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# A GIS Approach Land Suitability and Availability Analysis of *Jatropha Curcas* L. Growth in Mexico as a Potential Source for Biodiesel Production

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**Abstract:** *Jatropha curcas* L. (JCL) commercial plantations in Mexico, one of the most important JCL origin centers, have failed due to a variety of biological, political and technical factors affecting their productivity. This study explores feasible sites of JCL cultivation as a potential source for biodiesel production in Mexico, given agroclimatic and agroecological considerations. We propose a GIS-based approach for estimating suitable and available lands to grow JCL by integrating an Analytical Hierarchy Process (AHP) in the ArcGIS software. Spatial analysis combined multiple data, different evaluation criteria, three land availability classes (high, medium and low potential) and took into account ecological, ethical, and political restrictions, and considering two scenarios with different restriction levels. Suitability and availability maps were generated using agroclimatic information (climatic, land use/soil, and climate change and extreme weather events risk) together with other socioeconomic factors. Approximately 15.3% of Mexican territory is available for JCL production yielding a biodiesel production of 9.683 $Mm^3$/year. Amelioration of the available land is necessary to improve land selection. GIS-based analysis represents a first approach to establish a successful biodiesel project that avoids, competition with food or feed production, maintains biodiversity conservation, and promotes biofuel supply chain development. This procedure would also be applicable to other energy crops such as oil palm and *Ricinus communis*.

**Keywords:** agroenvironmental mapping; energy crop; *Jatropha curcas* L.; land suitability

## 1. Introduction

The increased interest in the exploitation of inedible oilseed crops as biomass to produce second-generation biofuel has been essentially motivated by diversification of the energy matrix to energy security in order to decrease greenhouse gas emissions and to promote urban and rural sustainable development [1,2]. The renewable energy feedstock selection for conversion to biofuels depends on key factors for achieving success and sustainability, emphasizing economic, social and environmental aspects such as land availability, ecosystem conservation, future food security, and agriculture productivity [3,4]. Currently, the world supply of biodiesel is based on edible crops with relatively low productivity of biofuel per unit area such as soybean (566 kg $ha^{-1}$ year) and rapeseed (862 kg $ha^{-1}$ year) [5]. Thus, the main limitation of this industry to produce biofuel from oily crops is the upstream oil productivity (L $ha^{-1}$), because the refined oils transesterification process is a mature technology. In addition, low productivity at the agricultural stage is directly associated to the operating cost to produce biodiesel since the price of vegetable oil can represent up to 77% of its total manufacturing cost [6].

*Jatropha curcas* L. (JCL) has emerged as a promising alternative feedstock for biodiesel production due to multiple attributes, notable agronomic characteristics and economic viability with environmental benefits such as its remarkable oil yield (1892 L $ha^{-1}$) higher than other energy crops like soybean and canola (446 L $ha^{-1}$ and 1190 L $ha^{-1}$, respectively) [7]. Likewise, its oil content (40–60%) that is greater than that of soybean (12–24%), and its fatty acid profile that is suitable for obtaining biodiesel with good vehicle performance in blends with diesel fuel [8–11], In addition, it is susceptibility to only a few pests and diseases and is resilient to environmental stresses such as droughts and soil hardness [12,13]. However, several efforts and production projects in countries such as Mexico, India, China, Ethiopia, Mozambique, and Ghana have failed or were truncated due to factors affecting levels of productivity like soil requirements, agroclimatic conditions, agronomic practices and supply chain network challenges, among others [14,15]. Despite setbacks and inherent risks, there is persistent focus to take advantage of JCL multi-dimensional capacity to primarily produce biodiesel, in addition to other products [16–18].

Nowadays, the identification and selection of suitable and available land to grow inedible oilseed crop, like JCL, demands observance of three dimensions—societal, economic and environmental—to reduce negative environmental impacts and avoid displacing other crops used for food and/or animal feed [19,20]. From this perspective, several research groups have focused their efforts to integrate territorial characteristics (e.g., land use), climatic information and some socioeconomic aspects to improve land allocation for biomass crop cultivation [21,22].

Countries like China, Uganda and India have shown awareness in agroecological zoning of JCL using an integrated Geographical Information System (GIS) and Remote Sensing (RS) approach that combined meteorological conditions, ecosystem services, roads, settlements, transmission, distribution lines, population density, transportation costs, cost of cultivation, land use policy and regulation and local economic structures. Their studies have shown that abandoned, degraded, and/or marginal lands could represent a good opportunity for biomass energy production [23–25]. A GIS approach in land use suitability mapping and analysis has been used as a decision support tool for spatial planning and management for agriculture. The integration of GIS technology into the multicriteria decision-making approach (MCDA) has become an updated trend in agricultural land suitability classification [26]. The Analytical Hierarchy Process (AHP), based on human judgment ability to structure a multicriteria problem can combine qualitative and quantitative aspects of opinions given by the experts and is formed by main goal, criteria, sub-criteria or variables, and alternatives [27]. This procedure enables integration of different environmental, social and economic data, and depends on the basic units of aggregated observations (according to the selected criteria). Likewise, it allows for questions to be answered that are either related to possible sites that meet natural resource potential, or on the other hand, restricted areas; nevertheless, it can certainly help make a decision on sustainable production of biodiesel [28,29].

Biomass energy use and its production in Mexico has been anticipated since 2007 [30], but the bioenergy potential of the country remains largely unexploited [31]. Unfortunately, the Mexican strategies to assess the potential land availability for energy crops production has been carried out without integrating joint ecological, ethical, political, and technical restrictions, and were mostly based on decisions starting from studies that basically evaluated land agroecological attributes to grow this energy crop [32–37], while disregarding many other key factors that affect its sustainable cultivation.

Mexico, one of the most important JCL centers of origin, has high diversity and genetic richness as well as the potential for the creation of various JCL varieties with favorable agronomic characteristics and high-quality oil (12 to 60%) for biodiesel. These features are worth bearing in mind, in such a way that rational planning could derive a crop with higher and long-term profitability [38–42]. Furthermore, Mexico is part of the North American continent, where the main biodiesel producer—the United States—is located, [5]. Recognizing these viewpoints, the goal of this study was to explore feasible sites of JCL cultivation for biodiesel production in Mexico. To meet this goal, we performed a GIS approach land suitability and availability analysis for growing JCL. The identification and quantification of propitious land integrated several factors, like areas with suitable growth conditions for JCL and others. For equally important sustainability and ecological considerations, we collected ecological, ethical, political, and technical restrictions with the purpose of reducing both probable competition with food crops and controversies from environmental and socioeconomic perspectives. This study is the first in Mexico to consider this kind of information to guarantee food security, ecosystem conservation and promoting the biomass supply chains compared with other studies [33,37]. Also, the article contributes by highlighting the productive capacity of Mexico for JCL cultivation and provides a detailed analysis on where it could be exploited it, considering other limiting factors. For this reason, a MCDA was applied, specifically AHP method, and integrated with GIS application environments to assess of suitable and available land for the growth of JCL to produce biodiesel [43–46] and supports decision-making in the development of bioenergy projects. The AHP is especially helpful when it is difficult to recognize the precise interactions between several evaluation criteria [46]. Finally, based on Google Earth's high-resolution data, and vegetation layers of corn, bean, sorghum and wheat crops from imagery SPOT [47], we carried out a visual inspection to confirm or ratify estimated areas.

## 2. Materials and Methods

### *2.1. Study Area*

JCL grows and is distributed worldwide in tropical and subtropical regions (Asia, Africa, North America and South America), primarily in the Neotropics. For this reason, the study area is the entire Mexican territory, which has a continental area of 1,959,248 km$^2$, located at 19°23′26.31″ N 99°6′8.73″ W (Figure 1), has a mean annual temperature of 22.3 °C, a mean annual precipitation of 1777 mm with a single rainy season as the main rainfall supplier, and has a Neotropical region that includes the humid and sub-humid tropical areas of southern Mexico (Mexican Pacific Coast, Mexican Gulf, Chiapas and Yucatan Peninsula), which is a region where the genus *Jatropha* has a wide natural distribution. The region also includes seasonally dry tropical forest [48,49].

### *2.2. Data Sources and Analysis*

First of all, the datasets were converted to raster format and homogenized to a spatial resolution of 1 km$^2$. Also, they were projected to geographic coordinate system, datum WGS84. The parameters selected in this study, based on literature reviews studies about land suitability analysis [43–45], were grouped in the following four criteria groups: (a) climatic criteria; (b) land and soil criteria; (c) climate change and extreme weather events criteria and (d) socioeconomic criteria, which are all identified as significant criteria that affect biodiesel projects. Figure 1 presents the spatial distribution of the thematic maps used in this study while Table 1 presents a description of datasets and data sources.

(1) Climate criteria. Annual mean temperature (since 1910 to 2009, in range value −1 to >28 °C) and averages of annual rainfall (from 1950 to 2016, values ranging 62 to 3698 mm).

(2) Land and soil criteria. Elevation (values ranged from 0 to 5610 m.a.s.l); soil type including 21 dominant classes (acrisol, andosol, arenosol, cambisol, castañozem, chernozem, feozem, fluvisol, greysol, litosol, luvisol, nitosol, planesol, ranker, regosol, rendzina, solonchak, solonetz, vertisol,

xerosol, yermosol); land cover/land use types that were gruped into 13 categories (temporary and irrigation agriculture, aquaculture, arid lands, bare land, forest, cultivated and natural grassland, jungle, mangrove, savanna, scrub, urban areas, water); food crops (corn, bean, sorghum and wheat); protected natural areas and RAMSAR sites that included beaches, mangroves, estuary, swamps, parks, biosphere reserves, among others in accordance with the creation decrees published in the Official Gazette of the Mexican Federation. Additionally, erosion grouped as water, wind, and anthropic erosion was analyzed.

(3) Climate change and extreme weather events criteria. In addition to erosion information (grouped as water, wind, and anthropic erosion), the following data was used: vulnerability to climate change; degree of drought risk; freeze hazard rate; frost duration in days; flooding vulnerability that makes areas unsuitable for JCL cultivation.

(4) Socioeconomic criteria. Aspects like distances to road networks, transportation infrastructure, to gas stations, and to power generation plants that can help promote a social value or value chain for distribution of the raw material and distribution of the final product, in this case, the biodiesel produced from the oil obtained from the JCL seed.

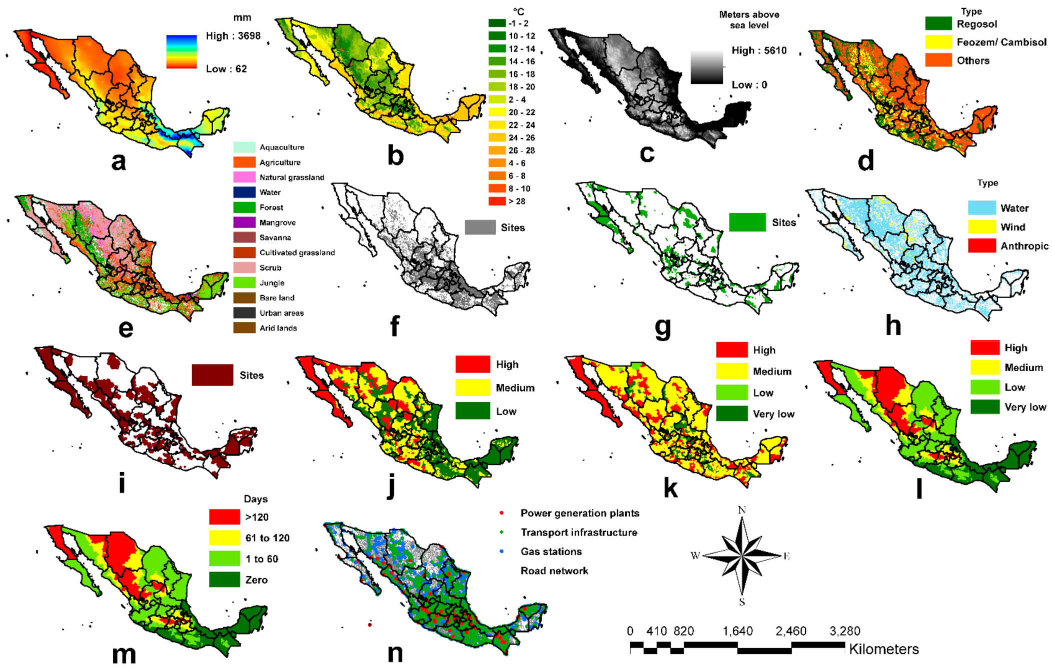


**Figure 1.** Input data: (**a**) rainfall; (**b**)temperature; (**c**) elevation; (**d**) soil type; (**e**) land use/land cover; (**f**) food crops; (**g**) protected natural areas and RAMSAR sites; (**h**) erosion; (**i**) vulnerability to climate change; (**j**) degree of drought risk; (**k**) flooding vulnerability index; (**l**) freeze hazard rate; (**m**) frost duration in days; (**n**) socioeconomic factor.

**Table 1.** Data sets and georeferenced data layers used in the GIS-based suitability and availability analysis.

| Criteria | Description of Parameters | | | | | Source |
|---|---|---|---|---|---|---|
| | Designation | Scale or Spatial Resolution | Format/Reference Method | Conversion | Reference Year | |
| Climatic | Rainfall | Each 11 km | Vector layer/Grid point data from field and cabinet work | Raster data Interpolation "Ordinary Kriging method, circular semi variogram" tool "Spatial Analyst" ArcGIS | 2016 | [50] |
| | Temperature | 1:1,000,000 | | Raster data | 2015 | [51] |

**Table 1.** *Cont.*

| Criteria | Description of Parameters | | | | | Source |
| --- | --- | --- | --- | --- | --- | --- |
| | **Designation** | **Scale or Spatial Resolution** | **Format/Reference Method** | **Conversion** | **Reference Year** | |
| Land and Soil | Elevation | 1:7500 | Raster data/Terrain-digital elevation models (DEM map) | Reclassified with tool 'Resample' ArcGIS/Raster data | 2017 | [52] |
| | Soil type | 1:250,000 | Vector layer/Photointerpretation techniques using Landsat TM-8 imagery selected in 2014 | Raster data | 2016 | [53] |
| | Land cover /Land use | 1:250,000 | | Raster data | 2016 | [53] |
| | Food crops (corn, bean, sorghum and wheat) | 1 m | Vector layer/SPOT imagery from Spring-Summer 2018 and field work | | 2019 | [47] |
| | Protected natural areas | 1:50,000 | | Raster data | 2017 | [54] |
| | RAMSAR sites | 1:50,000 | | Raster data | 2015 | [54] |
| | Erosion | 1: 250,000 | | | 2014 | [53] |
| Climate Change and Extreme Weather Events | Vulnerability to climate change | 1:50,000 | Vector layer/high spatial resolution imagery data and field work | Raster data | 2018 | [55] |
| | Degree of drought risk | 1:50,000 | | | | |
| | Flooding vulnerability index | 1:50,000 | | | | |
| | Freeze hazard rate | 1:50,000 | | | | |
| | Frost duration in days | 1: 50,000 | | | | |
| Socioeconomic | Road network | 1:50,000 | | | 2019 | [53] |
| | Transportation infrastructure | 1:50,000 | | | 2017 | |
| | Gas stations | 1:50,000 | | | | |
| | Power generation plants | 1:50,000 | | | | |

## 2.3. Methodology

The GIS-based approach to estimate suitable and available lands to grow JCL inedible oilseed crop in Mexico, was developed by integrating AHP in ArcGIS software, where the Weighted Overlay (WO) tool which was used to overlay the map layers for determining suitability [45,46,56–59]. Figure 2 presents an example of a hierarchal structure of the breakdown of a problem [58].

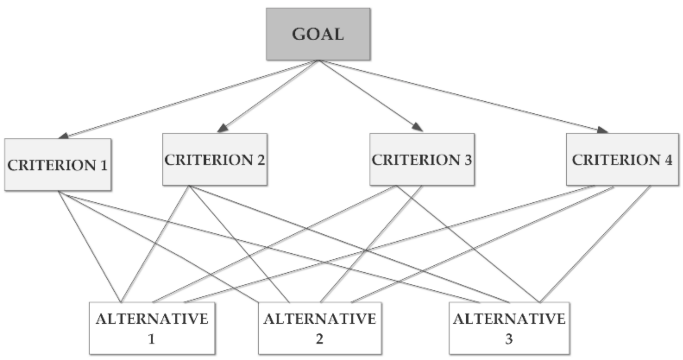


**Figure 2.** Example of a hierarchy of criteria in AHP analysis.

First, the criteria are pairwise compared for their importance of each criterion in relation to others in order to determine the main eigenvector. The importance values of each criterion were determined through the methodology developed by Saaty [58] (See Table 2).

**Table 2.** Scale for pairwise comparison.

| Intensity of Importance | Definition |
|---|---|
| 1 | Equal importance |
| 2 | Equal to moderate importance |
| 3 | Moderate importance |
| 4 | Moderate to strong importance |
| 5 | Strong importance |
| 6 | Strong to very strong importance |
| 7 | Very strong importance |
| 8 | Very to extremely strong importance |
| 9 | Extreme importance |

Ref. [58].

A pairwise comparison matrix can be mathematically expressed in the following Equation (1) [59]. The number of rows and columns is defined by the number of criteria in order to be weighed by the criteria used [58,59]. This process was conducted by using the experience of the authors and based on literature review of previous experimental studies of JCL cultivation in Mexico [60–67].

$$A = [a_{ij}],\ i, j = 1, 2, 3, \ldots, n \quad (1)$$

The spatial analysis functions of GIS through steps included the flowing: identification and collection of spatial data, weighting with the AHP, data integration and GIS analysis; output evaluation. The flowchart in Figure 3 shows the procedures carried out to achieve the objective in this study [44,45,57,58]. The suitability classes used in this study were "high potential", "medium potential" and "low potential" where "high potential" represents that the area with favorable climatic conditions for profitable production of JCL. A "medium potential" area indicates a second priority for JCL growing. Lastly, "low potential" areas represent the zones that are not appropriate for JCL cultivation. For standardization of each criterion selected, they were reclassified based on their suitability for JCL production. These levels were established based on National Institute of Forestry, Agriculture and Livestock Research (INIFAP, by its acronym in Spanish) technical reports on the cultivation of JCL in Mexico [40,68,69].

The first step was to obtain a spatial assessment of suitable areas for JCL plantation in Mexico, rethinking agroclimatic zones. Table 3 presents the classes, potentiality and suitability score of the four criteria, to achieve Agroclimatic Zoning (AZ). The suitability criteria were defined with four main physiological requirements for growth and yield of JCL: rainfall, temperature, elevation, and soil type. Based on existing literature, we selected physiological requirements that have been analyzed and evaluated in the field for the states of Michoacan, Jalisco and Chiapas [40] (p. 28) [68,69]. The elevation and rainfall information were reclassified to obtain the ranges where JCL is growing with a high, medium and low potential (Table 3). The annual rainfall between 900–1500 mm is considered optimal ranges for field-based growing conditions. Rainfall higher than 1500 mm could cause problems with fungal attack, root rot, and other diseases [43]. The suitability scores were defined for each criterion, where score 3 represents a "high potential", score 2 represents a "medium potential" and score 1 means "low potential" for JCL cultivation.

A second crucial point was to identify the type of land that can be dedicated or replaced to grow JCL in Mexico and can be used in the sustainable development of biodiesel. At this point, it is possible to evaluate several alternatives. We introduced social, environmental and economic constraints mainly based on current national government regulation, environmental policy to limit land use, climatic risk factors that can damage JCL plantation, and energy policies, such as the Law on the Promotion and Sustainable Development of Biofuel from energy crops.

In the first scenario, land use/land cover classes with environmental value and ecological relevance were included, such as forest, agriculture, mangrove and cultivated grassland, but they were classified as low potential. Meanwhile, in the second scenario, we restricted these types of areas in order to promote sustainable feedstock production within the context of food security, ecosystem conservation and reducing land use change. We worked to avoid converting given portion of the following types of land: land currently dedicated to food and livestock production; protected natural areas, and RAMSAR sites; land with climate change vulnerabilities such as, flooding, drought and frost. The output product was a land availability map that displays "high potential", "medium potential" and "low potential" areas of JCL production in Mexico, with a scale of 1:50,000. Table 4 summarizes the list of the nine criteria used to develop Agroecological Zoning (AEZ) and the score assigned to each criterion for two scenarios representing different level of restriction.

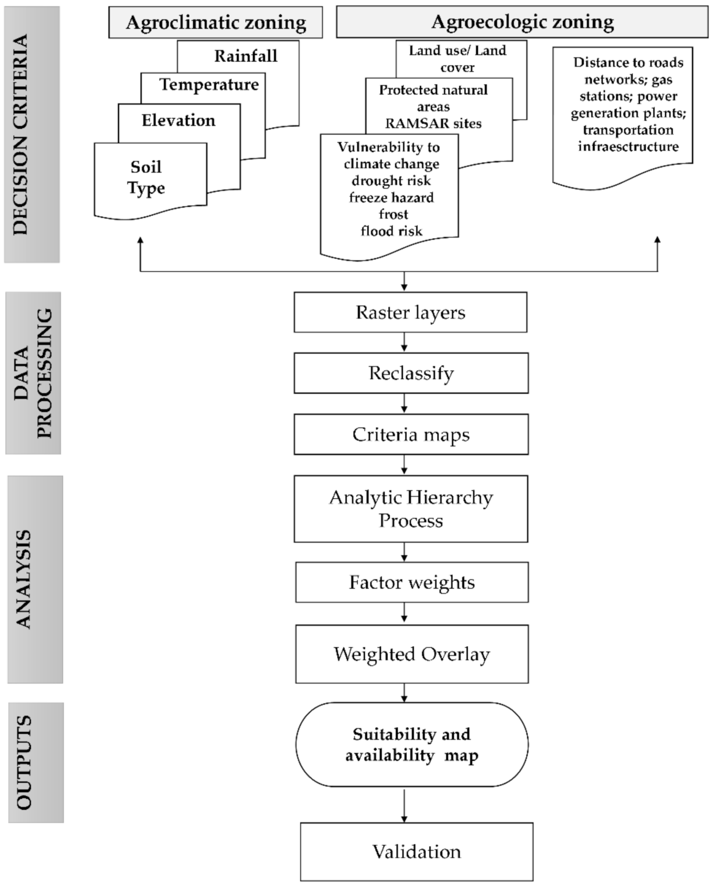


**Figure 3.** Methodological workflow developed to estimate suitability and availability of land (high potential, medium potential and low potential) for JCL cultivation in Mexico.

**Table 3.** Land Suitability Criteria for JCL cultivation to perform the AZ.

| Criteria | Units | Classes | Potentiality | Score |
|---|---|---|---|---|
| Elevation | Meters above sea level | 0–900 | High | 3 |
| | | 900–1500 | Medium | 2 |
| | | <1500 | Low | 1 |
| Rainfall | mm | 900–1500 | High | 3 |
| | | 300–900 | Medium | 2 |
| | | <300/>1500 | Low | 1 |
| Temperature | °C | 18–28 | High | 3 |
| | | 12–18 | Medium | 2 |
| | | <10/>28 | Low | 1 |
| Soil type | Type | Regosol | High | 3 |
| | | Cambisol/Feozem | Medium | 2 |
| | | Others | Low | 1 |

**Table 4.** AEZ criteria for JCL cultivation. Variables and scores of the two scenarios.

| Criteria | Classes | Scenario 1 | | Scenario 2 | |
|---|---|---|---|---|---|
| | | Potential | Score | Potential | Score |
| ACLIM | High | High | 3 | High | 3 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low | Low | 1 | Low | 1 |
| LU/LC | Aquaculture | Restricted | Restricted | Restricted | Restricted |
| | Urban zone | Restricted | Restricted | Restricted | Restricted |
| | Forest | Low | 1 | Restricted | Restricted |
| | Water | Restricted | Restricted | Restricted | Restricted |
| | Agriculture | Low | 1 | Restricted | Restricted |
| | Jungle | Low | 1 | Restricted | Restricted |
| | Cultivated grassland | Low | 1 | Restricted | Restricted |
| | Mangrove | Low | 1 | Restricted | Restricted |
| | Savanna | Low | 1 | Restricted | Restricted |
| | Scrub | Low | 1 | Restricted | Restricted |
| | Natural grassland | Medium | 2 | Medium | 2 |
| | Bare land | High | 3 | High | 3 |
| | Arid lands | High | 3 | High | 3 |
| PA | Restricted | Restricted | Restricted | Restricted | Restricted |
| NON_PA | High | High | 3 | High | 3 |
| RAM | Restricted | Restricted | Restricted | Restricted | Restricted |
| NON_RAM | High | High | 3 | High | 3 |
| VCC | Restricted | Restricted | Restricted | Restricted | Restricted |
| W_VCC | High | 3 | 3 | 3 | 3 |
| DR | High | Low | 1 | Low | 1 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low | High | 3 | High | 3 |
| FLUV | High | Low | 1 | Low | 1 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low | High | 3 | High | 3 |
| FHR | High | Low | 1 | Low | 1 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low/Very low | High | 3 | High | 3 |
| FDD | >120/61–120 | Low | 1 | Low | 1 |
| | 01–60 | Medium | 2 | Medium | 2 |
| | Zero | High | 3 | High | 3 |

ACLIM: agroclimatic zoning; LU/LC: land use/land cover; PA: protected areas; NON_PA: non-protected areas; RAM: RAMSAR sites; NON_RAM: non-RAMSAR sites; VCC: vulnerability to climate change; W_VCC: sites without vulnerability to climate change; DR: degree of drought risk; FLUV: flooding vulnerability index; FHR: freeze hazard rate; FDD: frost duration in days.

Afterwards, we completed a final analysis in which included consideration of logistical conditions around the estimated areas in scenario 2, such as the spatial distribution of road networks of road networks, gas stations, power generation plants and transportation infrastructure; "high potential" areas are represented by a distance from 0 to 15 km; "medium potential" areas by a distance from 15 to 30 km; and "low potential" area by distances greater than 30 km (Table 5).

The weights are calculated by normalizing the pairwise comparison matrix that was obtained by dividing the column elements of the matrix by the sum of each column (Equation (2)). Then, row elements in the obtained matrix were summed, and the total value was divided by the number of elements in the row as is presented in Equation (3) [59]:

$$\mathrm{A}' = [\mathrm{a}'_{ij}],\ i, j = 1, 2, 3, \ldots, n \quad (2)$$

where A′ is the normalized matrix and the $\mathrm{a}'ij$ is defined as:

$$\mathrm{a}'_{ij} = \mathrm{a}'_{ij} / \sum_{i=1}^{n} \mathrm{a}'ij \quad (3)$$

For all $i, j = 1, 2, 3, \ldots, n$. Before, criteria weights were estimated as a priority vector or weight vector as is presented in Equations (4) and (5):

$$wi = \sum_{i=1}^{n} a'ij / \sum_{i=1}^{n} \sum_{j=1}^{n} a'ij \quad (4)$$

Weights values are within 0 and 1, and their sum is equal to 1:

$$\sum_{i=1}^{n} w_i = 1 \quad (5)$$

**Table 5.** Proximity influence on available land for JCL cultivation.

| Criteria | Classes | Potentiality | Score |
|---|---|---|---|
| Agroecological zoning | High | High | 3 |
| | Medium | Medium | 2 |
| | Low | Low | 1 |
| Distance to roads (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |
| Distance to gas stations (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |
| Distance to power generation plants (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |
| Distance to transportation infrastructure (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |

Finally, the WO tool in ArcGIS software was used to estimate categories of "high potential", "medium potential" and "low potential" lands for JCL cultivation. Each criterion was multiplied with the weights assigned for each criterion to estimate the suitability index and develop the final suitability and availability maps [45,57]. For determining the relative importance of each criterion in the resultant of AHP, pair-wise comparison matrix using a Saaty's method was performed. The relative importance of the criterion of each row is calculated in relation to the criterion of its corresponding column. The entire matrix was completed by entering the upper right triangle, the values of the lower left triangle being the inverse values of those of the corresponding cells [57]. Similarly, the Consistency Ratio (CR), a measure to evaluate whether an AHP is acceptable for decision making, was calculated. Values of CR exceeding 0.10 are indicative of inconsistent judgments during pair-wise comparison because they are too close for randomness [45,57]. CR was estimated using Equations (6) and (7):

$$CR = (\lambda_{max} - n)/(n - 1) \quad (6)$$

$$CR = CI/RI \quad (7)$$

where $n$ is the number of criteria being compared, $\lambda_{max}$ is the largest Eigen value of the matrix comparation, RI is the random index representing consistency of a randomly generated pair-wise comparison matrix, which depends on the number of elements being compared (See Table 6), and CI is the consistency index (values closer to zero are more acceptable).

**Table 6.** The order of the matrix (n) and the equivalent random index (R).

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| R | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.3 | 1.4 | 1.45 | 1.49 |

## 3. Results and Discussion

Land suitability analysis for growing JCL in Mexico was determined considering historical spatial and temporal variability of two agroclimatic parameters (rainfall and temperature) for the period spanning 1950 to 2016 and 1910 to 2009, respectively, and was accompanied by terrain attributes (elevation and soil type). Table 7 presents the pair-wise comparison matrix of AZ, while Table 8 shows weights of the four criteria. The results indicate that suitable areas for JCL cultivation were mainly attributed to elevation and rainfall with importance weights of 46% and 32%, respectively. Figure 3 shows the spatial result of this analysis after applying the weight values in order to estimate categories of “high potential”, “medium potential” and “low potential” lands for the JCL cultivation. The consistency property of matrices was estimated. Table 9 presents the CR with a value less than 0.1, indicating acceptable.

**Table 7.** Pairwise comparison matrix for factor criteria in the AZ analysis.

| Criteria | ELV | RAI | TEM | SOI |
|---|---|---|---|---|
| ELV | 1 | 2 | 3 | 5 |
| RAI | 1/2 | 1 | 3 | 5 |
| TEM | 1/3 | 1/3 | 1 | 3 |
| SOI | 1/5 | 1/5 | 1/3 | 1 |
| Total | 2.03 | 3.53 | 7.33 | 14.00 |

ELV: elevation; RAI: rainfall; TEM: temperature; SOI: soil type.

**Table 8.** Weights of the four criteria of the AZ analysis using the AHP.

| Criteria | Relative Weight | Weight (%) |
|---|---|---|
| ELV | 0.46 | 46 |
| RAI | 0.32 | 32 |
| TEM | 0.15 | 15 |
| SOI | 0.07 | 7 |
| Total | 1.00 | 100 |

ELV: elevation; RAI: rainfall; TEM: temperature; SOI: soil type.

**Table 9.** Consistency indices.

| Criteria | Total of Rows |
|---|---|
| Consistency index (CI) | 0.05 |
| Random index (RI) | 0.89 |
| Consistency ratio (CR) | 0.052 |

The AZ results allowed the identification of areas with similar combinations of limitations and potential for JCL crop growth, based solely on agronomic potential. Figure 4 presents a suitability map of suitable and unsuitable lands that allows the understanding of attainable grown of JCL in certain regions.

We can see the geographical distribution of estimated areas under high potential category exhibited higher proportions of land extending towards coastal areas, mainly land adjoining the Gulf and Caribbean coasts, and to a lesser proportion, land adjoining the Pacific region. Interestingly, medium potential regions are positioned in greater proportion to the North of Mexico.

Mexico’s territorial extension estimated with “high potential”, “medium potential” and “low potential” represent 95% of the national territory (Table 10), whereas “high potential” and “medium potential” represents 82.4%.

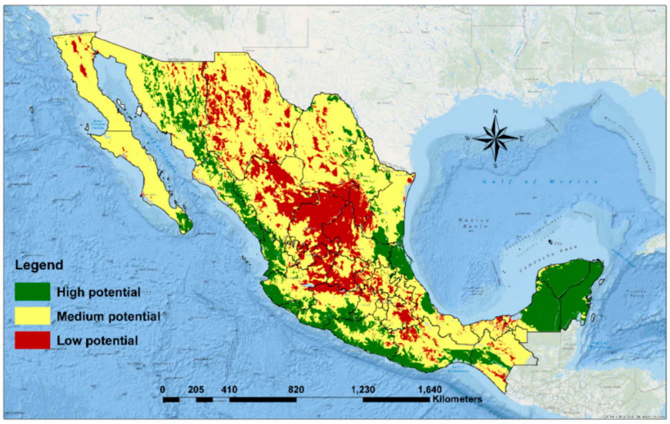


**Figure 4.** Agroclimatic spatial areas estimated for JCL cultivation in Mexico. High potential (green polygon), medium potential (yellow polygon) and low potential (red polygon).

**Table 10.** Suitable areas for JCL cultivation in Mexico.

| Potential | Area (ha) | % [1] |
|---|---|---|
| High | 39,204,911 | 21.1 |
| Medium | 113,728,651 | 61.3 |
| Low | 32,684,173 | 17.6 |
| Total | 185,617,735 | 100 |

[1] Land requirement (% of national territory).

These findings are not entirely consistent with the incipient bibliographic data available for Mexico, such as the case reported by [32], in which they reported 6,089,023 hectares for two suitability classes (high, and medium). Based on the GIS approach applied, we estimated nearly 92.5 million ha. It is very reasonable to think that the divergence from that study is of methodological nature, although the process of assigning land suitability classes was not explained in the referred study. On the other hand, we detected a significantly higher value for medium suitable land in the northern region of Mexico, where arid lands, bare land and shrubland are present and they could be used to grow JCL, without a great water supply because its cultivation subjected to an irrigation system, tends to present an increase in yield [70]. We also obtained a limited high-potential suitable land towards West, Central, Gulf, and Southern regions with the exception of the Yucatan Peninsula.

Based on the two scenarios analyzed and the assessment criteria applied on GIS-based AEZ land evaluation, the available land for JCL cultivation in Mexico is reduced. For the first scenario, Tables 11 and 12 presents the results of AHP and Table 13 show that the analysis is acceptable because CR has a value less than 0.1.

**Table 11.** Pairwise comparison matrix for factor criteria in the AEZ analysis.

| Criteria | ACLIM | LU/LC | PA | RAM | VCC | DR | FLUV | FHR | FDD |
|---|---|---|---|---|---|---|---|---|---|
| ACLIM | 1 | 1/7 | 1/5 | 1/5 | 1/7 | 1/7 | 1/7 | 1/7 | 1/7 |
| LU/LC | 7 | 1 | 1/3 | 1/3 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 |
| PA | 5 | 3 | 1 | 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| RAM | 5 | 3 | 1 | 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| VCC | 7 | 5 | 3 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 |
| DR | 7 | 5 | 3 | 3 | 2 | 1 | 1/2 | 1/2 | 1/2 |
| FLUV | 7 | 5 | 3 | 3 | 2 | 2 | 1 | 1/2 | 1/2 |
| FHR | 7 | 5 | 3 | 3 | 2 | 2 | 2 | 1 | 1 |
| FDD | 7 | 5 | 3 | 3 | 2 | 2 | 2 | 1 | 1 |
| Total | 53.0 | 32.14 | 17.53 | 17.53 | 3.93 | 9.93 | 8.43 | 4.43 | 4.43 |

ACLIM: agroclimatic zoning; LU/LC: land use/land cover; PA: protected areas; RAM: RAMSAR sites; VCC: vulnerability to climate change; DR: degree of drought risk; FLUV: flooding vulnerability index; FHR: freeze hazard rate; FDD: frost duration in days.

In contrast with previous estimations in our AZ, the AEZ projections clearly demonstrates that, after the consideration of restrictions, the potential areas for growing JCL are reduced by about 40% in scenario 1 (less restrictive conditions), Mexico's territorial extension estimated with "high potential", "medium potential" and "low potential" represent 57.32% of the national territory (Table 14).

**Table 12.** Weights of the nine criteria of the AEZ analysis using the AHP.

| Criteria | Relative Weight | Weight (%) |
|---|---|---|
| ACLIM | 0.02 | 2 |
| LU/LC | 0.04 | 4 |
| PA | 0.06 | 6 |
| RAM | 0.06 | 6 |
| VCC | 0.12 | 12 |
| DR | 0.14 | 14 |
| FLUV | 0.16 | 16 |
| FHR | 0.20 | 20 |
| FDD | 0.20 | 20 |
| Total | 1.00 | 100 |

ACLIM: agroclimatic zoning; LU/LC: land use/land cover; PA: protected areas; RAM: RAMSAR sites; VCC: vulnerability to climate change; DR: degree of drought risk; FLUV: flooding vulnerability index; FHR: freeze hazard rate; FDD: frost duration in days.

**Table 13.** Consistency indices.

| Criteria | Total of Rows |
|---|---|
| Consistency index (CI) | 0.08 |
| Random index (RI) | 1.45 |
| Consistency ratio (CR) | 0.053 |

**Table 14.** Available areas for JCL cultivation in Mexico, scenario 1.

| Potential | Area (ha) | % [1] |
|---|---|---|
| High | 421,501 | 0.22 |
| Medium | 92,080,663 | 47.00 |
| Low | 19,807,528 | 10.11 |
| Total | 112,309,692 | 57.32 |

[1] Land requirement (% of national territory).

The highest percentage is in "medium potential" with 47%, covering mainly the northern states of Mexico. Figure 5 illustrates the spatial distribution of the land areas available for JCL cultivation under the perspective of this same scenario.

Additionally, the map of Figure 5 shows a comparison between the land areas available pattern obtained for the scenario 1 and preexisting JCL plantations reported in different Mexican studies and located according to authors criteria in high suitable potential lands. We overlaid geographical points where it has been described that JCL grows; 406 points correspond to living fences, common gardens, plant nurseries and wild populations; 68 points correspond to experimental and commercial plantations; 306 points were none of the previous, and were located mainly in Baja California, Durango, Chiapas, Colima, Guerrero, Hidalgo, Jalisco, Michoacan, Morelos, Nuevo Leon, Oaxaca, Puebla, Quintana Roo, Sinaloa, Sonora, Tabasco, Tamaulipas, Veracruz and Yucatan [63,71–78]. Based on our data and method applied it is detected that the JCL plantations could be relocated to medium available land areas.

On the other hand, in scenario 2 (with more restrictive conditions), Mexico's territorial extension estimated with "high potential" and "medium potential" represent only 15.3% of the national territory (Table 15).

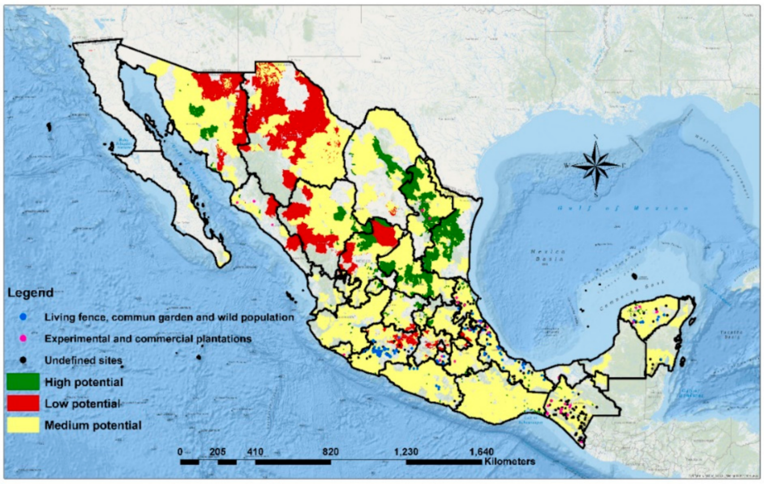


**Figure 5.** Agroecological spatial areas estimated for JCL cultivation in Mexico, scenario 1. High potential (green polygon), medium potential (yellow polygon) and low potential (red polygon).

**Table 15.** Available areas for JCL cultivation in Mexico, scenario 2.

| Potential | Area (ha) | % [1] |
|---|---|---|
| High | 5,331,477 | 2.7 |
| Medium | 24,740,998 | 12.6 |
| Total | 30,072,474 | 15.3 |

[1] Land requirement (% of national territory).

Figure 6 illustrates the spatial distribution of land areas available for JCL cultivation under more restrictive conditions. Interestingly, lands with "low potential" do not appear, because they overlapped with other committed land cover/land use areas like forest, jungle, mangrove, agriculture, cultivated grassland and those restricted in accordance with national government regulation, environmental policy that limits land use, and energy policies such as the Law on the Promotion of Bioenergy Production and Sustainable Development. On the other hand, a notable percentage of land with "high potential" and "medium potential" areas for JCL cultivation were vulnerable to both flooding and drought risk, in addition to freeze hazards and vulnerability to climate change. Also, the length of frost duration is greater for medium potential lands. Finally, the total estimated area in AZ analysis decreased sharply after adjustments based on the AEZ analysis to around of 84%.

Turning to the analysis of extreme weather events that may damage or have a negative effect on seed yield of JCL, and linked to the effect of a more restrictive scenario, we explored the spatial distribution of land availability for JCL in the scenario 2. Notwithstanding the restrictions, we observed that all the federal states of Mexico present sites with "high potential" and "medium potential" (Table 16), with a total estimated area nearly 92.5 million ha and a significantly higher value for medium suitable land (81.99%) in the northern region of Mexico and a limited "high potential" and "low potential" suitable land (18.01%) towards West, Central, Gulf, Southern and Yucatan Peninsula regions. A data comparation with study reported by [32], allowed to examine in more detail the methodological differences and identify areas with greater portion of available sites.

Lastly, it is convenient to analyze the accessibility of roads and energy infrastructure, because this factor can help reduce JCL feedstock transportation costs in these regions. The consideration of socioeconomic dimensions in the selection of candidate sites for the cultivation and exploitation of this inedible oilseed crop became even more relevant. This more detailed analysis of the local potentials enables better planning of agroenergy chain sustainability.

When reviewing the results of AHP to determinate the influences of distance to road networks, gas stations, power generation plants and transportation infrastructure from the socioeconomic parameter on JCL cultivation for scenario 2, we can observe that judgments selected in Tables 17 and 18 are consistent and acceptable because CR has a value less than 0.1 (Table 19).

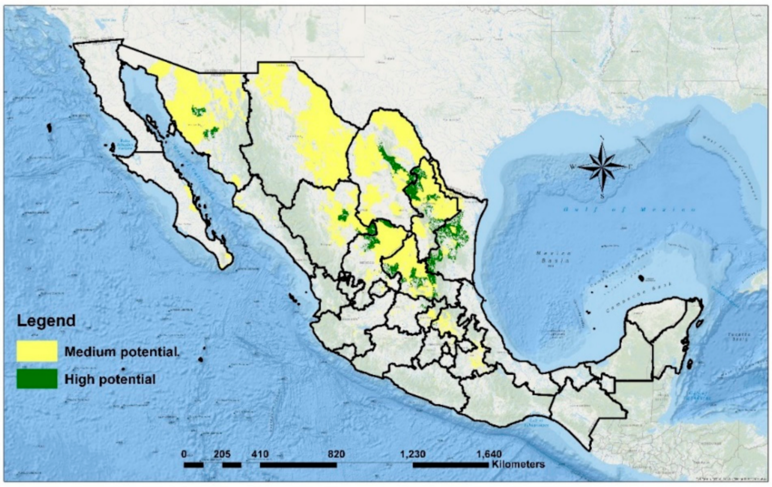


**Figure 6.** Agroecological spatial areas estimated for JCL cultivation in Mexico, scenario 2. High potential (green polygon) and medium potential (yellow polygon).

**Table 16.** Summarized high and medium suitable land areas by federal state per findings in our study in contrast to findings of [32].

| State | This Study Calculation Scenario 2 | | | [32] | |
|---|---|---|---|---|---|
| | Level of Suitability | | | Level of Suitability | |
| | High | Medium | Low | High | Medium |
| | Area (hectares) | | | | |
| Northern region | | | | | |
| Chihuahua | | 7,614,523 | 8,003,358 | - | - |
| Coahuila | | 7,143,153 | 74,091 | - | - |
| Durango | | 5,405,175 | 2,586,587 | - | - |
| Nuevo Leon | | 4,820,849 | 258 | >100,000, <175,000 | - |
| San Luis Potosi | 1458 | 5,523,643 | 256 | - | - |
| Zacatecas | | 1,954,229 | 3,629,927 | - | - |
| Northwest region | | | | | |
| Baja California | | | 2724 | - | - |
| Baja California Sur | | 411,620 | | - | - |
| Sinaloa | | 789,045 | 880,833 | 557,641 | - |
| Sonora | | 8,346,748 | 3,324,948 | - | 348,446 |
| West region | | | | | |
| Colima | | 411,151 | | >100,000, <175,000 | - |
| Jalisco | | 5,719,559 | 8286 | >100,000, <175,000 | - |
| Michoacan | | 3,839,363 | 668,607 | 197,288 | - |
| Nayarit | | 773,796 | 131 | - | - |
| Central region | | | | | |
| Estado de Mexico | | 1,010,179 | 249,505 | - | - |
| Guanajuato | | 1,780,169 | 138,827 | - | - |
| Hidalgo | 102 | 1,551,709 | 4059 | - | - |
| Puebla | 69,100 | 2426 | 144,197 | - | - |
| Queretaro | 356 | 580,708 | 3547 | - | - |
| Gulf region | | | | | |
| Tamaulipas | | 4,853,378 | | 317,690 | 442,935 |
| Tabasco | | 522,530 | | - | - |
| Veracruz | | 5,684,942 | | - | 336,314 |

**Table 16.** *Cont.*

| State | This Study Calculation Scenario 2 | | | [32] | |
|---|---|---|---|---|---|
| | Level of Suitability | | | Level of Suitability | |
| | High | Medium | Low | High | Medium |
| | Area (hectares) | | | | |
| Southern region | | | | | |
| Chiapas | 78,850 | 3,750,786 | | 230,273 | - |
| Guerrero | | 5,186,786 | | 282,158 | 283,191 |
| Oaxaca | 271,529 | 8,351,109 | | >100,000, <175,000 | - |
| Yucatan Peninsula region | | | | | |
| Campeche | | 464,602 | | - | - |
| Yucatan | 376 | 2,995,017 | | >100,000, <175,000 | - |
| Other 10 states | | 2,596,593 | 87,927 | <25,000 | - |
| Total | 421,501 | 92,080,663 | 19,807,528 | 2,614,425 | 3,474,598 |

**Table 17.** Pairwise comparison matrix for factor criteria in Socioeconomic Analysis.

| Criteria | AEZ | DR | DGS | DP | DT |
|---|---|---|---|---|---|
| AEZ | 1 | 5 | 5 | 5 | 5 |
| DR | 1/5 | 1 | 2 | 2 | 2 |
| DGS | 1/5 | 1/2 | 1 | 2 | 2 |
| DP | 1/5 | 1/2 | 1/2 | 1 | 1 |
| DT | 1/5 | 1/2 | 1/2 | 1 | 1 |
| Total | 1.80 | 7.50 | 9.00 | 11.00 | 11.00 |

AEZ: agroecological zoning; DR: distance to roads; DGS: distance to gas stations; DP: distance to power generation plants; DT: distance to transportation infrastructure.

**Table 18.** Weights of the five criteria of the socioeconomic analysis using the AHP.

| Criteria | Relative Weight | Weight (%) |
|---|---|---|
| AEZ | 0.54 | 54 |
| DR | 0.17 | 17 |
| DGS | 0.13 | 13 |
| DP | 0.08 | 8 |
| DT | 0.08 | 8 |
| Total | 1.00 | 100 |

AEZ: agroecological zoning; DR: distance to roads; DGS: distance to gas stations; DP: distance to power generation plants; DT: distance to transportation infrastructure.

**Table 19.** Consistency indices.

| Criteria | Total of Rows |
|---|---|
| Consistency index (CI) | 0.05 |
| Random index (RI) | 1.12 |
| Consistency ratio (CR) | 0.048 |

Figure 7 also shows the spatial distribution of the suitable and available lands that have greater closeness to communication and energy infrastructure. It was recognized that high potential lands have greater proximity than medium potential lands to roads, gas stations, power generation plants and transportation infrastructure with radius of 30 km. So, we calculated Euclidean distance using vector layers [79]. The proximity of a road network is a very important criterion in site suitability analysis, so the need for transportation access should be considered. The incorporation of these socioeconomic criteria enabled us to keep the proposed areas, which were associated with the best regions discussed by [22].

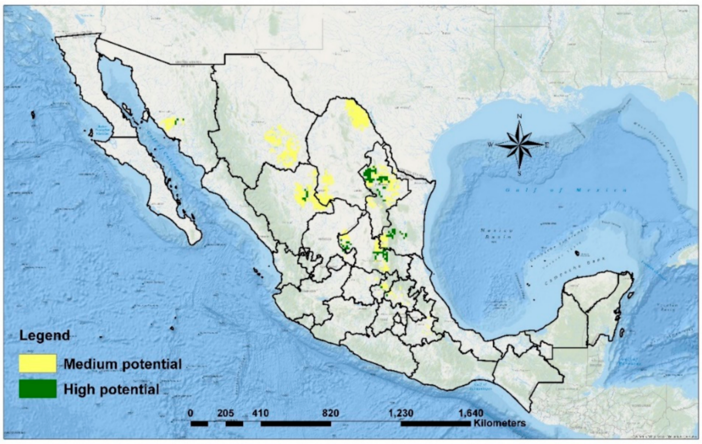


**Figure 7.** Distance to gas stations, power generation plants and transportation infrastructure in high potential and medium potential areas, distance less than 30 km in scenario 2.

Additionally, the results of several reports about JCL studies in Mexico showed that technical and socioeconomic factors have limited the success of biodiesel projects and profits for farmers. This is due to inadequacies for the following: the establishment of a production chain; the structured production of raw material, recollection of fruit, commercialization and distribution of the final product, in this case, biodiesel, along with byproducts [80–85]. For this reason, the introduction of these parameters can help promote a social value or value chain for distribution of the raw material and distribution of biodiesel produced from oil obtained from the JCL seed. Ultimately, the analysis of economic and social information can impact the supply chain (e.g., proximity to transportation or fuel and energy supply) for creating and sustaining competitive advantages that contribute to biodiesel project profitability.

Conforming to several studies, the incorporation of environmental and socioeconomic factors and criteria, as well as detailed data of those factors for choosing land allocation for biomass energy crop cultivation, contribute to the sustainability of biofuel production [21,22]. Our findings from the AZ and AEZ mapping for JCL offer the opportunity to understand both risks and opportunities in sustainable cultivation and exploitation of this energy crop in Mexico, and to promote a successful biodiesel market and local development of communities where it is cultivated through the creation of jobs and well-being. The findings in this study concerning estimates of available areas for JCL cultivation also help avoid those susceptible to risk of extreme weather events.

The integration of GIS-MCDA on the analysis of suitability and availability land for the growth of JCL allows us to get closer to projections related with technical potential of JCL as source for biodiesel production in Mexico. For instance, if we decide selecting candidate locations for JCL inedible oilseed crop cultivation in Mexico under the perspective of scenario 2, we could get a more realistic situation for sustainable production of biodiesel because:

(1) Some 5,331,477 hectares from available land with "high potential" was projected
(2) Valuable information that integrates aspects related with value chain of raw materials, such as proximity of the road and transportation infrastructure was considered.
(3) It is known that 70.48% of total available estimated area is affected by erosion (around of 3.57 million hectares)
(4) Principally, there is no competition with food or animal feed production, while considering biodiversity conservation.
(5) Finally, we consider an oil yield of 1892 L $ha^{-1}$ [86]; a density of 901–922 kg/$m^3$ [87]; a calorific value of the oil 39.5 MJ/kg [88] and a biodiesel production yield of 96% [89]. With this data, the biodiesel production potential could be estimated in 9.683 $Mm^3$ biodiesel/year, which is equivalent to 344.636–352.669 Giga J/year. With this biodiesel production potential, Mexico would

become one of the top five producers in the world of this biofuel and the most positive aspect is that it would be through the use of areas that meet sustainability criteria [5].

Non-edible biofuel crops are expected to use lands that are largely unproductive and those that are located in degraded forests [90], and/or the largest amount of suitable and potentially available land with arid and semiarid conditions [91]. In our study, we found that the northern part of Mexico exhibits arid (desert) and semiarid characteristics; it is the region with predominantly localized availability of land with a medium suitability level for JCL cultivation. In Mexico, there is currently no consensus about better land allocation for JCL cultivation, and a persistent attentiveness to benefit from its multi-dimensional potentials exists. The GIS-based approach was applied to allow project-level analyses or decision-support beyond the 'site-searching' process for investors, policy makers and prospective developers who wish to perform a techno-economic study using site specific inputs, and consider the methodology of this study, with the aim of promoting the bioenergy industry in any country in the world. Alternatively, several studies show that JCL has the ability to be employed for dry land reforestation because it is helpful for restoration of degraded ecosystem, to alleviate soil and degradation [92–94]. In this sense a comprehensive promotion of JCL cultivation can be planned in regions like southeastern Mexican states challenged with a high rate of change in its ecosystems and land use in the last 10 years, with increments in the incidences of deforestation processes, forest conversions to grassland and slash-burning practices [95–97].

Finally, to validate the consistency of the results we carried out a visual inspection of the estimated areas of the scenario 2, we compared (through overlay operations) Google Earth's high-resolution data and food crop SPOT satellite data provided by [50], which, pertain to vector layer/SPOT imagery from Spring-Summer 2018 and field work (1 m spatial resolution). This verification was performed using a random sample of 927 pixels, a 95% confidence level and a 3% margin of error. Additionally, Kappa Coefficient (k) was calculated in accordance with Equation (8). In Table 20 we present the confusion matrix. The value k represents a very good concordance [98]:

$$k = N\sum_{i=1}^{r} x_{ii} - \left(\sum_{i=1}^{r} x_{ij} \times x_{ji}\right)/N^2 - \sum_{i=1}^{r} x_{ij} \times x_{ji} \quad (8)$$

where $r$ is the number of rows in error matrix; N is the total number of pixels observed; $x_{ii}$ is the number of observations in row $i$ and column $i$; $x_{ij}$ is the total number of observations in row I; $x_{ji}$ is the total number of observations in column I; k = 1 indicates perfect agreement.

**Table 20.** Error matrix of the MCDA analysis in scenario 2.

| | **Estimated** | | |
|---|---|---|---|
| **Observed** | **High Potential** | **Medium Potential** | **Row Total** |
| High potential | 109 | 0 | 109 |
| Medium potential | 17 | 729 | 746 |
| Errors of commission | 38 | 34 | 72 |
| Column total | 164 | 763 | 927 |
| Overall Accuracy = 0.90; k = 0.90 | | | |

After visual inspection, it was found that nearly the whole feasible space analyzed for scenario 2 showed consistency, and, the regions categorized as "medium potential" presented a better level of confirmation, followed by the regions categorized as "high potential".

## 4. Conclusions

The use of AHP was integrated with GIS application environment to assess land suitability and availability for "high potential", "medium potential" and "low potential" to cultivate JCL in Mexico, combining agroclimatic criteria, land cover/land uses, soil type, extreme weather events and socioeconomic information, allowing the identification of suitable and available lands where this inedible oilseed crops can grow in a more sustainable way while avoiding competition with food or animal feed production, and considering biodiversity conservation, promoting the biomass supply chain, and addressing climate-related extreme weather event risks to crop production. So, a GIS approach is beneficial by including other key factors that affect its sustainable plantation, which improves land allocation for biomass JCL cultivation and provides reliable data for preliminary planning of biodiesel production.

The result of the MCDA analysis for AEZ (in both scenarios) indicates that around of 82% of the area estimated in Mexico has a "medium potential". Important extensions of land with medium potential sites for JCL cultivation were found in the northern part of Mexico corresponding to 53.88% of the area estimated, in states such as Chihuahua, Coahuila and Sonora. We consider that the scenario 2 is the most important analysis because it suggests the guarantee of the food security, ecosystem conservation and the reduction land use change. So, in this scenario 15.3% of Mexican territory is available for JCL production. Overall, our findings focused on producing a preliminary study that aggregated information supporting regional and national planning of JCL cultivation in Mexico. Future studies could integrate indicators about other social externalities like harvesting and transportation costs. Finally, the visual images of the sample areas inspected (using high resolution satellite data), allowed us to observe that within the areas estimated for JCL cultivation, there were marginal areas (i.e., abandoned lands) that were previously dedicated to the cultivation of food crops, but that currently do not produce. Related to this, it is also invaluable to acquire the most updated reference data and perform field visits to confirm the availability of land.

Although, further research is recommended, the calculated potential of biodiesel production in Mexico though the proposed methodology resulted in 9000 million liters which implies that it would become one of the leading production countries in the world of this biofuel, with the additional advantage of being located in a strategic geographical position next to the major consumer of this product, the United States of America. Future research should be oriented on data quality and model improvement, including enhancement of data sampling and enhanced selection of predictive variables.

**Author Contributions:** Conceptualization, J.A.C.-N., M.E.G.-C. and V.Y.M.-C.; methodology, J.A.C.-N. and Á.R.T.-C.; software, Á.R.T.-C. and M.E.G.-C.; validation, J.A.C.-N. and Á.R.T.-C.; formal analysis, J.A.C.-N., Á.R.T.-C., V.Y.M.-C., M.E.G.-C., L.R.T.-G. and J.V.; investigation, J.A.C.-N. and M.E.G.-C.; resources, Á.R.T.-C., M.E.G.-C., V.Y.M.-C. and J.A.C.-N.; data curation, J.A.C.-N.; writing-original draft preparation, J.A.C.-N., M.E.G.-C. and V.Y.M.-C.; writing-review and editing, J.A.C.-N., M.E.G.-C., V.Y.M.-C., L.R.T.-G., J.V. and Á.R.T.-C.; visualization, J.A.C.-N.; supervision, M.E.G.-C., V.Y.M.-C. and Á.R.T.-C.; project administration Á.R.T.-C., M.E.G.-C. and V.Y.M.-C.; funding acquisition, M.E.G.-C., V.Y.M.-C. and Á.R.T.-C. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Correa, D.F.; Beyer, H.L.; Fargione, J.E.; Hill, J.D.; Possingham, H.P.; Thomas-Hall, S.R.; Schenk, P.M. Towards the Implementation of Sustainable Biofuel Production Systems. *Renew. Sust. Energy Rev.* **2019**, *107*, 250–263. [CrossRef]
2. Hartley, F.; van Seventer, D.; Samboko, P.C.; Arndt, C. Economy-Wide Implications of Biofuel Production in Zambia. *Dev. S. Afr.* **2019**, *36*, 213–232. [CrossRef]

3. Araújo, K.; Mahajan, D.; Kerr, R.; Silva, M.D. Global biofuels at the crossroads: An overview of technical, policy, and investment complexities in the sustainability of biofuel development. *Agriculture* **2017**, *7*, 32. [CrossRef]
4. Rajaona, A.M.; Sutterer, N.; Asch, F. Potential of waste water use for *Jatropha* cultivation in arid environments. *Agriculture* **2012**, *2*, 376–392. [CrossRef]
5. REN21. *Renewables 2020. Global Status Report*; REN21 Secretariat: Paris, France, 2020; ISBN 978-3-948393-00-7.
6. Gebremariam, S.N.; Marchetti, J.M. Economics of biodiesel production. *Energy Convers. Manag.* **2018**, *168*, 74–84. [CrossRef]
7. Gouveia, L.; Oliveira, A.C. Microalgae as a raw material for biofuels production. *J. Ind. Microbiol. Biotechnol.* **2009**, *36*, 269–274. [CrossRef] [PubMed]
8. Alburquerque, N.; García-Almodóvar, R.C.; Valverde, J.M.; Burgos, L.; Martínez-Romero, D. Characterization of *Jatropha Curcas* Accessions Based in Plant Growth Traits and Oil Quality. *Ind. Crop. Prod.* **2017**, *109*, 693–698. [CrossRef]
9. Ashraful, A.M.; Masjuki, H.H.; Kalam, M.A.; Rizwanul Fattah, I.M.; Imtenan, S.; Shahir, S.A.; Mobarak, H.M. Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review. *Energy Convers. Manag.* **2014**, *80*, 202–228. [CrossRef]
10. Breene, W.M.; Lin, S.; Hardman, L.; Orf, J. Protein and Oil Content of Soybeans from Different Geographic Locations. *J. Am. Oil Chem. Soc.* **1988**, *65*, 1927–1931. [CrossRef]
11. Pramanik, K. Properties and Use of *Jatropha Curcas* Oil and Diesel Fuel Blends in Compression Ignition Engine. *Renew. Energy* **2003**, *28*, 239–248. [CrossRef]
12. Achten, W.M.J.; Verchot, L.; Franken, Y.J.; Mathijs, E.; Singh, V.P.; Aerts, R.; Muys, B. *Jatropha Bio-Diesel Production and Use. Biomass Bioenergy* **2008**, *32*, 1063–1084. [CrossRef]
13. Francis, G.; Edinger, R.; Becker, K. A Concept for Simultaneous Wasteland Reclamation, Fuel Production, and Socio-Economic Development in Degraded Areas in India: Need, Potential and Perspectives of *Jatropha* Plantations. *Nat. Resour. Forum* **2005**, *29*, 12–24. [CrossRef]
14. Antwi-Bediako, R.; Otsuki, K.; Zoomers, A.; Amsalu, A. Global Investment Failures and Transformations: A Review of Hyped *Jatropha* Spaces. *Sustainability* **2019**, *11*, 3371. [CrossRef]
15. Ianda, T.F.; Sales, E.A.; Nascimento, A.N.; Padula, A.D. Optimizing the Cooperated "Multi-Countries" Biodiesel Production and Consumption in Sub-Saharan Africa. *Energies* **2020**, *13*, 4717. [CrossRef]
16. Lang, A.; Farouk, H.A.E. *Jatropha Oil Production for Biodiesel and Other Products—A Study of Issues Involved in Production at Large Scale*; World Bioenergy Association—Aeronautical Research Centre: Khartoum, Sudan, 2013; pp. 26–39.
17. Procházka, P.; Smutka, L.; Hönig, V. Using Biofuels for Highly Renewable Electricity Systems: A Case Study of the Jatropha curcas. *Energies* **2019**, *12*, 3028. [CrossRef]
18. Moniruzzaman, M.; Yaakob, Z.; Shahinuzzaman, M.; Khatun, R.; Aminul Islam, A.K.M. Jatropha Biofuel Industry: The Challenges. In *Frontiers in Bioenergy and Biofuels*, 1st ed.; Jacob-Lopes, E., Queiroz, L.Q., Eds.; InTech: Rijeka, Croatia, 2017; pp. 223–2256. [CrossRef]
19. Blanco-Canqui, H. Growing Dedicated Energy Crops on Marginal Lands and Ecosystem Services. *Soil Sci. Soc. Am. J.* **2016**, *80*, 845–858. [CrossRef]
20. Allen, B.; Kretschmer, B.; Baldock, D.; Menadue, H.; Nanni, S.; Tucker, G. *Space for Energy Crops–Assessing the Potential Contribution to Europe's Energy Future*, 1st ed.; Institute for European Environmental Policy: London, UK, 2014; pp. 21–27.
21. Recanatesi, F.; Tolli, M.; Lord, R. Multi Criteria Analysis to Evaluate the Best Location of Plants for Renewable Energy by Forest Biomass: A Case Study in Central Italy. *Appl. Math. Sci.* **2014**, *8*, 6447–6458. [CrossRef]
22. Woo, H.; Acuna, M.; Moroni, M.; Taskhiri, M.S.; Turner, P. Optimizing the Location of Biomass Energy Facilities by Integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS). *Forests* **2018**, *9*, 585. [CrossRef]
23. Wu, W.G.; Huang, J.K.; Deng, X.Z. Potential Land for Plantation of *Jatropha Curcas* as Feedstocks for Biodiesel in China. *Sci. China Ser. D Earth Sci.* **2010**, *53*, 20–127. [CrossRef]
24. Rodrigues-Barata, E. A GIS Approach to Estimate the Bioenergy Potential in Uganda. Master's Thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden, 30 October 2017.

25. Ahmed, A.; Jarzebski, M.P.; Gasparatos, A. Using the ecosystem service approach to determine whether jatropha projects were located in marginal lands in Ghana: Implications for site selection. *Biomass Bioenerg.* **2018**, *114*, 112–124. [CrossRef]
26. Mistri, P.; Sengupta, S. Multi-criteria Decision-Making Approaches to Agricultural Land Suitability Classification of Malda District, Eastern India. *Nat. Resour. Res.* **2019**, *29*, 1–20. [CrossRef]
27. Siksnelyte, I.; Zavadskas, E.K.; Streimikiene, D.; Sharma, D. An overview of multi-criteria decision-making methods in dealing with sustainable energy development issues. *Energies* **2018**, *11*, 2754. [CrossRef]
28. Singha, C.; Swain, K.C.; Swain, S.K. Best Crop Rotation Selection with GIS-AHP Technique Using Soil Nutrient Variability. *Agriculture* **2020**, *10*, 213. [CrossRef]
29. Fekadu, E.; Negese, A. GIS assisted suitability analysis for wheat and barley crops through AHP approach at Yikalo sub-watershed, Ethiopia. *Cogent Food Agric.* **2020**, *6*, 1743623. [CrossRef]
30. SENER. *Prospectiva de Energías Renovables 2012–2026*; Secretary of Energy: Distrito Federal, México, 2012; pp. 103–104.
31. Alemán-Nava, G.S.; Meneses-Jácome, A.; Cárdenas-Chávez, D.L.; Díaz-Chavez, R.; Scarlat, J.F.; Dallemand, N.; Ornelas-Soto, R.; García-Arrazola, N.; Parra, R. Bioenergy in Mexico: Status and Perspective. *Biofuel Bioprod. Bior.* **2015**, *9*, 8–20. [CrossRef]
32. Zamarripa-Colmenero, A.; Díaz-Padilla, G. Áreas de Potencial Productivo Del Piñón *Jatropha Curcas* L., Como Especie de Interés Bioenergético En México. *Oleaginosas* **2008**. Available online: http://www.oleaginosas.org/impr_211.shtml (accessed on 10 November 2020).
33. Núñez-Colín, C.A.; Goytia-Jiménez, M.A. Distribution and Agroclimatic Characterization of Potential Cultivation Regions of Physic Nut in Mexico. *Pesq. Agropec. Bras.* **2009**, *44*, 1078–1085. [CrossRef]
34. Rodríguez-Acosta, M.; Vega-Flores, K.; De Gante-Cabrera, V.H.; Jiménez-Ramírez, J. Distribución Del Genero *Jatropha* L. (Euphorbiaceae) En El Estado de Puebla, México. *Polibotánica* **2009**, *28*, 37–48.
35. Valdés-Rodríguez, O.A.; Pérez-Vázquez, A.; García-Pérez, E.; Inurreta-Aguirre, H.D.; Ávila-Resendiz, C.; Ruíz-Rosado, O. Condiciones Agroecológicas de Procedencias Nativas de *Jatropha Curcas* L. en el estado de Veracruz. In *Energía Alterna y Biocombustibles, Innovación e Investigación Para Un Desarrollo Sustentable*, 1st ed.; Pérez-Vázquez, A., García-Pérez, E., Eds.; Colegio de Postgraduados: Veracruz, México, 2013; pp. 143–152.
36. Solís-Guzmán, B.F. Integración de *Jatropha Curcas* L. En Agroecosistemas Como Materia Prima Para Biodiesel En La Región Centro de Chiapas, México. Ph.D. Thesis, Colegio de Postgraduados, Montecillo, México, 15 September 2011.
37. González-Mancillas, R.; Juárez-López, J.; Aceves-Navarro, L.A.; Rivera-Hernández, B.; Guerrero-Peña, A. Zonificación Edafoclimática Para El Cultivo de *Jatropha Curcas* L., En Tabasco, México. *Investig. Geográficas* **2015**, *86*, 25–37. [CrossRef]
38. Martínez-Herrera, J.; Martínez-Ayala, A.L.; Makkar, H.; Francis, G.; Becker, K. Agroclimatic Conditions, Chemical and Nutritional Characterization of Different Provenances of *Jatropha Curcas* L. from Mexico. *Eur. J. Sci. Res.* **2010**, *39*, 396–407.
39. Ovando-Medina, I.; Espinosa-García, F.J.; Núñez-Farfán, J.; Salvador-Figueroa, M. Genetic Variation in Mexican *Jatropha Curcas* L. Estimated with Seed Oil Fatty Acids. *J. Oleo Sci.* **2011**, *60*, 301–311. [CrossRef]
40. Zamarripa-Colmenero, A.; Solís-Bonilla, J.L.; González-Ávila, A.; Teniente-Oviedo, R.; Martínez-Valencia, B.B.; Hernández-Martínez, M. *Guía Técnica Para La Producción de Piñón Mexicano (Jatropha Curcas L.) en Chiapas*, 1st ed.; National Institute of Forestry, Agriculture and Livestock Research: Chiapas, Mexico, 2011; pp. 8–10.
41. Montes, J.M.; Melchinger, A.E. Domestication and Breeding of *Jatropha Curcas* L. *Trends Plant. Sci.* **2016**, *21*, 1045–1057. [CrossRef] [PubMed]
42. Martiñón-Marínez, A.; Figueroa-Brito, R.; Martínez-Ayala, A.; Martínez-Herrera, J.; Pacheco-Vargas, G.; García-Dávila, J. Chemical and Physical Characterizaton of *Jatropha Curcas* L. Seed from the Northern Sierra of Puebla, México. *J. Plant. Sci.* **2018**, *6*, 25–30. [CrossRef]
43. Taddese, H. Suitability Analysis for *Jatropha Curcas* Production in Ethiopia-a Spatial Modeling Approach. *Environ. Syst. Res.* **2014**, *3*, 25. [CrossRef]
44. Vázquez-Quintero, G.; Prieto-Amparán, J.A.; Pinedo-Alvarez, A.; Valles-Aragón, M.C.; Morales-Nieto, C.R.; Villarreal-Guerrero, F. GIS-Based Multicriteria Evaluation of Land Suitability for Grasslands Conservation in Chihuahua, Mexico. *Sustainability* **2020**, *12*, 185. [CrossRef]

45. Yalew, S.G.; van Griensven, A.; Mul, M.L.; van der Zaag, P. Land suitability analysis for agriculture in the Abbay basin using remote sensing, GIS and AHP techniques. *Modeling Earth Syst. Environ.* **2016**, *2*, 101. [CrossRef]
46. Zabihi, H.; Alizadeh, M.; Kibet Langat, P.; Karami, M.; Shahabi, H.; Ahmad, A.; Noir Said, M.; Lee, S. GIS Multi-Criteria Analysis by Ordered Weighted Averaging (OWA): Toward an integrated citrus management strategy. *Sustainability* **2019**, *11*, 1009. [CrossRef]
47. SIAP. (Mexico). Estimated Area of Maize, Bean, Sorghum and Wheat Crops. In *Agricultural Information Service and Fishing*; SIAP: Ciudad de Mexico, Mexico, 2019.
48. Morrone, J.J. Hacia una síntesis biogeográfica de México. *Rev. Mex Biodivers* **2005**, *76*, 207–252. [CrossRef]
49. Fresnedo-Ramírez, J.; Orozco-Ramírez, Q. Diversity and Distribution of Genus Jatropha in Mexico. *Genet. Resour Crop. Evol.* **2013**, *60*, 1087–1104. [CrossRef]
50. Terán-Cuevas, A.R. Escenarios de Lluvia En México. Ph.D. Thesis, Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Amiente y Desarrollo—Instituto Politécnico Nacional, Distrito Federal, México, July 2010.
51. National Biodiversity Information System (SNIB)—National Commission for the Knowledge and Use of Biodiversity (CONABIO). Available online: http://www.conabio.gob.mx/informacion/gis/ (accessed on 10 August 2019).
52. Mexican Digital Elevation Model—National System of Statistical and Geographical Information (INEGI). Available online: https://www.inegi.org.mx/app/geo2/elevacionesmex/ (accessed on 10 August 2019).
53. National System of Statistical and Geographical Information. Available online: http://en.www.inegi.org.mx/default.html (accessed on 10 August 2019).
54. Spatial Information—National Commission for Protected Natural Areas. Available online: http://sig.conanp.gob.mx/website/pagsig/info_shape.htm (accessed on 10 August 2019).
55. National Risk Atlas—National Center for Disaster Prevention (CENAPRED). Available online: http://atlasnacionalderiesgos.gob.mx/archivo/visor-capas.html (accessed on 10 August 2019).
56. Saaty, T.L. Decision making with the Analytic Hierarchy Process. *Int. J. Serv. Sci.* **2008**, *1*, 83–98. [CrossRef]
57. Jozi, S.A.; Ebadzadeh, F. Application of multi-criteria decision-making in land evaluation of agricultural land use. *J. Indian Soc. Remote Sens.* **2014**, *42*, 363–371. [CrossRef]
58. Saaty, T.L. A Scaling Method for Priorities in Hierarchical Structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]
59. Camargo-Hernández, M.F. Land Suitability Analysis to Assess the Potential of Public Open Spaces for Urban Agriculture Activities. Ph.D. Thesis, Universidade Nova de Lisboa, Lisboa, Portugal, 24 February 2020.
60. Ríos-Camey, J.M. Caracterización y modelo de predicción de contenido de aceite de semillas de Jatropha curcas L. en el Estado de Chiapas. Master's Thesis, Universidad Autónoma de Nuevo León, Nuevo Leon, México, September 2014.
61. Valdés-Rodríguez, O.A.; Pérez-Vázquez, A.; Palacios-Wassenaar, O.M.; Sánchez-Sánchez, O. Seed diversity in native mexican *Jatropha curcas* L. and their environmental conditions. *Trop. Subtrop. Agroecosystems* **2018**, *21*, 521–537.
62. García-Pérez, E.; García-Alonso, F.; Zavala-Del Ángel, I.; Pérez Vázquez, A.; Valdés-Rodríguez, O.A. Fenología de *Jatropha curcas* L., en condiciones del trópico sub-húmedo. In *Manual de Buenas prácticas para el cultivo de Jatropha curcas L.*, 1st ed.; García-Pérez, P.-V.A., Valdés-Rodríguez, O.A., Eds.; Colegio de Postgraduados: Veracruz, México, 2013; pp. 28–35.
63. Díaz-Sánchez, Á.A. Determinación de La Factibilidad Técnica y Económica Del Cultivo de *Jatropha Curcas* L. En Área de La Zona Citrícola de Nuevo León. Master's Thesis, Universidad Autónoma de Nuevo León, Nuevo León, México, December 2011.
64. Lovio-Fragoso, J.P.; Medina-Juárez, L.A.; Gamez-Meza, N.; Martínez, O.; Hernández-Oñate, M.Á.; Hayano-Kanashiro, C. Expression analysis of genes involved in the synthesis of oleic and linoleic acids in Jatropha cinerea seeds from Northwestern Mexico. *Ciência Rural* **2018**, *48*, e20170610. [CrossRef]
65. Valdés-Rodríguez, O.A.; Sánchez-Sánchez, O.; Pérez-Vázquez, A.; Caplan, J.S.; Danjon, F. *Jatropha curcas* L. root structure and growth in diverse soils. *Sci. World J.* **2013**, 827295. [CrossRef]
66. Pérez-Vázquez, A.; Hernández-Salinas, G.; Ávila-Reséndiz, C.; Valdés-Rodríguez, O.A.; Gallardo-López, F.; García-Pérez, E.; Ruiz-Rosado, O. Effect of the soil water content on *Jatropha* seedlings in a tropical climate. *Int. Agrophys.* **2013**, *27*, 351–357. [CrossRef]

67. Valdes-Rodriguez, O.A.; Sánchez-Sánchez, O.; Pérez-Vázquez, A.; Ruiz-Bello, R. Soil texture effects on the development of *Jatropha* seedlings–Mexican variety 'piñón manso'. *Biomass Bioenergy* **2011**, *35*, 3529–3536. [CrossRef]
68. Teniente-Oviedo, R.; Tapia-Vargas, L.M.; Zamarripa-Colmenero, A.; González-Ávila, A.; Solís-Bonilla, J.L.; Martínez-Valencia, B.; Hernández-Martínez, M. *Guía Técnica Para La Producción de Piñón Mexicano (Jatropha Curcas L.) en Michoacán*, 1st ed.; National Institute of Forestry, Agriculture and Livestock Research: Michoacán, México, 2011; p. 13.
69. González-Ávila, A.; García-Mariscal, K.P.; Hernández-García, M.A.; Teniente-Oviedo, R.; Solís-Bonilla, J.L.; Zamarripa-Colmenero, A. *Guía Para Cultivar Piñón Mexicano (Jatropha Curcas L.) en Jalisco*, 1st ed.; National Institute of Forestry, Agriculture and Livestock Research: Michoacán, México, 2011; p. 16.
70. Andrade, G.A.; Caramori, P.H.; Caviglione, J.H.; Oliveira, D.; Ribeiro, A.M.A. Zoneamento Agroclimático para a cultura do pinhão manso (*Jatropha curcas* L.) no Estado do Paraná. *Rev. Bras. Agrometeorol.* **2007**, *15*, 178–183. [CrossRef]
71. López-Guillén, G.; Gómez-Ruiz, J.; Barrera-Gaytán, J.F.; Hernández-Arenas, M.; Herrera-Parra, E.; Bravo Mosqueda, E.; Zamarripa-Colmenero, A. *Artrópodos Asociados a Piñón (J. Curcas L.) En el Sur de México*, 1st ed.; National Institute of Forestry, Agriculture and Livestock Research: Chiapas, México, 2013; p. 70.
72. Adriano-Anaya, M.L.; Gómez-Pérez, J.A.; Ruiz-González, S.; Vásquez-Ovando, J.A.; Salvador-Figueroa, M.; Ovando-Medina, I. Oleosomas de Semillas de *Jatropha Curcas* L. Como Estimadores de Diversidad En Poblaciones Del Sur de México. *Grasas Aceites* **2014**, *65*, e031. [CrossRef]
73. Martínez-Díaz, Y.; González-Rodríguez, A.; Rico-Ponce, H.R.; Rocha-Ramírez, V.; Ovando-Medina, I.; Espinosa-García, F.J. Fatty Acid Diversity Is Not Associated with Neutral Genetic Diversity in Native Populations of the Biodiesel Plant *Jatropha Curcas* L. *Chem. Biodivers.* **2017**, *14*, e1600188. [CrossRef]
74. Valdés-Rodríguez, O.A.; Sánchez-Sánchez, O.; Pérez-Vázquez, A.; Zavala del Angel, I. Alometría de Semillas de *Jatropha Curcas* L. Mexicanas. *Rev. Mex. Cienc. Agríc.* **2013**, *5*, 967–978.
75. Córdova-Téllez, L.; Bautista-Ramírez, E.; Zamarripa-Colmenero, A.; Rivera-Lorca, J.A.; Pérez-Vázquez, A.; Sánchez-Sánchez, O.M.; Martínez-Herrera, J.; Cuevas-Sánchez, J.A. *Diagnóstico y Plan. Estratégico de La Red Jatropha Spp. En México*, 1st ed.; National Seed Certification Inspection Service/National System of Plant Genetic Resources: Distrito Federal, México, 2015; p. 116.
76. Bautista-Ramírez, E. Tolerancia a La Desecación y Caracterización Química de Semillas de Piñón Mexicano (*Jatropha Curcas* L.) Colectadas En El Totonacapan. Master's Thesis, Colegio de Posgraduados, Montecillo, México, 2010.
77. Nolasco-Guzmán, V.; Calyecac-Cortero, H.G.; Muñoz-Orozco, A.; Miranda-Rangel, A.; Cuevas-Sánchez, J.A. Evaluación Experimental de Germinación y Emergencia En Semillas de Piñón Mexicano Del Totonacapan. *Rev. Mex. Cienc. Agrícolas* **2016**, *7*, 1959–1971. [CrossRef]
78. Vera-Castillo, Y.B.; Cuevas, J.A.; Valenzuela-Zapata, A.G.; Urbano, B.; González-Andrés, F. Biodiversity and Indigenous Management of the Endangered Non-Toxic Germplasm of *Jatropha Curcas* L. in the Totonacapan (Mexico), and the Implications for Its Conservation. *Genet. Resour Crop. Evol.* **2014**, *61*, 1263–1278. [CrossRef]
79. Abdelkarim, A.; Al-Alola, S.S.; Alogayell, H.M.; Mohamed, S.A.; Alkadi, I.I.; Ismail, I.Y. Integration of GIS-Based Multicriteria Decision Analysis and Analytic Hierarchy Process to Assess Flood Hazard on the Al-Shamal Train Pathway in Al-Qurayyat Region, Kingdom of Saudi Arabia. *Water* **2020**, *12*, 1702. [CrossRef]
80. Ando, T.; Tsunekawa, A.; Tsubo, M.; Kobayashi, H. Identification of factors impeding the spread of Jatropha cultivation in the state of Chiapas, Mexico. *Sustain. Agric. Res.* **2013**, *2*, 54. [CrossRef]
81. Banerjee, A.; Halvorsen, K.E.; Eastmond-Spencer, A.; Sweitz, S.R. Sustainable Development for Whom and How? Exploring the Gaps between Popular Discourses and Ground Reality Using the Mexican Jatropha Biodiesel Case. *Environ. Manag.* **2017**, *59*, 912–923. [CrossRef] [PubMed]
82. Castellanos-Navarrete, A. Illusions, hunger and vices: Smallholders, environmentalism and the green agrarian question in Chiapas' biofuel rush. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 16 December 2015.
83. Valdes-Rodriguez, O.A.; Perez-Vazquez, A.; Muñoz-Gamboa, C. Drivers and consequences of the first *Jatropha curcas* plantations in Mexico. *Sustainability* **2014**, *6*, 3732. [CrossRef]
84. Soto, I.; Ellison, C.; Kenis, M.; Diaz, B.; Muys, B.; Mathijs, E. Why do farmers abandon jatropha cultivation? The case of Chiapas, Mexico. *Energy Sustain. Dev.* **2018**, *42*, 77–86. [CrossRef]

85. Díaz-Peña, L.C.; Chavez-Capo, A.S.; Tinoco-Castrejón, M.A.; Rosano-Ortega, G.; Pérez-Armendariz, B. Financial assessment of a biodiesel value chain: Case study of Chiapas, Mexico. *Manag. Res. Rev.* **2013**, *36*, 1291–1302. [CrossRef]
86. Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25*, 294–306. [CrossRef]
87. Reyes-Reyes, A.L.; Solís-Bonilla, J.L.; López-Guillén, G.; Zamarripa-Colmenero, A.; Wong-Villarreal, A. Calidad fisicoquímica del aceite de *Jatropha curcas* para la producción de biodiesel. In *Estado del arte en la Ciencia y Tecnología Para la Producción y Procesamiento de Jatropha no Tóxica*, 1st ed.; Osuna-Canizalez, F.J., Atkinson, C.J., Vázquez-Alvarado, J.M.P., Barrios-Gómez, E.J., Hernández-Arenas, M., Rangel-Estrada, S.E., Cruz-Cruz, E., Eds.; Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias: Morelos, México, 2015; p. 62.
88. Solís-Bonilla, J.L.; Pecina-Quintero, V.; Reyes-Reyes, A.L.; Martínez-Valencia, B.B.; Zamarripa-Colmenero, A.; López-Ángel, L.J.; Riegelhaupt, E.; López-Guillen, G.; Barrios-Gómez, E.J. Comportamiento agronómico, energético y emisiones de gases de piñón mexicano (*Jatropha curcas* L.). In *Estado del arte en la Ciencia y Tecnología Para la Producción y Procesamiento de Jatropha no Tóxica*, 1st ed.; Osuna-Canizalez, F.J., Atkinson, C.J., Vázquez-Alvarado, J.M.P., Barrios-Gómez, E.J., Hernández-Arenas, M., Rangel-Estrada, S.E., Cruz-Cruz, E., Eds.; Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias: Morelos, México, 2015; p. 44.
89. Corro, G.; Pal, U.; Tellez, N. Biodiesel production from *Jatropha curcas* crude oil using $ZnO/SiO_2$ photocatalyst for free fatty acids esterification. *Appl Catal B-Environ.* **2013**, *129*, 39–47. [CrossRef]
90. Ahmia, A.C.; Danane, F.; Bessah, R.; Boumesbah, I. Raw Material for Biodiesel Production. Valorization of Used Edible Oil. *Rev. Des. Energ. Renouvelables* **2014**, *17*, 335–343.
91. Negm, N.A.; Maram, T.H.; Kana, A.; Youssif, M.A.; Mohamed, M.Y. Biofuels from Vegetable Oils as Alternative Fuels. In *Surfactants in Tribology*; Biresaw, G., Mittal, K.L., Eds.; CRC Press Taylor & Francis Group: New York, NY, USA, 2017; Volume 5, pp. 289–367.
92. Reubens, B.; Achten, W.M.J.; Maes, W.H.; Danjon, F.; Aerts, R.; Poesen, J.; Muys, B. More than Biofuel? *Jatropha Curcas* Root System Symmetry and Potential for Soil Erosion Control. *J. Arid Environ.* **2011**, *75*, 201–205. [CrossRef]
93. Tomar, N.S.; Ahanger, M.A.; Agarwal, R.M. Jatropha Curcas: An Overview. In *Physiological Mechanisms and Adaptation Strategies in Plants Under Changing Environment*; Parvaiz Ahmad, P., Wani, M.R., Eds.; Springer: New York, NY, USA, 2014; Volume 2, pp. 361–383. [CrossRef]
94. Winaya, A.; Maftuchah; Zainudin, A. The Identification of Osmoprotectant Compounds from *Jatropha Curcas* Linn. Plant for Natural Drought Stress Tolerance. *Energy Rep.* **2020**, *6*, 626–630. [CrossRef]
95. Bonilla-Moheno, M.; Aide, T.M. Beyond Deforestation: Land Cover Transitions in Mexico. *Agric. Syst.* **2020**, *178*, 102734. [CrossRef]
96. Díaz-Gallegos, J.R.; Mas, J.F.; Velázquez, A. Trends of Tropical Deforestation in Southeast Mexico. *Singap. J. Trop Geogr.* **2010**, *31*, 180–196. [CrossRef]
97. Mendoza-Ponce, A.; Corona-Núñez, R.O.; Galicia, L.; Kraxner, F. Identifying Hotspots of Land Use Cover Change under Socioeconomic and Climate Change Scenarios in Mexico. *Ambio* **2019**, *48*, 336–349. [CrossRef]
98. Noguchi, R.; Ahamed, T. Change Detection and Land Suitability Analysis for Extension of Potential Forest Areas in Indonesia Using Satellite Remote Sensing and GIS. *Forests* **2020**, *11*, 398. [CrossRef]