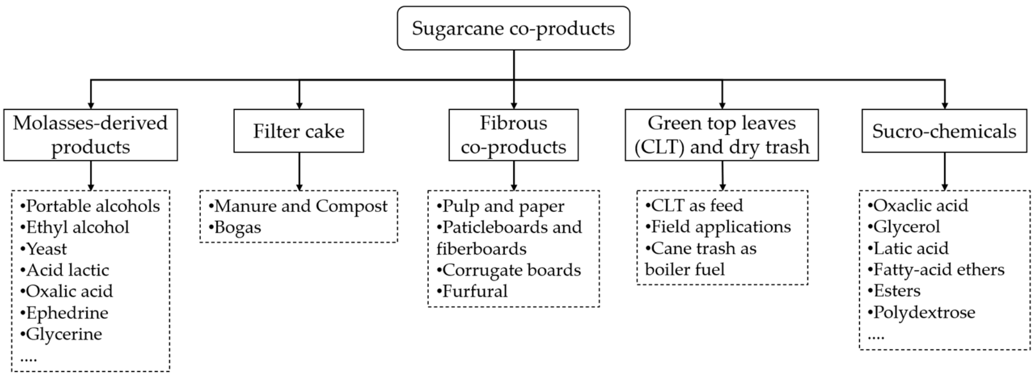

Figure 1. Sugarcane beyond sugar and ethanol [16].

Furthermore, sugarcane can also be grown on land that is either unused or unsuitable for food crop production or cultivated using food–energy integrated approaches [16]. In addition, as it is a semi-perennial crop, sugarcane fields can be utilized to grow other crops during rotation practices, typically every five years [17]. Due to these facts, sugarcane can face the triple challenge of energy insecurity, climate change, and rural poverty in Sub-Saharan Africa [18,19].

Approximately 96.6 million tons of sugarcane are produced annually in Africa, mainly in South Africa (19.5%), Nigeria (1.6%), Egypt (15%), and Ethiopia (1.4%) [20]. Despite the existence of suitable areas for sugarcane cultivation in African countries, the overall potential of countries is varied and depends on specific agricultural and economic issues. The Southeast region has the greatest potential for rainfed sugarcane production, with additional potential for cultivation with irrigation [21].

However, most studies on the potential of biomass as a renewable energy resource in Africa address superficially the geographical suitability of bioenergy [22–24] or develop an overview of the potential energy supply [25–27]. On the other hand, specific studies evaluating and quantifying the land suitable for sugarcane production in Sub-Saharan Africa are scarce. One exception is the 2019 report by IRENA [28], which assessed the sugarcane production potential in seven Southern African Development Community (SADC) countries: Eswatini (formerly Swaziland), Malawi, Mozambique, South Africa, Tanzania, Zambia, and Zimbabwe. The findings highlight that the sugarcane agro-industry can offer significant socio-economic benefits, particularly in terms of job creation due to its high labor demands. Additionally, small farmers can benefit from sugarcane cultivation, enhancing both food and energy security. Nyambane et al. [29] explore the significance of ethanol as a clean alternative cooking fuel in Sub-Saharan Africa, focusing on Malawi and Mozambique. Their study indicates that trade-offs emerge during sugarcane production between provisioning, regulating, and cultural ecosystem services. These trade-offs are mediated by land-use changes associated with converting agricultural and forest lands into large-scale irrigated sugarcane fields. Additionally, several factors influence the adoption and discontinuation of ethanol stoves by end users, with cost being the most significant. The study concludes that the sustained adoption of clean stoves and sustainable raw material production can support progress toward multiple Sustainable Development Goals (SDGs). Government support, utilizing existing marketing structures, raising awareness, and providing after-sale services are crucial for establishing a successful bioethanol fuel and stove distribution chain. Finally, Souza et al. [18] evaluated the energy potential of sugarcane in Angola, Mozambique, Malawi, South Africa, Tanzania, Zambia, and Zimbabwe based on the premise that sugarcane can be cultivated on 1% of pasture land. Their findings confirm sugarcane's potential as a modern energy alternative for southern Africa.

Based on the literature review focusing on the sugarcane agro-industrial sector, there is a notable lack of research analyzing and quantifying the potential to replace current and future uses of traditional biomass and fossil fuels. Additionally, there is a shortage of studies examining the capacity to expand access to electricity in line with current and projected demand in Sub-Saharan African countries, particularly Angola. This question inspired the present study.

Angola has excellent conditions for the development of sustainable systems for the production and use of biofuels and bioelectricity due to its suitable climate, availability of water resources, and land suitable for the expansion of bioenergy crops (like sugarcane) without affecting agricultural production for domestic consumption and export and without occupying forest or protected areas. However, it is important that such production occurs under sustainable conditions, preserving natural resources, and without negatively impacting food production, and a careful assessment of land use is indispensable.

Given this, the evaluation of the areas available for cultivating and producing bioenergy from any crop must take into account the suitability of an area considering its physical characteristics, such as precipitation, temperature, the availability of water resources, and the type of soil [10]. In light of the above, the present study applies agroecological zoning, which is the ideal methodology to define the suitability, production potential, and environmental impacts linked to a study area [30]. Therefore, the present research focuses on the quantitative evaluation of the potential for sustainable sugarcane production for bioenergy (ethanol and bioelectricity), which involves a soil cover analysis, the exclusion of protected areas, and slope classes. However, the study also includes analyzing qualitative aspects to distinguish the areas that are effectively suitable and available for sugarcane culture to produce biofuels, allowing us to estimate the theoretical potential for producing bioenergy in selected areas.

Overview of Energy Development in Angola

Angola is located on the coast of southern Africa, with a territorial extension of approximately 125 million hectares (Mha) divided into 18 provinces (Figure 2), with an estimated population of 33 million inhabitants. About one-third of Angola's population live in rural areas. The expanding urban areas contrast with large sparsely populated areas, especially in the provinces located along the country's coast [31].

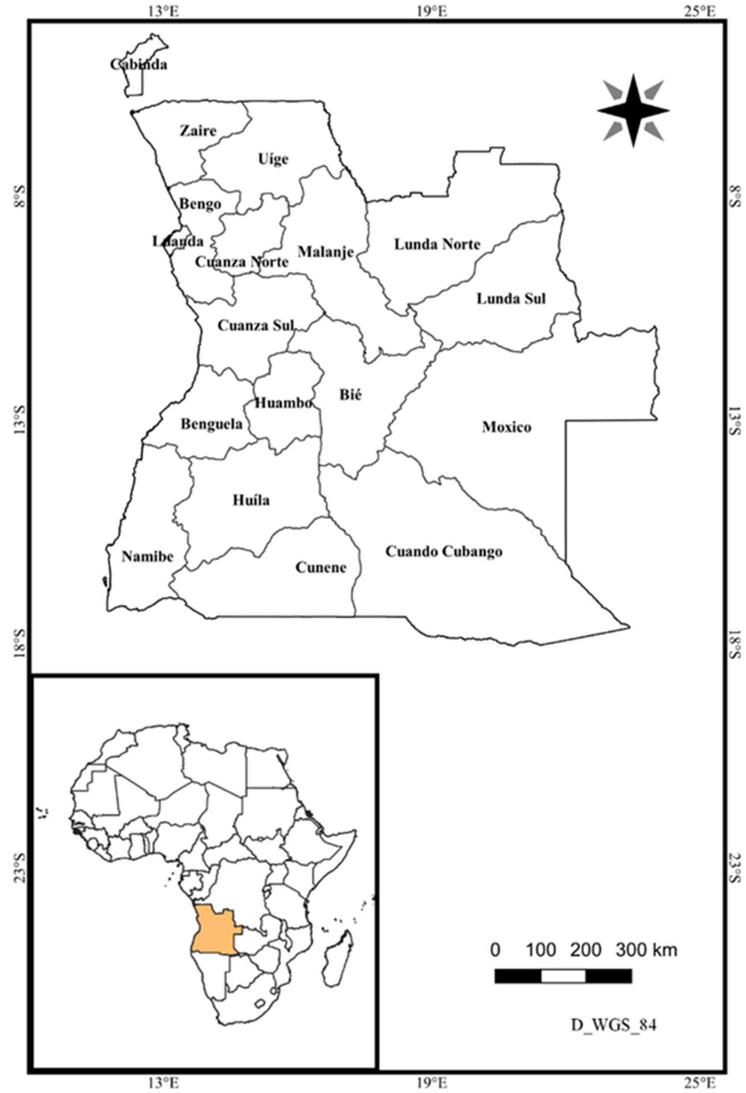

Figure 2. Location of Angola in Africa and its provinces.

In 2002, Angola emerged from 27 years of civil war that devastated the country after independence and left much of its infrastructure destroyed or damaged and most of its population displaced. Much of the existing infrastructure was built well before independence, which took place in 1975. Angola is potentially one of the richest countries in the world in mineral and natural resources [32]. Oil production and its supporting activities contribute to approximately 50% of GDP (Gross Domestic Product), more than 70% of government revenues, and more than 90% of the country's exports [31,33] The unemployment rate in Angola reaches almost half of the population, and approximately 70% of Angolans live below the poverty line (with less than 2 USD per day), with poverty being more prevalent in rural areas (58%) than in urban areas (19%) [31]. Rapid industrialization and urbanization have led Angola to become a major consumer of energy, and its energy expansion has caused much concern [34].

Access to energy is a particular difficulty in Angola. Around 46% of the population has access to electricity, corresponding to 61% in urban areas and dropping to 6.2% in rural areas. In addition, the supply has not been reliable, as blackouts occur frequently. More than half of the population, i.e., 18.3 million Angolans, do not have access to electricity [35]. Angola's electricity is generated essentially by hydropower plants (61%) and thermal plants burning oil products (38%). New renewables, such as wind, solar, and bioenergy, represent less than 1% of the energy consumed in the country [31,36]. It is estimated that 58% of the energy used by the population for cooking comes from biomass (Figure 3), mainly in rural areas, where most of the country's poor population is concentrated [37,38].

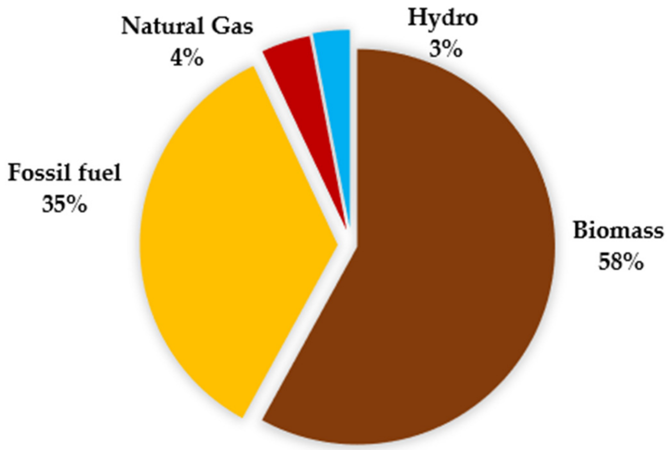

Figure 3. Angola's primary energy consumption, 2021 [38].

For the Angolan government, the energy sector is seen as essential for improving the country's socio-economic situation, and investments in bioenergy seem attractive [32]. By introducing bioenergy, in addition to energy security, it would provide access to energy services without adverse impacts on health and the environment and income-generating activities for the poor, which could alleviate poverty [22]. Specifically, the production of ethanol from sugarcane is considered a way to reduce dependence on oil revenues and make Angola self-sufficient in energy. The potential use of electricity from sugarcane bagasse can serve as an incentive for the implementation of bioenergy and mitigate energy poverty in the Angolan electricity sector.

In 2015, the Angolan government implemented the National Strategy for Renewable Energy. This strategy seeks to contribute to the National Energy Security Policy and Strategy by promoting the diversification of the national energy matrix, as well as the Integrated Rural Development and Poverty Fighting Programme, and promoting growth and employment. In the international context, this strategy contributes to the fight against climate change and is articulated with Angola's participation in SADC (Southern Africa Development Community) and IRENA [39].

Angola has an abundance of arable land, freshwater, and a diversity of climate conditions suitable for the production of a variety of agricultural products, including sugarcane, but this potential is underutilized [40]. Over the last decade, the area covered with sugarcane in Angola has experienced an annual growth rate of 192.3%, increasing from 12.5 thousand hectares in 2014 to 28.5 thousand hectares in 2022 (Figure 4). However, in 2022, only 1.66 thousand hectares of cane were processed by BIOCOM (Portuguese acronyms for Companhia de Bioenergia de Angola), the country's sole sugarcane mill. This processing yielded 1.17 million tons of cane, producing 109.8 thousand tons of sugar, just over 17 thousand m^3 of neutral ethanol, and more than 7.9 GWh of exported energy [41]. Given its potential for promoting bioenergy, the objective of this study was to evaluate the availability of suitable land and the production of sugarcane, which is highly efficient in the conversion of solar energy into biomass for sustainable ethanol production and electricity generation in Angola.

As follows, the methodology for this assessment is introduced, the main data sources and the computational tool used, the scenarios studied, and the criteria adopted for land suitability. Finally, the results are introduced and discussed.

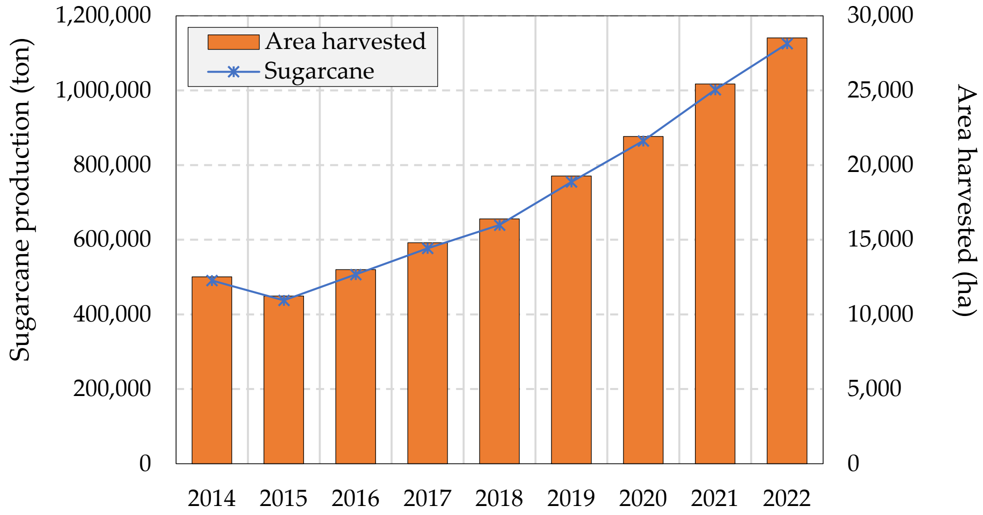

Figure 4. Area harvested and sugarcane production in Angola over the past decade (2014–2022) [42].

2. Materials and Methods

The materials and methods of this study are depicted in a flowchart (Figure 5) to visualize how the results were achieved. First, the existing literature about bioenergy was evaluated, with a focus on biofuels. Therefore, the data collection, processing, and analysis of the study were divided into two sections. In the first section, the GAEZ (Global Agroecological Zones) database and the QGIS (Quantum Geographic Information System) software (version 3.22.5) were used to evaluate land available for sugarcane in Angola. In the second section, the FAOSTAT (Food and Agriculture Statistics of FAO) database was used to complement data that could not be obtained in the first section. Areas with different restrictions were successively eliminated to obtain a pool of land available for the sustainable expansion of sugarcane. Protected areas, cultivated areas by other crops, and areas unsuitable for sugarcane cultivation were excluded. Finally, an agricultural productivity model was used to estimate the yield potential of sugarcane in the respective available areas as a function of climate parameters. The outcome of this analysis is the potential amount of sugarcane available annually, which is evaluated as ethanol and electricity possible to be produced with current technology.

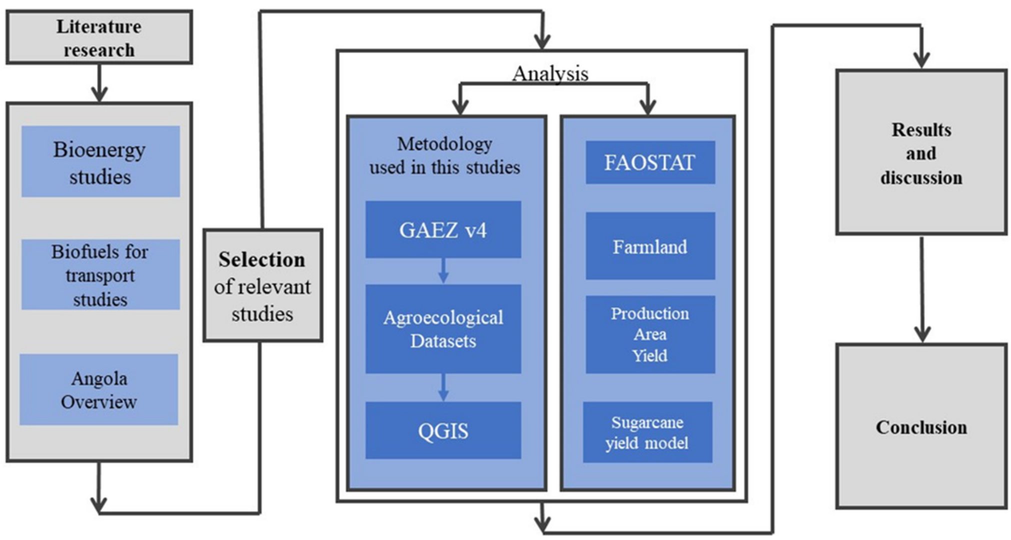

Figure 5. A flowchart of the methodology adopted in this study.

2.1. Databases and Computational Tools Employed

2.1.1. Global Agroecological Zones (GAEZ)

The agroecological zoning methodology was developed by the FAO and the International Institute for Applied Systems Analysis (IIASA) over the last 30 years. In its more recent version, GAEZ v4 is based on well-established land assessment principles to evaluate natural resources and identify appropriate agricultural land-use options. It identifies resource constraints and opportunities based on the ecophysiological characteristics of plants, soil, and climate requirements of crops and uses them to assess suitability and production potentials for individual crop types under specific input and management conditions, classifying areas into six different levels from very suitable (VS) to not suitable (NS), as shown in Table 1. According to GAEZ, total suitability of the land and cultivated areas can be summarized by the Suitability Index (SI), which ranges from SI = 0 (totally unsuitable conditions) to SI = 100 (the best conditions for a given culture), reflecting the expected productivity of a pixel of land, as indicated in Table 1 [30].

Table 1. GAEZ suitability classes.

GAEZ Suitability Classes			Maximum Achievable Yield (%)
First-class land	VS	Very suitable	80–100
Good land	S	Suitable	60–80
	MS	Moderately suitable	40–60
Poor land	ms	Marginally suitable	20–40
	vmS	Very marginally suitable	5–20
	NS	Not suitable	<5

Results are given in categories of land use, impacts of climate change on crop production potential, and irrigation water needs for current and future climates. For Angola, the sugarcane production potential was estimated for the reference climate (period 2011–2040).

2.1.2. QGIS Software

In this study, the geographic information software QGIS-Białowieża (version 3.22.5) was used, which allows for users to create, edit, view, analyze, and publish georeferenced map information. This software was used to process data and vector layers obtained from GAEZ and to process and display data results, such as land cover maps, Digital Elevation Models, and calculation of areas in the region of interest, in the frame of the Angolan territory, for which administrative maps were obtained from the Global Administrative Areas database, GADM, July 2015, in version 2.5. [43].

2.1.3. Global Food and Agriculture Statistics of FAO (FAOSTAT)

This large database provides access to food and agriculture data for over 245 countries and territories and covers all activities of the Food and Agriculture Organization of the United Nations, collected since 1961, including land cover and use, agricultural activities (annual, permanent), input consumption, irrigation, production volume, prices and trade, environmental impacts and constraints, sustainability, and SDG indicators.

2.2. Scenarios Studied and Minimum Suitability Index

To evaluate the suitability of sugarcane culture in the Angolan territory, two scenarios were studied: under rainfed conditions and irrigation conditions. Considering the SI for sugarcane, it was assumed that the area for implementing this culture, both under rainfed and irrigation conditions, to be adopted in the bioenergy production scenarios would be only those with SI > 75 (very suitable and top quality suitable), i.e., only land with high potential for sugarcane.

2.3. Restrictions

Sugarcane expansion areas must comply with sustainability and current legislation, especially regarding areas designated by law for environmental conservation. GAEZ respects landmarks with protected status or with recognized biodiversity value. Therefore, area exclusions were made to estimate the land available for sugarcane production in Angola. Many of these exclusions may be related to soil and climate conditions. Assessing the current land cover was essential for sustainable land management to obtain information for the planning, development, and management of the Angolan territory.

The first screening considered the protection of biodiversity in sugarcane production, excluding protected areas, as indicated by the International Union for Conservation of Nature and other sources. The second screening excluded the current cultivated area of sugarcane and other temporary and permanent crops. Even though they were not considered unsuitable, areas with sugarcane were excluded at this stage of the study, as the objective of the study is to seek new frontiers for expansion.

The third screening focused on topography, aiming to protect the soil and reduce the risk of erosion. Sloping terrain is subject to higher rates of water runoff and soil erosion, and it is generally understood that the steeper the slope, the greater the restriction on productivity potential, especially relevant when considering mechanized cultivation [30]. Although sugarcane has been cultivated in some countries in lands with slopes up to 30% and even higher, a maximum slope of 16% was considered a safe suitability criterion for sugarcane cultivation in this study.

2.4. Sugarcane Yield Model and Bioenergy Potential

Assuming that the GAEZ considers soil fertility requirements for sugarcane cultivation, we adopted the model presented by IRENA [28] apud Moraes et al. [44] to estimate the productivity potential of sugarcane under appropriate agricultural practices in various climatic conditions. This model, which predicts sugarcane productivity in southern Africa, takes into account thermal and climatic effects according to Van Köppen's classification (mostly Aw, tropical savanna, and Cw, subtropical with dry winter):

$$Y = 80.0 + 0.01\ DD - 0.1\ HD \tag{1}$$

where

Y = Average yield of sugarcane stalks [t/ha];
DD = Degree Days for temperature based on 20 °C [°C-day];
HD = Annual hydric deficiency for 100 cm depth [mm].

The theoretical energy potential of sugarcane and its associated annual GHG mitigation were estimated based on the ethanol and electricity potential production from sugarcane annually produced in Angola under the following assumptions, reflecting the current state of the art in modern sugarcane agro-industry:

1. Ethanol production from direct sugarcane juice: 85 L/t of sugarcane [28].
2. Electricity surplus generation: 185 kWh/t, as observed in cogeneration schemes burning bagasse from mills and 40% sugarcane straw from harvest without preharvest burning and adopting high-quality live steam conditions (65 bar/485 °C) [28].
3. Life Cycle Analysis (LCA) emission factors of gasoline and anhydrous ethanol assumed respectively as 86.4 and 21 gCO_2-eq/MJ [45].
4. LCA emission factors for power generation by diesel and natural gas adopted as 829 and 518 gCO_2-eq/kWh, respectively [46].
5. LCA emission factor for generating electricity using sugarcane bagasse and straw assumed as 227 gCO_2-eq/kWh [47].
6. Lower Heating Value (LHV) of gasoline and anhydrous ethanol, as 32.10 MJ/L and 22.30 MJ/L, respectively [48].

3. Results and Discussion

This section presents the main data on land use in Angola and the areas estimated as suitable and with potential for sugarcane cultivation and their production potential. The current coverage of Angolan territory is depicted in Figure 6 and Table 2, confirming the great importance of forests and wooded lands, about 61% of the national territory. On the contrary, a relatively small area is dedicated to agriculture. Figure 7 and Table 3 show the percentages of the protected areas, totaling approximately 13.2 Mha, which represents around 11% of Angola's territory (the percentages in all tables are related to the national land).

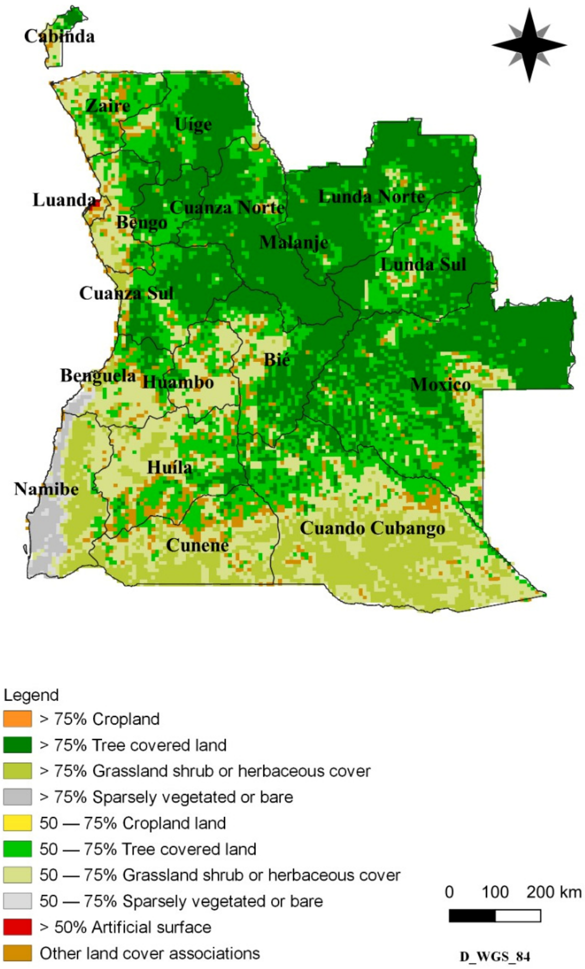

Figure 6. Land cover map of Angola.

Table 2. Angola's land cover areas.

Land Cover	Areas (1000 ha)	%
Forest land: >75%	44,490	35.7
Shrub or herbaceous cover: >75%	14,540	11.7
Sparse or bare vegetation: >75%	1660	1.3
Cultivated land: 50–75%	10	0.008
Wooded land: 50–75%	31,740	25.5
Shrub or herbaceous cover: 50–75%	25,220	20.2
Sparse or bare vegetation: 50–75%	690	0.55
Artificial surface: >50%	50	0.04
Other	7350	6.0

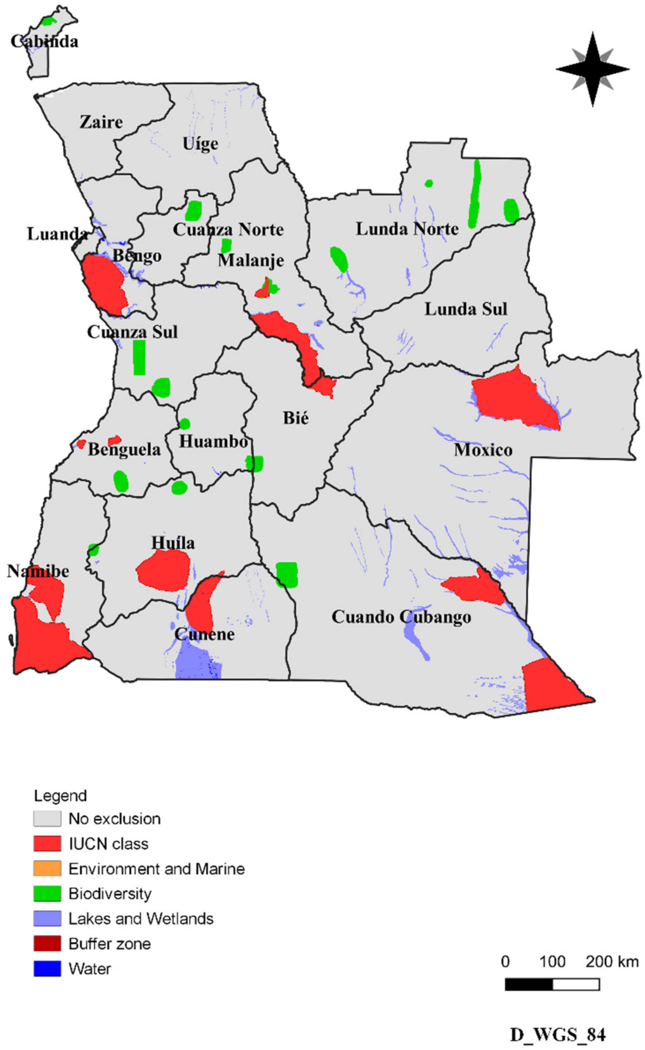

Figure 7. Angola's protected areas.

Table 3. Angola's protected areas.

Classes	Areas (1000 ha)	%
IUCN classes	8269	6.6
Marine and environment	2	0.002
Biodiversity	1828	1.5
Lakes and wetlands	2697	2.2
Neutral zone	376	0.3
Water bodies	64	0.05
Total	13,236	10.6

The area currently planted with sugarcane and other crops was obtained from FAOSTAT [42]. These areas were identified to ensure that the additional production of sugarcane does not affect the country's current level of agricultural production. The actual area with sugarcane in Angola is estimated at 20,000 ha, with a production of 951 kt/year. The land suitable for agriculture in Angola accounts for 57 Mha, which represents 45.7% of the country's total land, of which only 14.3 Mha are in activity; areas that have been excluded represent almost 11.4% of the country's area (Table 4).

Table 4. Angola's areas suitable for agriculture and that are in use.

Land Use	Area (1000 ha)	%
Area of land suitable for agriculture	56,952	45.7
Cultivated area	5215	4.2
Area of arable land	4900	3.9
Area of land under temporary crops	3721	3.0
Area of land under permanent crops	315	0.3
Area of land equipped for irrigation	86	0.07
Area planted with sugarcane	20	0.02

As mentioned in the Methodology section, a maximum slope of 16% was adopted as a criterion of suitability for sugarcane cultivation, resulting in a total of 37.7 Mha, representing approximately 30% of the country's area (Figure 8).

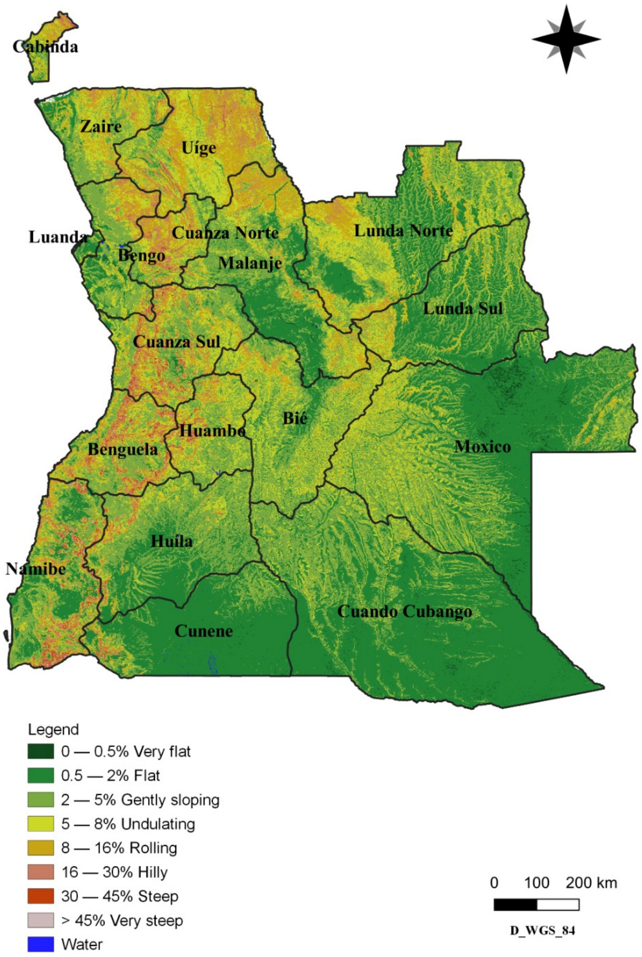

Figure 8. Slope map of Angola.

In synthesis, from the country's total area, around 125 Mha, approximately 60 Mha (48%) can be considered without strong restrictions and, in principle, is available for sugarcane focusing on bioenergy production. The next topics explore additional constraints related to water availability for irrigation needs and productivity levels.

3.1. Sugarcane Suitability in Rainfed Conditions

The suitability for growing sugarcane under rainfed conditions varies substantially between the country's regions, with prime and good land for rainfed sugarcane largely concentrated in the northern and eastern parts of the country (Figure 9). When considering just rainfed cultivated land, the GAEZ results (Table 5) show that approximately 0.6% of Angola's territory is prime land with a high production potential, 35% of the territory represents good land with an average yield for sugarcane cultivation, and 42% of the country's area is poor land with a low yield for sugarcane cultivation. The good-to-very high SI land corresponds to 44.8 Mha.

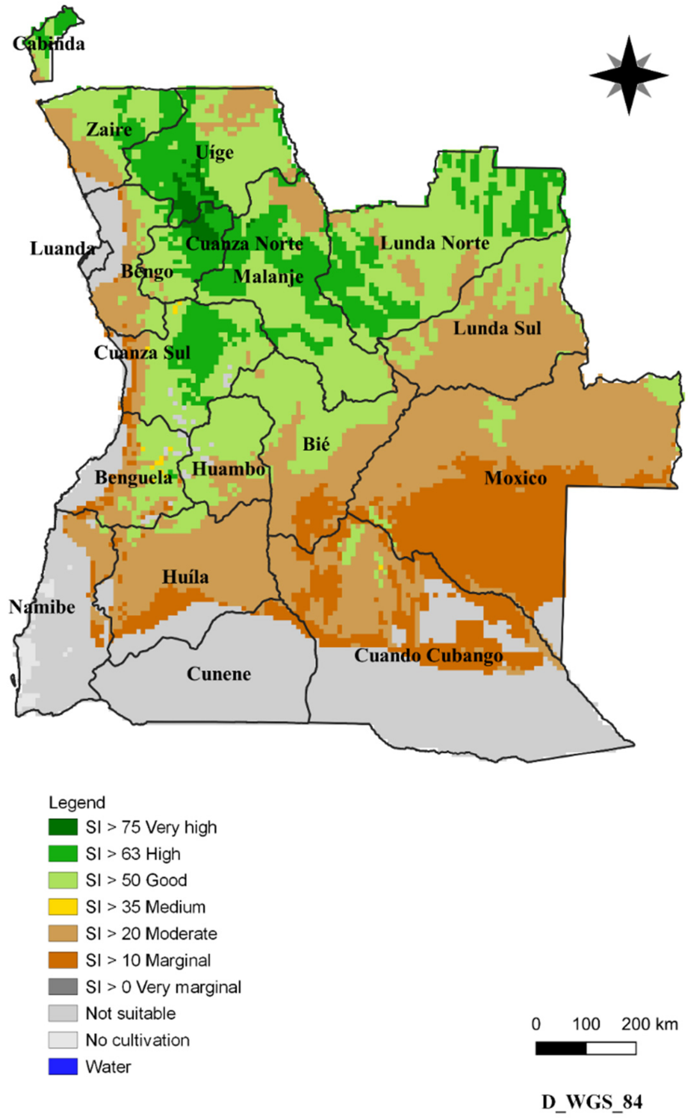

Figure 9. Sugarcane Suitability Index under rainfed conditions.

Table 5. Sugarcane suitable area under rainfed conditions.

Suitability Index	Areas (1000 ha)	%
SI > 75 Very High	740	0.6
SI > 63 High	12,190	9.8
SI > 50 Good	31,930	25.6
SI > 35 Medium	120	0.1
SI > 20 Moderate	36,670	29.0
SI > 10 Marginal	15,620	12.5
SI > 0 Very marginal	0	0
Not suitable	27,960	22.0

3.2. Suitability of Sugarcane under Irrigated Conditions

With irrigation (Figure 10), the suitability of sugarcane cultivation is improved, including areas with a low rainfall rate and significantly increasing land for the expansion of sugarcane cultivation for bioenergy purposes. From the results obtained from the GAEZ assessment, approximately 6.3 Mha (5%) of prime land for irrigated sugarcane cultivation, 117 Mha (94%) of good land, and 1.7 Mha (1%) of poor land with low yield/potential for irrigated sugarcane cultivation were identified (Table 6). Therefore, in regards to the rainfed land, irrigation increased in 275% of the potential land for sugarcane in Angola.

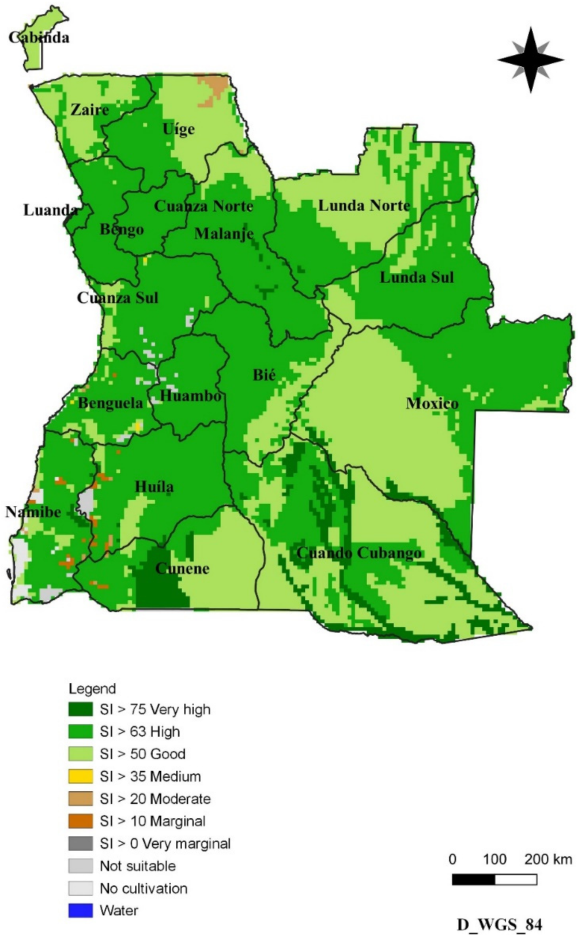

Figure 10. Sugarcane Suitability Index under irrigated conditions.

Table 6. Sugarcane suitable area under irrigated conditions.

Suitability Index	Areas (1000 ha)	%
SI > 75 Very High	6259	5.0
SI > 63 High	73,790	59.0
SI > 50 Good	43,290	34.0
SI > 35 Medium	30	0.02
SI > 20 Moderate	470	0.4
SI > 10 Marginal	330	0.3
SI > 0 Very marginal	0	0
Not suitable	910	0.7
Water	530	0.4

3.3. Rainfed vs. Irrigated Conditions

Considering Tables 5 and 6, as the land for sugarcane expansion for both conditions would be high-quality land with high potential, i.e., very suitable (SI > 75), approximately 0.7 Mha would be land for sugarcane cultivation under rainfed conditions, which would not be viable due to the terrain conditions. The areas suitable for dry farming are concentrated in the provinces of Uíge and Cuanza-Norte, which represent mostly non-mechanizable areas (slopes above 16%) that have been excluded from the availability of land for sugarcane cultivation.

On the other hand, 6.3 Mha (SI > 75) of land suitable for growing irrigated sugarcane has been identified in seven provinces of the country with characteristics and availability for the introduction of sugarcane bioenergy. The area currently planted with sugarcane in Angola represents 0.3% of the potential area estimated under irrigated conditions in this study, i.e., that area identified as suitable and available for irrigated sugarcane in Angola is 315 times larger than the area currently used to grow sugarcane.

Although sugarcane is relatively more efficient in water use than most other plants, enough water is essential to improve sugarcane yields. Angola has a large hydrological network, with 6152 rivers spanning 154,035 km in length, providing considerable water flow rate, and in principle, the regions suitable for irrigated sugarcane have compatible water resources according to the results obtained by [23,49] and the MINEA (Angola Ministry of Energy and Water) projections [39] on irrigation. Nevertheless, a detailed evaluation of water resource availability is essential before considering any area as effectively available for promoting irrigated sugarcane culture.

3.4. Distribution of Prime Land and Production Model by Province

Disregarding logistic constraints, seven provinces have the best potential areas (top-quality land) for expanding sugarcane production under irrigated conditions (Table 7). Particularly the provinces of Cuando Cubango and Cunene in southern Angola present 5.34 Mha of very suitable land, which means 85% of the identified best land for sugarcane in this country, corresponding to 11.9% of both provinces and 4.3% of the national area. Jointly, these provinces have about 1.54 million inhabitants, less than 5% of Angolan population, mostly dedicated to subsistence rural activities, such as livestock breeding, charcoal production, and the cultivation of vegetables [50]. In this context, projects to grow and process sugarcane, properly designed and implemented, can promote sustainably the regional economy. Other provinces with suitable areas have larger populations [51].

Table 7. Province area and sugarcane suitable area under irrigated conditions.

Province	Province Area (Mha) [1]	% [2]	Suitable and Available Land SI > 75 (1000 ha)	% [2]
Cuando Cubango	18	14.4	3866	3.10
Cunene	8	6.4	1474	1.18
Huíla	7	5.6	76	0.06
Lunda-Norte	9	7.4	34	0.03
Malanje	9	7.4	152	0.12
Moxico	20	16.0	539	0.43
Namibe	4	3.2	118	0.09
Total	85	53	6259	5.01

[1] Remaining areas after excluding protected areas; [2] Refers to the national area.

From the slope map (Figure 8), it is evident that the selected areas for sugarcane cultivation are within favorable slope ranges for implementing irrigation systems and introducing mechanized harvesting: Cuando Cubango (0.5–2% slope grade), Cunene (0.5–2%), Huíla (2–5%), Lunda-Norte (2–5%), Malanje (2–5%), Moxico (0.5–2%), and Namibe (2–5%).

The fertility of the soil is determined by its physical and chemical properties for optimal use and the production of crops. In [52], the reference soils suitable for planting sugarcane are Ferralsols, Arenosols, Nitisols, and Acrisols. In the provinces of Huíla and Malanje, the high-potential soils are mainly Latosols; they are deep, porous, well-drained, and permeable, even when very clayey, and they are easy to prepare. In the provinces of Cuando Cubango, Cunene, Lunda Norte, Moxico, and Namibe, the soils with high potential are Arenosols, with limited moisture (Figure 11), but they become productive when well managed and irrigated.

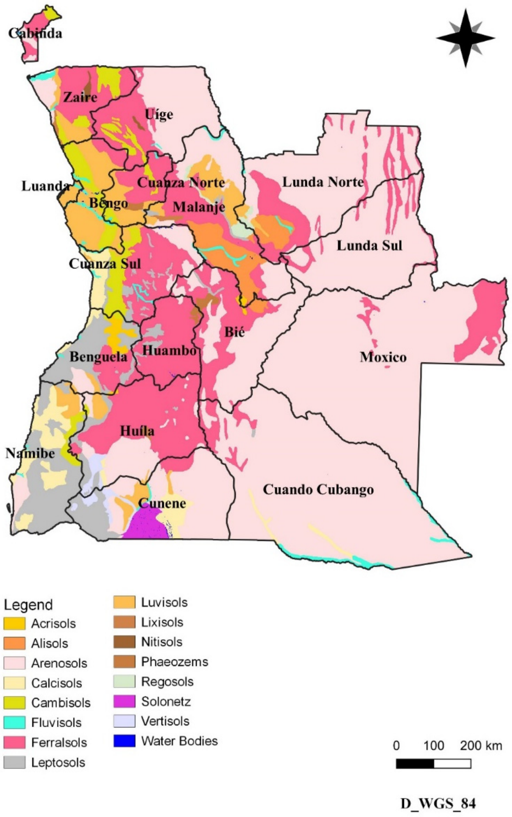

Figure 11. Soil types in Angola.

The estimated sugarcane yield depends, as previously stressed, on ensuring enough water resources. Specifically on irrigation, particularly the provinces of Cuando Cubango and Cunene encompass an extensive network of rivers, with a good water supply as well [53].

The production model presented in Equation (1) was readily applied using available climate data. Data on climate conditions, measured in degree days, were based on the GAEZ platform. Water deficiency was assumed zero for irrigated conditions. Table 8 summarizes the data and yield estimates for irrigated culture, as modeled for the Angolan provinces under analysis in this study.

Table 8. Sugarcane production modeling data and estimated yield under irrigation.

Province	Degree's Day (°C-day)	Yield (ton/ha)
Cuando Cubango	8907	155.5
Cunene	8917	146.8
Huíla	8433	132.0
Lunda-Norte	9347	157.9
Malanje	7589	155.9
Moxico	8906	155.6
Namibe	8579	133.5

3.5. Theoretical Bioenergy Potential and Associated GHG Mitigation from Irrigated Sugarcane in Angola

Considering the 6.26 Mha of land identified as suitable and available for expanding sugarcane under irrigation, circa 5% of Angola national land (Table 7), and applying the yield estimates from Equation (1) for irrigated conditions (Table 8), approximately 956 million tons of sugarcane could be produced annually. Processing this amount of feedstock could produce 81.3 billion liters of ethanol and generate 176.9 TWh of surplus electricity for the grid.

This impressive potential is even higher than the current bioenergy production from sugarcane in Brazil, where around 10 Mha are cultivated with sugarcane, basically in rainfed conditions, producing annually circa 600 Mton, about 50% processed for ethanol. The better performance of Angola must be attributed to the irrigation, which allows for an average yield estimate of 153 ton/ha for Angola, while in Brazil, it is 81 ton/ha and the full use of sugarcane for energy assumed in this assessment.

The use of anhydrous ethanol in Angola in an E10 blend with gasoline allows for a reduction in emissions of about 500 ktCO_2-eq/year in the transport sector. Alternatively, it is possible for a higher reduction, 8.3 MtCO_2-eq/year, by replacing all gasoline consumed in this country in 2021 [25]. Additionally, considering the export of a surplus volume of ethanol to replace gasoline consumed overseas and assuming a 10% reduction in mitigation to compensate GHG emissions from logistics, Angolan ethanol could mitigate the emission of more 49.1 MtCO_2-eq/year abroad.

In 2021, Angola produced 16.4 TWh of electricity, with over 70% of the country's electricity consumption coming from diesel-powered thermoelectric plants [54]. If the electricity produced from bagasse were to replace the electricity currently produced by the diesel and natural gas thermoelectric plant in Angola, it could potentially avoid approximately 3.4 MtCO_2-eq/year. This shift could contribute significantly to a cleaner electricity sector for Angola, a country highly reliant on fossil fuel generation. Summing up all contributions, a total reduction in emissions of up to 60.8 MtCO_2-eq/year could be expected.

These figures confirm Angola's large potential for bioenergy production as well as its relevant effect on the mitigation of GHG emissions.

4. Conclusions and Final Comments

This study was developed using an agroecological zone-modeling database, taking into account recommendations focused on environmental preservation and the sustainability of biofuel production. The results of the assessment of land suitability for sugarcane cultivation in Angola indicated that there is substantial potential to expand sugarcane bioenergy production. The growth of agricultural production in Angola can be accompanied by an expansion in the production of biofuels from sugarcane, helping to mitigate CO_{eq}, both in the electricity sector and in transportation, as well as helping the country to diversify its energy matrix.

As the main results, around 6.3 Mha of potential land suitable for growing irrigated sugarcane has been identified, around 5% of the Angolan territory, distributed across seven provinces in the country with characteristics and availability for the introduction of sugarcane bioenergy. In this area, Angola could produce approximately one billion tons of sugarcane annually, a feedstock amount large enough to produce ethanol to replace all gasoline domestically consumed and trade relevant surplus and generate ten times the current electricity consumption, thus promoting important reduction in GHG emissions.

This evaluation in Angola presented results like other countries in the African southern countries with low liquid fuel consumption and large land availability, indicating that sugarcane expansion has a high potential to replace fossil fuels with active bioenergy programs without compromising biodiversity and water use [18]. In Mozambique, for example, at least 33 Mha are considered to have good potential for promoting sugarcane expansion with high productivity [55]. In fact, these drivers have been progressively perceived, and a modern sugarcane processing plant, BIOCOM [41], aiming to produce sugar and bioenergy, was deployed in Angola by crushing 1.17 million tons of sugarcane per year, harvested in 28.5 thousand ha plantation; started to operate in 2018; and employs around 32,000 people (directly and indirectly).

Angola confronts socio-economic and energy challenges, underscoring the critical need for adopting clean energy sources. The absence of policies, government incentives, and investments in the bioenergy sector presents a significant barrier to developing sugarcane-based bioenergy. Introducing bioenergy would not only bolster energy security but also ensure access to energy services without compromising public health and the environment. Moreover, it would create income opportunities for marginalized communities, thereby contributing to poverty alleviation. Consequently, implementing bioenergy will facilitate the shift towards sustainable development, improving environmental quality, social well-being, and living standards across the nation.

In the southern provinces of the country, people engage in various activities to ensure food security, including participating in market activities and casual labor; selling livestock, charcoal, and firewood; and cultivating vegetables. Given these circumstances, introducing sugarcane cultivation in these regions could diversify agriculture and serve as an additional source of livelihood. Angola is currently rebuilding its infrastructure after a 27-year civil war, and sugarcane bioenergy presents a sustainable and economically viable development opportunity for the nation. With 85% of Angola's workforce involved in agriculture, growing raw materials for bioenergy has the potential to catalyze social and economic transformation within this sector.

Despite numerous barriers and obstacles, including food insecurity, poverty, and high population growth rates, the sugarcane agro-industry holds potential for fostering social and agricultural development, enhancing food security, and advancing modern bioenergy. However, achieving this synergy in Angola will require a clear vision, good governance, and the adaptation of technologies, knowledge, and business models to local circumstances. Integrated strategies to produce food crops, livestock, and bioenergy offer a promising alternative to specialized land-use models [14].

Sugarcane-based bioenergy can therefore be a transformative force in Angola, offering social benefits across multiple sectors that extend far beyond energy supply. To maximize these benefits, institutionally inclusive multisectoral legislative structures will be more effective than exclusive monosectoral approaches.

The authors expect that this study will be useful for promoting bioenergy projects in Angola as well as be used as a tool for sustainable energy planning in this country and others with similar conditions and prospects.

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