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Sustainability Evaluation of Non-Toxic *Jatropha curcas* in Rural Marginal Soil for Obtaining Biodiesel Using Life-Cycle Assessment

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Abstract: Using information from an experimental planting of non-toxic *Jatropha curcas* (NTJC) with minimal water and fertilization resources on rural marginal soil the objective of this article is to determine the sustainability of this raw material for producing biodiesel and the possibilities for improving it through life-cycle assessment (LCA). Three production scenarios were studied: minimal resources (MR), which focuses on the obtaining of biodiesel; minimal resources and utilization of sub-products (MRUS), which includes the utilization of the residual products in order to produce food and solid biofuels, as well as biodiesel; and utilization of biofertilizers, flood irrigation, and sub-products (UBIS), which incorporates the use of bio-fertilizers and irrigation in the production system. This study includes the selection of six sustainability indicators, as well as indicators by means of LCA methodology Finally, a sustainability index (SI) for each scenario was determined on the basis of an index of environmental sustainability of energy products (IESEP). Our results indicated that the MR scenario yielded the lowest SI 0.673, while the MRUS scenario had the highest SI 0.956. It concludes that sustainability is greater when it utilizes minimal water and fertilization resources during the raw material production stage, and the residual products are used for food and energy products made possible by the non-toxic properties of *Jatropha curcas*.

Keywords: non-toxic *Jatropha curcas*; LCA; sustainability index; sustainability indicators; biodiesel production scenarios

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1. Introduction

A problem that is the subject of an important global debate on land use is the question: food or bioenergy production? This is an entirely legitimate question, due to scarce resources of land, water, labor, and capital [1,2], as well as the ethical issues surrounding it [3]. However, this debate con be reconciled if systems that simultaneously produce food and energy are found [1,4]. It is true that the majority of biodiesel production systems that use *Jatropha curcas* as raw material have not considered the possibility of producing food, mainly due to the use of toxic varieties of the plant. The present study shows that the simultaneous production of food and energy may be feasible if varieties of non-toxic *Jatropha curcas* (NTJC) are used to produce biodiesel. This article thus tries to contribute to solving this problem and also improve the sustainability of NTJC.

Jatropha curcas is a second-generation raw material that has shown promise as a source of sustainable bioenergy production. It would fulfill its promise if it could prove useful in resolving the debate of food vs. energy production. This flowering plant is considered an especially viable option for the production of renewable energy in marginal soils, and in remote rural areas where energy supplies are scarce [5,6]. The plant also appears to hold the promise of generating value chains of productive activities, such as food production. A number of studies have been conducted on the sustainability of *Jatropha curcas* as a raw material for the production of biodiesel. However, the majority of such research has been limited to toxic varieties of *Jatropha curcas*, and has focused on environmental issues [7–9]. To a lesser extent, the research to date has also explored economic factors [5,7,10] as well as social factors [11,12].

Although many projects involving *Jatropha curcas* have proven to be unviable due to low seed production and high consumption of fertilizers and irrigation [7,13,14], environmental sustainability evaluations have consistently shown a positive balance as regards both energy and global warming emissions within the life-cycle assessment (LCA) [5,15]. Such findings have led in turn to proposals to improve the production system in order to further reduce adverse environmental impact, and to increase economic viability, especially during the cultivation phase in which most such impact occurs. Specific recommendations to this end include both the use of fertilizers and the consumption of fossil fuels [16].

Two improvements have been suggested in order to reduce environmental impact while increasing economic viability. The first of these involves utilization of the seed cake left after extraction of oil for the production of bio-fertilizers that replace chemical fertilizers in the cultivation of *Jatropha curcas* [17,18]. The second is the use of the residual biomass resulting from cultivation in order to obtain electrical and thermal energy, as well as for utilization in the production system of biodiesel [19,20].

Another improvement that is of topical interest is the development of strategies for improving varieties of *Jatropha curcas* that can be grown in arid and semi-arid soils [21,22]. Such strategies have included cultivation systems with a biological focus—specifically, a focus on the interaction between *Jatropha curcas* and micro-organisms through the introduction of endophytes, bacteria, and poisonous mushrooms for the purpose of promoting plant growth; the use of bio-fertilizers to improve the plant's seed production in soils with low levels of nutrients; and the possibility of utilizing crops of NTJC varieties in order to make use of the seed cake resulting from oil extraction for the manufacture of food products [23,24]. In this way, the valuation of sub-products and the production of value-added products could improve the sustainability of *Jatropha curcas* in marginal soils [14] and could also contribute to resolving the debate of food vs. energy production as it will be tried in this study integrating a variety of JCNT in the analysis.

A number of studies have reported that the seeds of varieties of NTJC can be consumed by humans and/or animals due to the high nutritional content of the chemical composition of the seed's endosperm [25–28]. In addition, these seeds can be consumed without subjecting them to detoxification treatments. This is because they either do not contain phorbol esters—a toxic compound that can lead to a number of human and animal diseases—or because they contain the compound in concentrations of 0.02 mg g^{-1}—well below the toxicity threshold [29–31].

In Mexico, there is no biofuel market. In the field of biodiesel, some experiences of biodiesel production using *Jatropha curcas* have emerged [11] and present marginal results [32]. In these experiences, toxic varieties of *Jatropha curcas* from foreign germplasms has been used [30], despite the fact that varieties of NTJC have been identified in several Mexican states [30,33–35]. There have been no recent studies regarding either the usefulness of NTJC as raw material for the production of biodiesel, or the improving the sustainability of bioenergy production through the possible utilization of their sub-products. Against this national background, the authors of this study believe that there is still an opportunity in Mexico to use endemic and non-toxic *Jatropha curcas* varieties as raw material to simultaneously produce biodiesel and food in the marginal soils of rural zones.

The authors Pérez et al. [36] identified two ecotypes of NTJC that can be cultivated in degraded soils via a production system that makes minimal use of water and bio-fertilization. These researchers indicated that the ecotypes in question have the characteristics required to produce biodiesel, and to utilize the seed cake for food production. In addition, they indicate that the two ecotypes can also be utilized as solid biofuels. For this reason, it is important to determine if the utilization of the waste products and sub-products of these ecotypes of NTJC improves the sustainability of the bioenergy production systems that are based on these kinds of ecotypes.

The purpose of this article is to evaluate the sustainability of one particular ecotype of NTJC for the production of biodiesel. Specifically, this study will attempt to identify the sustainability of this raw material through the analysis of production scenarios that involve the production of biodiesel, the utilization of the seed's sub-products in food and energy production, and the integration of both irrigation and the use of bio-fertilizers in order to improve productivity.

In order to attain this objective, a biodiesel production system was designed and defined for the present study. In addition, three production scenarios were devised that are based on the cultivation conditions required for the NTJC ecotypes studied by Pérez et al. [36]. These stepwise scenarios are as follows: MR, in which the production system focuses solely on obtaining biodiesel; MRUS, which, in addition to the foregoing, takes into account the utilization of waste products of the production system for energy and food; and UBIS, which also incorporates the use of biofertilizers and flood irrigation.

Afterward, the following indicators were selected for evaluation: greenhouse gas emissions (GHG emissions), land use, energy balance, production costs, added value, and employment. These indicators reflect the environmental, economic, and social factors that we consider important for the sustainability of these bioenergy production systems. Each of these indicators was analyzed using the Life Cycle methodology [37]. The functional unit utilized was 1 GJ of biodiesel produced.

Finally, the Index of Environmental Sustainability in Energy Products [38] was used to obtain a Sustainability Index for each experimental scenario. The results obtained for each scenario were compared with one another in order to determine the most sustainable production scenario.

State of the Art of Sustainability of Jatropha curcas for Obtaining Biodiesel

During the past decade, the production of *Jatropha curcas* elicited high expectations as a raw material for the production of biodiesel [6,18,39–43]. At the same time, sustainability was in and of itself a particular subject of interest in analyzing the production of biofuels. This interest was reflected in the formulation of sustainability criteria by the Roundtable of Sustainable Biomaterials (RSB) and the Global Bioenergy Partnership (GBEP) [44,45].

Some authors have reviewed performance on various sustainability criteria of the use of *Jatropha curcas* for the production of biodiesel [5,13]. However, as regards production of biodiesel utilizing *Jatropha curcas* as a raw material, there has been no evaluation of sustainability as a multidimensional process involving environmental, economic, and social factors as reflected by a set of criteria and indicators [46].

The majority of studies that have addressed sustainability have focused on environmental issues, reporting data with respect to greenhouse gas emissions, energy balance, and production of a biodiesel energy unit. The variables have generally been evaluated utilizing Life-Cycle Assessment methodologies [7–9,14,15,47–51].

On the other hand, previous studies have only addressed economic and social factors in marginal and isolated fashion. As regards economic issues, biodiesel production costs have been reported in a limit number of studies [7,14,48]. The social dimension of the use of *Jatropha curcas* has only been explored during its cultivation stage, which was found to be associated with job creation [13]. In this same vein, workers' annual salaries and the perception of *Jatropha curcas* plantations by the persons residing in the production area have also been studied [11].

It should be noted that very few studies have addressed production of biodiesel with *Jatropha curcas* in the marginal soils of rural zones. Furthermore, those studies that have been conducted in such settings have been limited to the evaluation of environmental factors [50,52]. These studies in marginal soils have reported that a biodiesel production system involving cultivation of *Jatropha curcas* in an intensive irrigation and fertilization system yields a balance of greenhouse gas emissions and positive energy in the production of diesel. The authors Baumert et al. [50] reported that cultivation under conditions similar to those of the present study showed no potential for the production of biodiesel, due to a lack of seed production.

Important as they were, such efforts did not explore performance within a multidimensional sustainability framework, and with integral utilization of sub-products of a bioenergy production system of NTJC in marginal soils with low irrigation and fertilization—in other words, under those conditions that prevail in the impoverished rural areas of developing countries.

The distinctive contribution of the present study resides in its use of a multidimensional conceptual and methodological framework vis-à-vis sustainability that employs indicators and a global index in evaluating a biodiesel production system that utilizes NTJC as a raw material in conditions of minimal water and fertilization resources for marginal soils in impoverished rural areas. Production scenarios have been designed in this study to simulate such conditions, while also involving the obtaining of sub-products of nutritional and energy value, and the use of bio-fertilizers and irrigation in order to improve sustainability of the utilization of NTJC.

2. Materials and Methods

The evaluation of sustainability was conducted by means of the methodology presented in Figure 1, which comprises the following five phases:

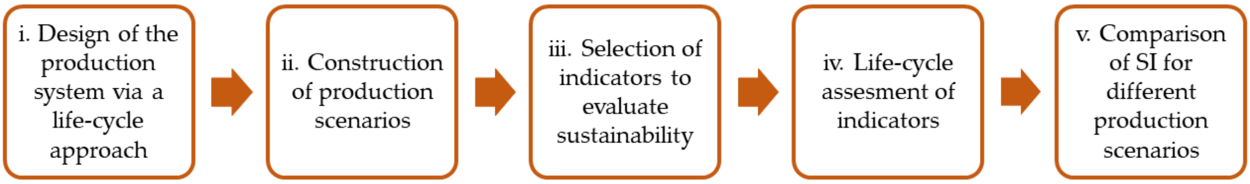

Figure 1. Methodological framework for the evaluation of sustainability of non-toxic *Jatropha Curcas.*

2.1. Design and Definition of Production System via a Life-Cycle Approach

The production system was designed and defined in a manner that took into account the critical stages of the life cycle within the production process of biodiesel. The design followed the methodology guidelines for Life Cycle Assessment that are set forth in ISO 14040 and ISO 14044 [53,54].

The objective of this study is to evaluate the sustainability of NTJC for the production of biodiesel in marginal soils, and to determine if the sustainability of use of this raw material in the conditions and for the purposes previously described improves in production scenarios that include both production of biodiesel and the utilization of subproducts for nutritional and energy purposes, and that also include the use of bio-fertilizers and flood irrigation in the cultivation of NTJC for improving seed production.

The scope of the study encompasses three distinct stages: (I) raw material production; (II) oil extraction; and (III) biodiesel production. For this reason, the system has only been subjected to a cradle-to-gate analysis. Figure 2 depicts the production system, as well as the life-cycle stages that comprise said system.

The functional unit for this study is the production of biodiesel with Mexican ecotypes of NTJC, with the production of 1 GJ of biodiesel energy utilized as a reference flow.

The raw material and oil extraction stages were designed on the basis of the information contained in the system regarding the cultivation of ecotype E2M of Mexican NTJC (E2M NTJC) and its yield of fruit, seeds, and oil, as reported in the study of Pérez et al. [36]. According to these authors, E2M NTJC has been successfully cultivated in rural marginal soils within a production system utilizing minimal water and biofertilization resources and has shown considerable promise for seed production.

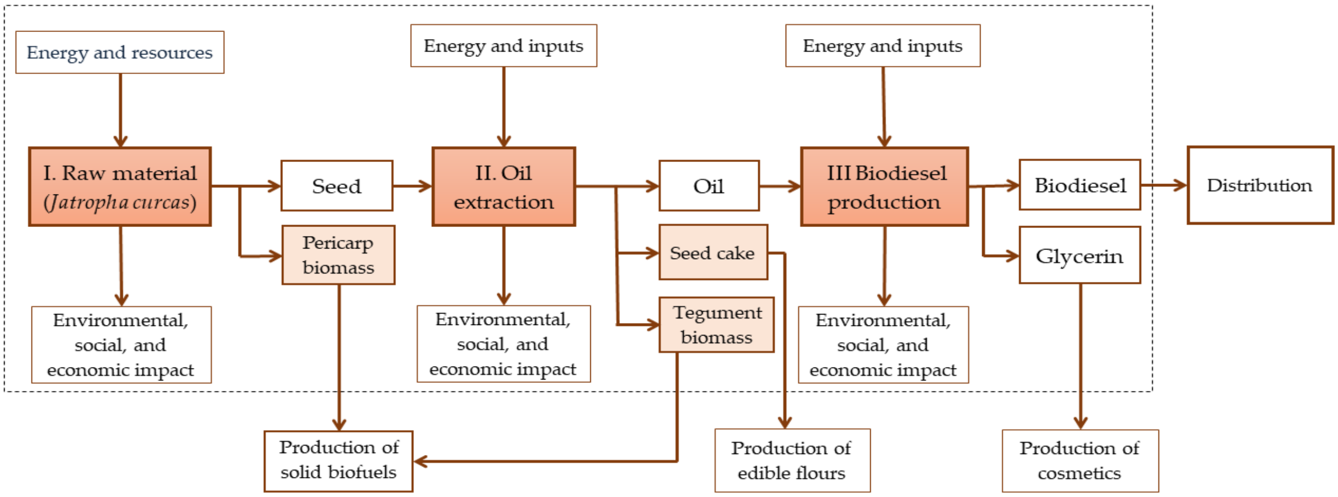

Figure 2. Life-cycle stages and system boundary of biodiesel production system utilizing NTJC as raw material.

In the same study, Pérez et al. [36] also reported that the oil and seed cake obtained have characteristics that are suitable for the production of biodiesel as well as food productions. These same researchers indicated that residual biomass shows considerable promise for utilization as a solid biofuel.

The source of the following information is the selfsame previously cited study [36]. The E2M NTJC was grown in an experimental plantation located in the municipality of Miacatlán, in the Mexican state of Morelos. This plantation was established on rural marginal soil that had previously been used for agricultural purposes. This soil was characterized by low levels of nutrient availability and had a measured pH of 7.6. The E2M NTJC was grown utilizing minimal resources, and under a regimen of low-intensity management. The soil was prepared for the planting of the seedlings utilizing a diesel-powered tractor. Compost was utilized solely during the transplanting of seedlings, and irrigation was employed during the first three months of planting, with 60 liters of water utilized per plant. After the first three months, the only water the plants received was from natural rainfall, the region having an annual average precipitation of 1026 mm. No fertilizers, insecticides, or fungicides were used under the aforementioned conditions; the eight-year-old E2M NTJC plants had a fruit yield of 0.81 kg/plant, and 1021 kg ha^{-1} in cultivation density of 1250 plants per hectare was also recorded. The planting of the seedlings, the ancillary irrigation, and the harvesting of seeds were all conducted manually. The procedures of the establishment, its maintenance, and the data periodicity of the E2M ecotype plantation, as well as other aspects of the evaluation of its performance are described in greater detail in the Tables S1 and S2 of the supplementary material.

The first stage is the raw material stage, which includes all of the previously mentioned data, and concluded with the transportation of seeds to enable implementation of the oil extraction stage, which was conducted at a site 40 km from the experimental plantation. The harvested fruits were transported utilizing a gasoline-powered pickup truck.

It is during the oil-extraction stage that oil is obtained via cold extraction, and in which the pericarp—i.e., the skin of the fruit—is removed. This skin is later used as part of the residual biomass. During this selfsame stage, the seeds, which are composed of tegument and endosperm, are also extracted. The tegument is the outer covering of the endosperm, which also constitutes part of the residual biomass. The endosperm, in turn, is the nucleus of the seed in which the oil is stored that is later utilized in the production of biodiesel. After the endosperm is pressed in order to obtain the oil, it is then considered for the purposes of this study a type of residual biomass that we call "seed cake." The data for the E2M NTJC reported by Pérez et al. [36] show that its fruit comprises seeds and skin that, respectively, represent 68.5% and 31.5% of the weight of the fruit. The oil yield of the cold extraction process was 46.5% of the weight of the endosperm, which translates into a yield of 191 kg per hectare.

The equipment utilized during this stage was as follows: a 22 kW cracking machine with a 300 kg h^{-1} capacity; a 7.5 kW oil extraction press with a capacity of 110 kg h^{-1}, and a 1.5 kW oil filter with a capacity of 180 kg h^{-1}.

During the third stage of biodiesel production, transesterification with sodium hydroxide as a basic catalyst was employed in a 1:9 v/v ratio, and with a transformation efficiency of 96% (Production data for biodiesel fuel were obtained from laboratory experiments that utilized 10 samples of oil from E2M NTJC. These experiments indicated a transformation efficiency of 96%, and these results are consistent with those reported by Ahmed et al [55]). The equipment employed during this stage was a 5.4 kW reactor with a capacity of 175 L h^{-1}.The subsequent stages of biodiesel production—i.e., distribution, use, and final disposition—were not considered for the purposes of the present study. In cases in which utilization of sub-products—i.e., residual biomass and seed cake—were analyzed, the system did not include the stages to obtain the final product. Finally, it is noted that the present study also omitted from consideration both the manufacture of the equipment and of the storage containers that were utilized.

2.2. Construction of Production Scenarios

Three production scenarios were devised for the purpose of determining the sustainability levels by means of Life-Cycle Assessment indicators obtained in a situation in which actions intended to improve system performance are undertaken. These three scenarios are depicted in Figure 3. A useful life of 20 years for NTJC was assumed for each of the three scenarios, given that said interval represents the life expectancy of *Jatropha curcas* [56].

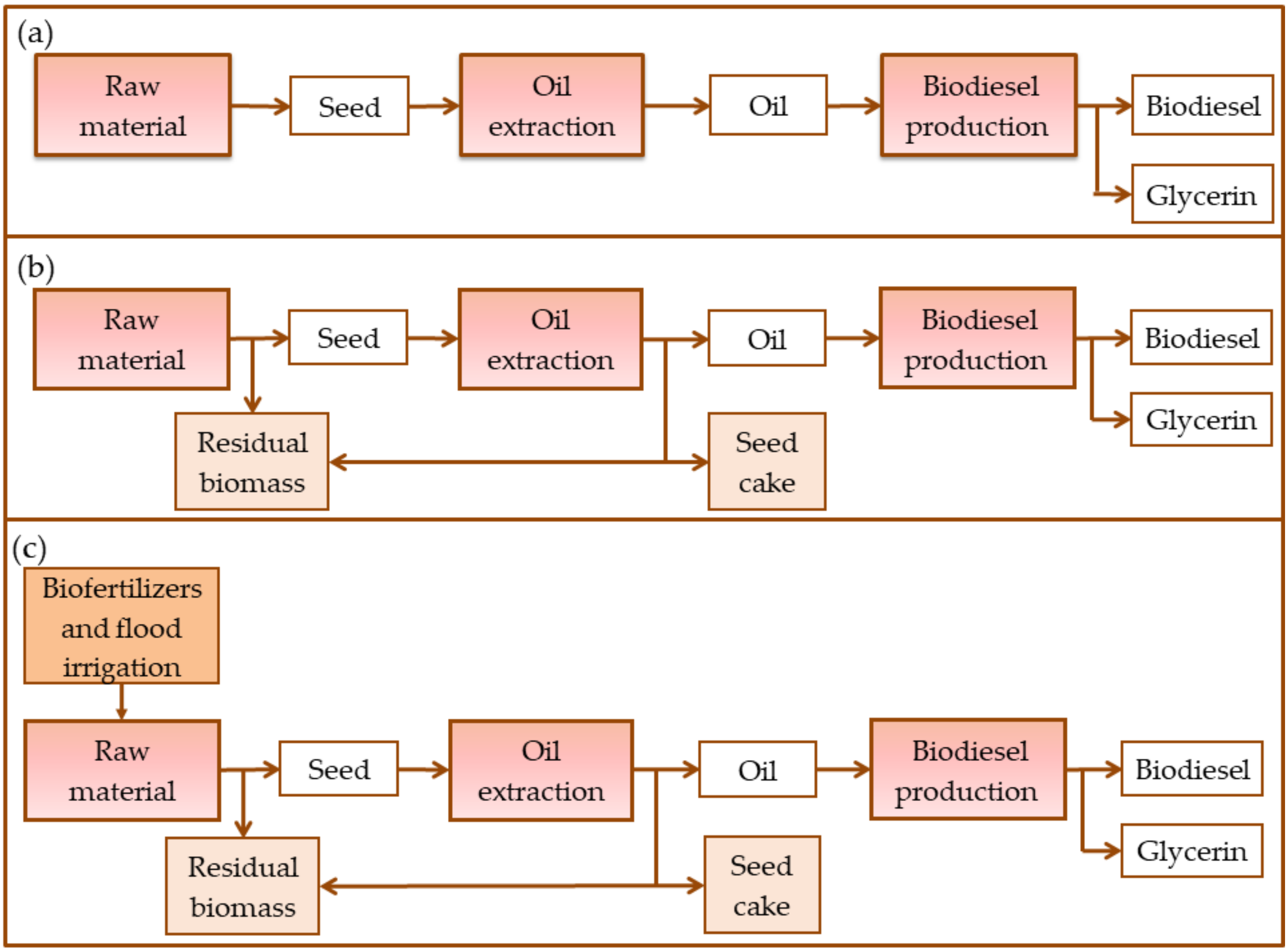

Figure 3. Depiction of the following production scenarios: (**a**) MR, (**b**) MRUS, and (**c**) UBIS.

2.2.1. Scenario 1. MR (Minimal Resources)

The MR scenario presented in Figure 3a reflects conditions of minimal water and biofertilization resources in the cultivation of the E2M NTJC. This scenario was constructed for the purpose of examining the performance of a production system in which the main product obtained is biodiesel, and in which glycerin is a sub-product. Within this scenario, residual biomass is not utilized, and the final disposition thereof is a release into the open air.

2.2.2. Scenario 2. MRUS (Minimal Resources and Utilization of Sub-Products)

This scenario, which is depicted in Figure 3b, reflects the same conditions of minimal water and biofertilization resources in the cultivation of the E2M NTJC. This scenario was constructed for the purpose of examining a production system designed not only to obtain biodiesel and glycerin as sub-products, but also to utilize the residual biomass consisting of pericarp and tegument as sub-products for energy use. In addition, the production system in this scenario was designed to use the seed cake resulting from oil extraction as a nutritional sub-product—a viable prospect given the fact that *Jatropha curcas* is non-toxic.

More precisely, this scenario includes the use of the biomass composed of the pericarp and the tegument for use as a solid biofuel for domestic use—i.e., as a substitute for firewood in rural areas, given the similarity in calorific value between the two substances. In effect, the calorific value of the pericarp has been reported as falling between 10 and 17.2 MJ kg^{-1}, while that of the tegument has been reported to fall between 16.5 and 20 MJ kg^{-1} [8,11,50,51]. Moreover, the pericarp and the tegument has been shown to have a humidity of 14.1% [36]. These parameters fall within the range of the heat energy of different types of firewood—i.e., between 15.5 and 18.4 MJ kg^{-1}—with a humidity between 13.1% and 21.8% [57,58].

In the case of utilization of the seed cake, this scenario includes its collection for later use in the production of edible flours, a prospect made feasible because of the seed cake's suitability for use in food products [36].

2.2.3. Scenario 3. UBIS (Utilization of Biofertilizers, Flood Irrigation and Sub-Products)

This scenario includes improvements in cultivation aimed at improving seed production. These improved conditions result from the use of biofertilizers and flood irrigation during the annual dry season, and over the course of the 20-year life cycle of *Jatropha curcas*. In addition, this scenario includes utilization of the residual biomass comprising the pericarp, the tegument, and the seed cake—see Figure 3c.

For the purposes of establishing criteria to properly gauge seed production through the use of biofertilizers and flood irrigation, the present study referenced data from two different studies [59,60]. These studies reported seed production (using the same density for the cultivation of the E2M NTJC of 1250 plants/ha) of 942 kg ha^{-1} with the application of biofertilizers and irrigation under environmental conditions similar to those required for cultivating the E2M NTJC.

The volume of irrigation applied was 72 L/plant/year via the utilization of manual flood irrigation that dispenses with the need for additional equipment such as water pumps and sprinklers.

The biofertilizer used in this scenario was cow manure, which was applied manually in a ratio of 5 kg/plant/year. The manure was obtained from cattle ranches located near the farm where the *Jatropha curcas* was planted.

The residual biomass consisting of the pericarp, tegument, and the seed cake, were obtained utilizing the proportions of percentages of the composition of the E2M NTJC that were mentioned previously in this section.

2.3. Selection of Sustainability Indicators

Six different indicators were established in order to evaluate the sustainability of each of the three scenarios on the basis of the environmental, economic, and social factors that have been most frequently reported in the literature [7,9,14,15,47,48], and in accordance with the information available vis-à-vis the production system. These indicators cover all three dimensions of sustainability and are evaluated for the entire life cycle of the production system for each of the scenarios included in this study.

The environmental indicators are: (1) GHG emissions, which reflect the potential for such emissions during the life cycle of the production system; (2) land use, which evaluates the efficiency of soil use for the production of biodiesel; and (3) energy balance, which reflects the relationship between the energy supplied and the energy delivered in the production system.

The economic indicators are: (4) production cost, which reflects the cost of producing one unit of energy; and (5) added value, which reflects the additional economic value obtained from the utilization of the sub-products of the production system. The two economic indicators take into account the associated local cost in at each stage of the life cycle of the production system and the national market prices of the inputs used. Thus, although both the economic indicators and the calculation method are of universal application, the analysis itself reflects the local cost of inputs, as well as the national reference price. For these reasons, the economic analysis is valid only for Mexico.

For the purposes of evaluating the social dimension, the indicator of (6) employment was included. This indicator reflects the number of persons that could potentially be hired in order to implement the production system.

2.4. Development of Indicators within the Context of the Life Cycle Assessment

After the indicators were selected, life-cycle inventories for each scenario were devised in accordance with the reference flow of the production of 1 GJ of biodiesel (the heat energy for biodiesel fuel of 40.64 MJ/kg reported by Rivero et al. [11] was utilized). Table 1 presents a life-cycle inventory for each of the scenarios.

Table 1. Inventory of inputs and outputs of the production system: (a) MR Scenario; (b) Stage 2 of the MRUS Scenario; and (c) Stage 1 of the UBIS Scenario.

Scenario	Stage	Inputs	Quantity	Unit	Outputs	Quantity	Unit
(a) MR	1. Obtaining of raw material	Soil	1351.9	m^2	*Jatropha curcas* fruits	139	Kg
		Irrigation water	506.9	L			
		Diesel fuel for tractor	0.215	kg			
		Transport of fruit	5.304	tkm			
	2. Oil extraction	Electricity for cracking	16.9	kWh	Oil	25.6	Kg
		Electricity for pressing	3.8	kWh	Biomass and seed cake	111.5	Kg
		Electricity for filtering	0.2	kWh			
	3. Production of biodiesel fuel	Electricity for reactor	4.6	kWh	Biodiesel	24.6	Kg
		Methanol	5.64	kg	Glycerin	1.03	Kg
		Sodium hydroxide	0.23	kg			
(b) MRUS	2. Oil extraction	Electricity for cracking	16.9	kWh	Oil	25.6	kg
		Electricity for pressing	3.8	kWh	Biomass pericarp and tegument	82.3	kg
		Electricity for filtering	0.2	kWh	Seed cake	29.5	kg
(c) UBIS	Stage 1. Obtaining of raw material	Soil	995.5	m^2	*Jatropha curcas* fruits	136.9	Kg
		Irrigation water	8959.1	L			
		Biofertilizers	622.2	kg			
		Diesel for tractor	0.1	kg			
		Transport of fruit	5.3	tkm			

Section (a) contains the three stages of the life cycle for the MR scenario. Section (b) presents a modification of the oil extraction stage for evaluating the MRUS scenario, with stages 1 and 3 remaining the same as in the MR scenario. In section (c), there is a modification of stage 1 (i.e., obtaining raw material) in order to evaluate scenario UBIS, with stages 2 and 3 remaining the same as in the MRUS scenario.

Environmental indicators were analyzed by means of the environmental Life Cycle Assessment methodology, and utilizing SimaPro v 9.0.0.35, Analyst Professional on the basis of the ReCiPe H method.

Indicator 1 (GHG emissions) was obtained on the basis of the impact category on global warming. Indicator 2 (land use) reflects the impact category "land occupation." Indicator 3 (energy balance) was estimated on the basis of the impact category "fossil fuels depletion" in order to obtain the consumption of non-renewable energy of the production system. The modeling of these impact categories is based on the LCA handbook, as cited in [61,62].

Mass allocation assignments were used for the impact evaluation, with different assignments corresponding to each stage and each scenario analyzed, and in accordance with the total quantity of products obtained during each stage and scenario. During the stage of obtaining raw material, the allocation of the quantity of fruit obtained has been set at 100% for all three scenarios.

During the oil extraction stage, the allocation for obtaining oil in the MR scenario was set at 100%. This is because it was determined that oil was the only useful material that could be obtained. Conversely, for the MRUS and UBIS scenarios, which both involve utilization of more than one sub-product, the following allocations were assigned: 19% for oil; 60% for biomass of pericarp and tegument; and 21% for the seed cake. These allocations reflect the relative weight of each of the three products. During the stage of biodiesel production, the allocations assigned were 96% for biodiesel and 4% for glycerin.

The two economic indicators were obtained by gauging the costs associated with stage of system production in terms of the life-cycle inventory for each production scenario and taking into account their market prices.

Indicator 4 (production cost) was calculated on the basis of net present value (NPV) of equipment costs, consumption of materials, fuel, and manual labor. These figures were in turn obtained on the basis of current market prices—see Table 2.

Table 2. Life cycle cost inventory of production system costs of each scenario, by stages: (a) raw material; (b) oil extraction; (c) biodiesel production.

<table>
<tr><th rowspan="2">Stage costs</th><th rowspan="2">Description</th><th colspan="3">Annual Cost (USD 2018)</th><th rowspan="2">References</th></tr>
<tr><th>MR</th><th>MRUS</th><th>UBIS</th></tr>
<tr><td rowspan="4">(a) Obtaining raw material for 1 ha</td><td>Investment cost—including cost of seedlings, clearing the land, and planting the seedlings</td><td colspan="3">$1305.14</td><td rowspan="4">Field data from the experimental plantation for E2M NTJC</td></tr>
<tr><td>Operation and maintenance costs—including manual labor for the clearing of the land, harvesting of fruit, and transportation—years 1 and 2</td><td colspan="2">$124.75</td><td>$530.22 *</td></tr>
<tr><td>Operation and maintenance costs—including manual labor for the clearing of the land, harvesting of fruit, and transportation—beginning in year 3</td><td colspan="2">$343.08</td><td>$748.54 *</td></tr>
<tr><td>Costs for tools and materials</td><td colspan="3">$363.87</td></tr>
<tr><td rowspan="3">(b) Oil extraction</td><td>Investment cost—including machine and equipment cost</td><td colspan="3">$36,287.37</td><td>[63,64]</td></tr>
<tr><td>Operation and maintenance costs—including manual labor and electricity costs</td><td colspan="3">$95,591.98</td><td>[65]</td></tr>
<tr><td>Storage costs</td><td colspan="2">$263.53 **</td><td>$692.16 ***</td><td>[66]</td></tr>
<tr><td rowspan="4">(c) Biodiesel production</td><td>Investment cost—including equipment costs</td><td colspan="3">$25,111.14</td><td>[67]</td></tr>
<tr><td>Operation and maintenance costs—including manual labor and electricity costs</td><td colspan="3">$62,787.39</td><td>[65]</td></tr>
<tr><td>Costs for input flow, i.e., methanol and sodium hydroxide</td><td colspan="3">$30,320.20</td><td>[68,69]</td></tr>
<tr><td>Costs for storage of biodiesel and glycerin</td><td colspan="3">$315.51</td><td>[66]</td></tr>
</table>

* Includes costs for the application of biofertilizers and flood irrigation. ** Includes only storage of oil. *** Includes storage of seed cake and residual biomass.

Net present value (NPV) was calculated on the basis of a discount rate of 10% and a useful life of 20 years. All costs are expressed in USD—at the 2018 value of this currency.

Indicator 5 (added value) was calculated on the basis of the economic value obtainable from the utilization of sub-products. For each one of the sub-products, the market price of the product to be replaced was referenced. In the case of the NTJC seed cake, a value of 0.21 USD kg^{-1} was utilized [70], which reflects the price of soybean paste.

The value of the biomass of pericarp and tegument was estimated on the basis of the price of the replacement product of firewood sold in a town near the experimental E2M NTJC plantation. According to Vazquez-Perales [71], this price was 0.12 USD kg^{-1}—at the 2018 exchange rate. The market cost of crude glycerin was 0.21 USD kg^{-1} [72].

Finally, for the social indicator (no. 6, employment), which reflects job creation in terms of workers/ha and work/days, data were used pertaining to jobs that were necessary in the production system, in accordance with the gauging of these costs by stage within the Life Cycle Assessment—see Table 3.

Table 3. Life cycle inventory for indicator 6 (job creation) for the production system of the MR, MRUS, and UBIS scenarios, by stage: (a) obtaining of raw material; (b) oil extraction; and (c) biodiesel production.

<table>
<tr><th colspan="7">(a) Stage 1. Obtaining Raw Materials *</th></tr>
<tr><th rowspan="2">Activity</th><th rowspan="2">Unity</th><th rowspan="2">Quantity</th><th colspan="3">Days Per Year for Each Scenario</th><th rowspan="2">Reference</th></tr>
<tr><th>MR</th><th>MRUS</th><th>UBIS</th></tr>
<tr><td>Manual labor for preparation of land.</td><td>Workers /ha</td><td>2</td><td colspan="3">17</td><td rowspan="7">Field data from the experimental plantation for the E2M NTJC</td></tr>
<tr><td>Manual labor for planting seedlings.</td><td>Workers /ha</td><td>2</td><td colspan="3">6</td></tr>
<tr><td>Manual labor for applying flood irrigation during Year 1.</td><td>Workers /ha</td><td>3</td><td colspan="2">4</td><td>-</td></tr>
<tr><td>Manual labor for application of flood irrigation.</td><td>Workers /ha</td><td>2</td><td colspan="2">-</td><td>5</td></tr>
<tr><td>Manual labor: application of biofertilizers.</td><td>Workers /ha</td><td>2</td><td colspan="2">-</td><td>12</td></tr>
<tr><td>Annual clearing of land</td><td>Workers /ha</td><td>2</td><td colspan="3">6</td></tr>
<tr><td>Cutting of fruit</td><td>Workers /ha</td><td>2</td><td colspan="3">20</td></tr>
<tr><th colspan="7">(b) Stage 2. Oil Extraction</th></tr>
<tr><th rowspan="2">Activity</th><th colspan="2" rowspan="2">Profile</th><th colspan="3">Quantity</th><th rowspan="2">Reference</th></tr>
<tr><th>MR</th><th>MRUS</th><th>UBIS</th></tr>
<tr><td>Plant supervisor</td><td colspan="2">Industrial engineer</td><td colspan="3">2</td><td>[73]</td></tr>
<tr><td>Machine operator</td><td colspan="2">Technical operator</td><td colspan="3">4</td><td>[74]</td></tr>
<tr><td>General assistant</td><td colspan="2">General assistant</td><td colspan="3">4</td><td>[75]</td></tr>
<tr><td>Machine maintenance</td><td colspan="2">Mechanical engineer</td><td colspan="3">1</td><td>[73]</td></tr>
<tr><td>Administration of plant</td><td colspan="2">Accountant</td><td colspan="3">1</td><td>[76]</td></tr>
<tr><td>Sales</td><td colspan="2">Degree in Marketing</td><td colspan="3">1</td><td>[76]</td></tr>
<tr><th colspan="7">(c) Stage 3. Biodiesel Production</th></tr>
<tr><td>Plant supervisor</td><td colspan="2">Industrial engineer</td><td colspan="3">2</td><td>[73]</td></tr>
<tr><td>Machine operator</td><td colspan="2">Technical operator</td><td colspan="3">2</td><td>[74]</td></tr>
<tr><td>General assistant</td><td colspan="2">General assistant</td><td colspan="3">2</td><td>[75]</td></tr>
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<tr><td>Sales</td><td colspan="2">Degree in Marketing</td><td colspan="3">1</td><td>[76]</td></tr>
</table>

* the raw material stage involves the creation of temporary jobs and the utilization of unskilled labor.

2.5. Obtaining of Sustainability Index (SI)

Evaluation of sustainability was conducted by means of the *IESEP* methodology: the Index of Environmental Sustainability of Energy Products [38].

For the purposes of the present study, the objective of the IESEP index is to provide quantitative information regarding the total effect that can be attributed to the trend of all sustainability indicators analyzed in the three scenarios. In this way, a comparison among the MR, MRUS, and UBIS scenarios can be conducted for the purpose of determining the total sustainability effect of the options for improved economic value reflected in scenarios MRUS and UBIS, as compared to the original MR scenario.

The aggregation of the indicators was conducted on the basis of the following equation:

$$IESEP_k = \sum_{i=1}^{N} w_{ik} \, I_{ik} \,, \tag{1}$$

In the above equation, $IESEP_K$ represents the value of the global sustainability index for scenario k; w represents the weight accorded to each indicator i that is analyzed in scenario k; and the term Î represents the normalized value of each indicator i.

The weighting factors (w) comply with the following constraint:

$$\sum_{i=1}^{N} w_i = 1 \tag{2}$$

To obtain the *IESEP* for each of the production scenarios analyzed in the present study, the results of the life cycle analysis indicators were normalized within a range from 0 to 1, with 1 representing the highest value in terms of sustainability. Afterward, the indicators were weighted equally. In other words, for the purposes of this study, all of the indicators selected have been accorded the same level of importance as regards sustainability.

Finally, for the comparative analysis of *IESEP* among the three scenarios analyzed, the scenario with the value closest to 1 is considered the best in terms of sustainability, while the scenario with the value closest to 0 is considered the worst.

3. Results and Discussion

Results for the six sustainability indicators—i.e., raw material, oil extraction, and biodiesel production for the MR, MRUS, and UBIS scenarios—within each of the three life cycle stages analyzed are presented in the following subsection.

3.1. Results of Sustainability Indicators

3.1.1. Indicator 1. Greenhouse Gas Emissions

Figure 4 displays the GHG emissions per biodiesel energy unit for the scenarios MR, MRUS, and UBIS, as well as their contributions to each of the three stages comprising the production system.

The MR scenario reflects the behavior of a production system that utilizes a variety of toxic *Jatropha curcas* in which the only products obtained in the production system are biodiesel fuel—the principal product—and glycerin—as a sub-product. This scenario resulted in potential GHG emissions 27.56 kgCO_2e per GJ of biodiesel.

Within this scenario, the highest GHG emissions occurred during the oil extraction stage (13.47 CO_2e per GJ of biodiesel). This was due to the fact that the equipment utilized involved the intensive use of electrical energy.

Results for the MRUS scenario showed a reduction of potential GHG emissions—as compared to the MR scenario. This is because, in addition to the production of biodiesel and glycerin, the MRUS scenario involved utilization of the seed cake, and the residual biomass comprising pericarp and tegument. This resulted in a GHG emissions of 16.65 kg CO_2e per GJ of biodiesel, representing a 27% reduction of GHG emissions, as compared to the MR scenario.

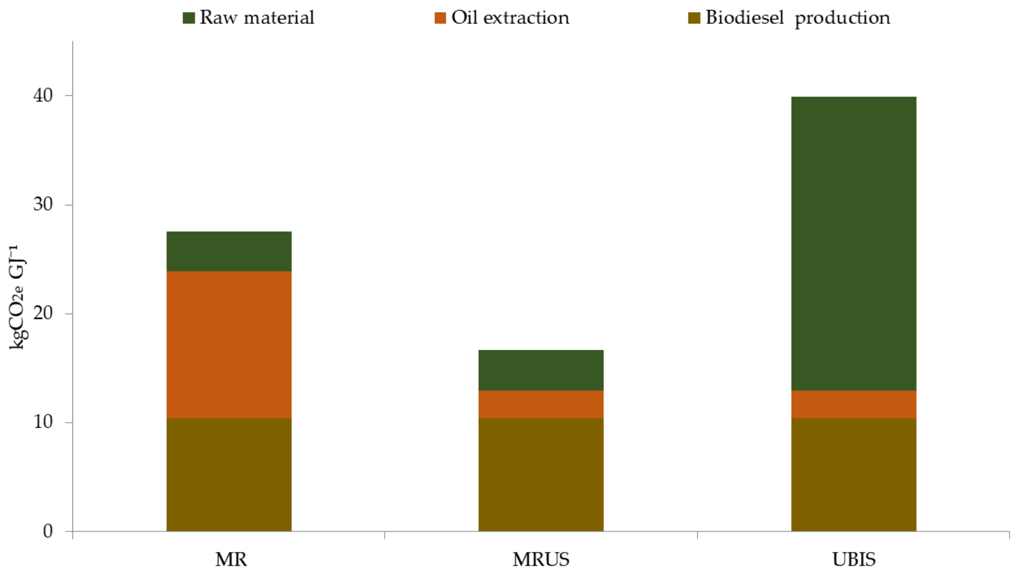

Figure 4. Potential emissions of greenhouse gases in the life cycle of the production system for the MR, MRUS, and UBIS scenarios.

The reduction reported in the MRUS scenario results from the fact that the residual products of the pericarp and the tegument, and of the seed cake, were utilized in later processes as either solid biofuels in rural zones—in the case of residual biomass, and in the production of edible flour—in the case of the seed cake. Any GHG emissions resulting from these subsequent processes would thus not be reflected in the figures reported for the production system analyzed in the scenarios included in the present study.

Thus, within the MRUS scenario, the biodiesel production stage has the greatest potential for emission of GHG (10.42 $kgCO_2e\ GJ^{-1}$). This same quantity applies to each of the three scenarios.

In contrast to the MRUS scenario, the UBIS scenario involves the highest potential emission of GHG. This is because, for the purpose of increasing seed production, the UBIS scenario includes the application of biofertilizers and flood irrigation in the cultivation of NTJC, and also because of subsequent utilization of the seed cake and residual biomass in addition to the production of biodiesel and glycerin. For the UBIS scenario, potential GHG emissions were 39.94 $kgCO_2e$ per GJ of biodiesel—i.e., 31% greater than in the MR scenario.

An increase in potential GHG emissions is noted during the stage of obtaining the raw material and is a result of the application of biofertilizers containing cow manure, the primary emission of which is N_2O.

3.1.2. Indicator 2. Land Use

Figure 5 depicts results for the indicator "land use" within each of the three scenarios. These results essentially reflect events that take place during the raw material stage. This is because the stages of oil extraction and biodiesel production only contributed 1% to the totals reported.

Soil use per energy unit of biodiesel fuel for the MR and MRUS scenarios was 0.0946 ha GJ^{-1}. This result was due to the fact that cultivation conditions in these two scenarios utilized minimal resources, while resulting in the same seed production level of 1021 kg ha^{-1}.

In the UBIS scenario, the use of biofertilizers and flood irrigation increased seed production of NTJC to 1375 kg ha^{-1}. This improved yield reduced soil use to 0.0697 ha per GJ of biodiesel, as compared to the MR and MRUS scenarios. The reduction in land use for each GJ of biodiesel fuel produced represents a production advantage within the available area for the kinds of crops represented by NTJC.

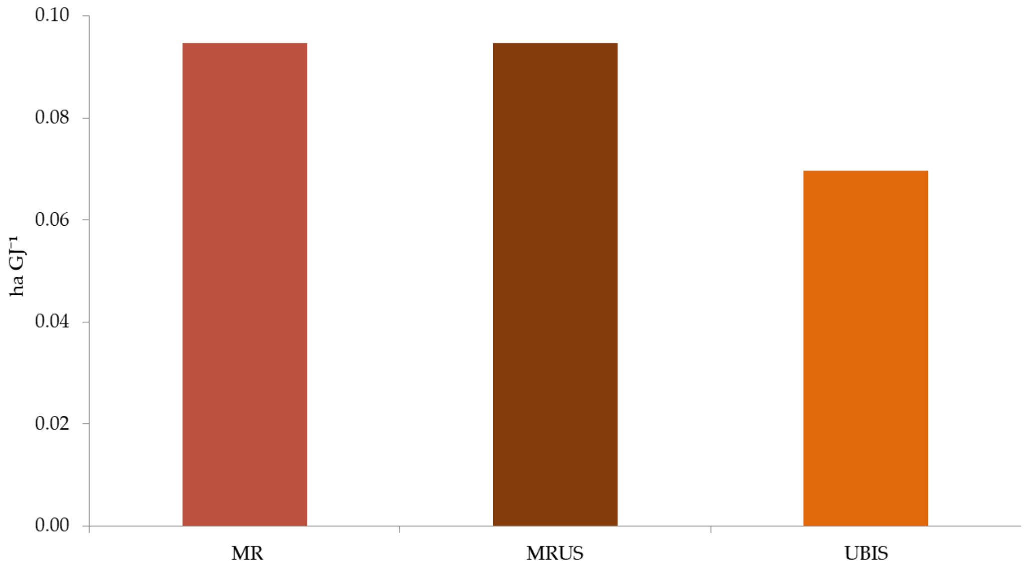

Figure 5. Land use per energy unit of biodiesel produced for the raw material stage.

3.1.3. Indicator 3. Energy Balance

Energy consumption per unit of biodiesel fuel for each scenario is depicted in Figure 6. In the three scenarios, the biodiesel production stage consumed the most energy, due to the methanol consumption required. Electrical energy consumed the second-highest amount of energy.

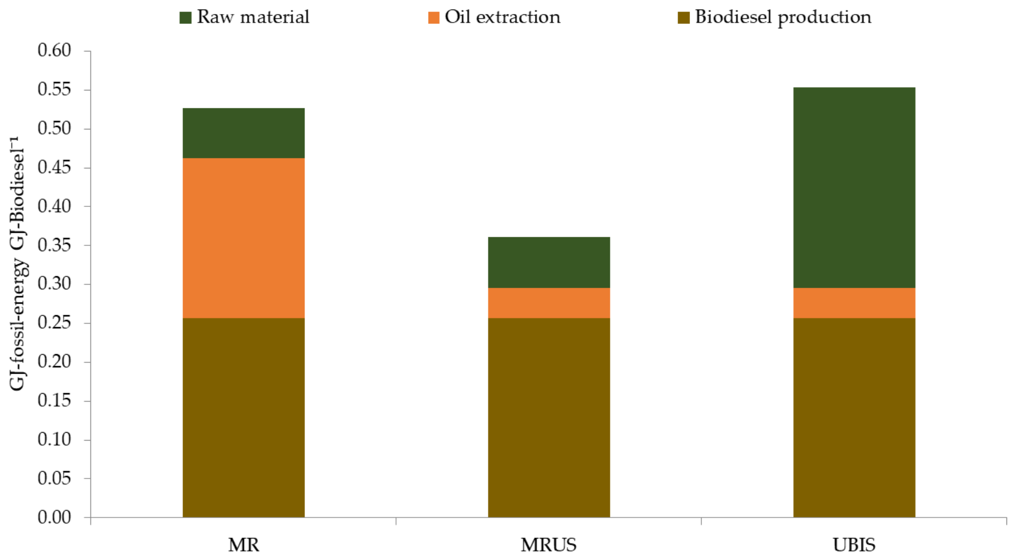

Figure 6. Energy balance in the MR MRUS, and UBIS scenarios.

It was the MRUS scenario that resulted in the lowest consumption of fossil fuels per unit of generated renewable energy, with a balance of 0.361 GJ of fossil fuels per GJ of biodiesel. Conversely, the scenarios MR and UBIS resulted in comparatively higher consumption of fossil fuels (0.527 and 0.553 GJ of fossil fuels per GJ of biodiesel, respectively).

The difference among the scenarios results from the fact that, in MR, oil is exclusively responsible for energy consumption during the oil extraction stage. This is because oil is the only useful product of that stage. On the other hand, in the MRUS and UBIS scenarios, residual biomass and seed cake are also responsible for energy consumption. This phenomenon is due to the fact that these two residual products constitute raw materials that entered into subsequent systems in which they were utilized either as solid biofuel in rural areas, or for the manufacture of food products. Due to the fact that these subsequent systems fall outside the production limits represented by the MRUS and UBIS scenarios, the energy load of biomass and seed cake are transferred to these subsequent systems, resulting in a reduction of fossil fuel consumption per GJ of biodiesel within the systems represented in the MRUS and UBIS scenarios.

However, UBIS was also shown to result in increased energy consumption during the raw materials stage. This increase is due to the transportation of biofertilizers from the location where it is obtained to the E2M NTJC plantation.

Finally, it was noted that the net energy ratio in all three scenarios is greater than 1. In other words, the quantity of biodiesel energy obtained in all three scenarios is greater than the amount of fossil fuels consumed in the production of said biodiesel energy. In this respect, MRUS has the greatest net energy ratio (2.77); followed by MR and MRUS (1.89 and 1.80, respectively).

3.1.4. Indicator 4. Production Costs

Figure 7 depicts production costs in each of the three stages for each of the three scenarios. Production costs in MR and MRUS were identical (43.50 USD per GJ of biodiesel). This identical result is due to the fact that these two scenarios involve the same input flow, materials, and equipment. Conversely, in the UBIS scenario, production costs increase to 54.70 USD per GJ of biodiesel because of the application of both biofertilizers and flood irrigation.

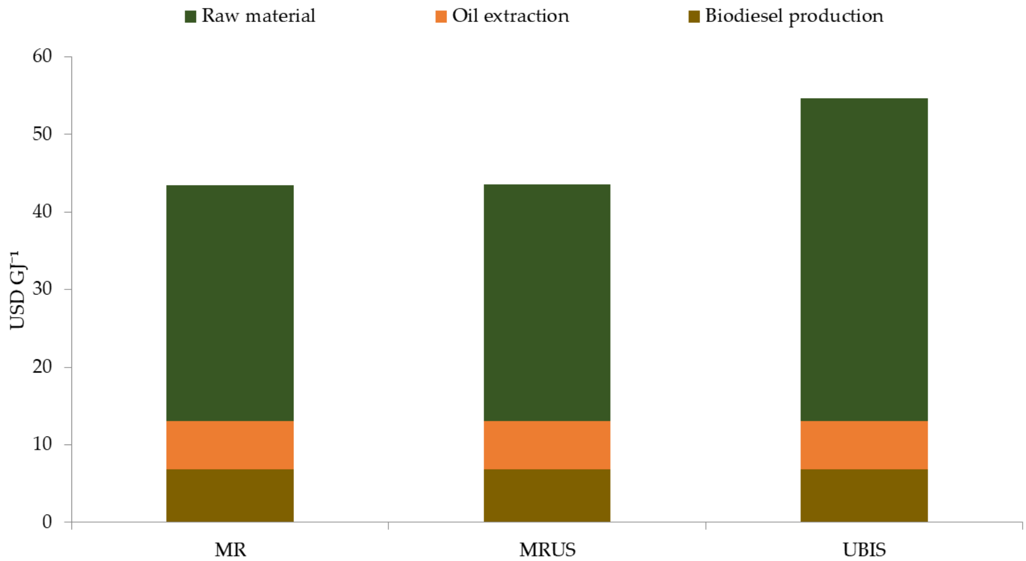

Figure 7. Production costs of one unit of biodiesel energy in scenarios MR, MRUS, and UBIS.

In all three scenarios, the highest cost was associated with the raw material production stage. Production cost of raw material in MR and MRUS is identical. This is due to the fact that these two scenarios involve the same growing conditions. However, production cost is higher in the UBIS scenario, due mainly to the cost of the manual labor required to apply biofertilizers and flood irrigation. At the same time, UBIS results in higher levels of seed production. However, this increased seed production does not compensate for the additional cost for the extra manual labor required.

Thus, the production cost of one liter of biodiesel under scenarios MR and MRUS is 1.55 USD, while the cost under the UBIS scenario is 1.03 USD.

3.1.5. Indicator 5. Added Value

The indicator "added value" represents an additional economic value that can be obtained from the utilization of seed cake, pericarp and tegument biomass, and glycerin. Figure 8 depicts this additional added value for each of the three scenarios.

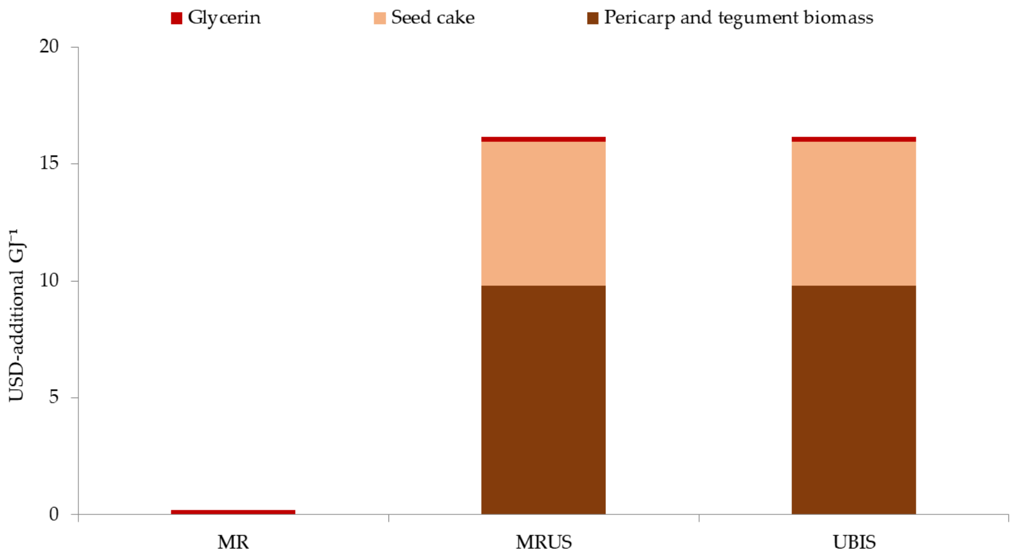

Figure 8. Additional economic value resulting from utilization of sub-products in the MR, MRUS, and UBIS scenarios.

The MR scenario has the least additional added value, due to the fact that its only source of said value is from the sale of the crude glycerin obtained from a transesterification process whose physiochemical characteristics have a low economic value on the Mexican national market. This low value results from the fact that the transesterification process used to obtain glycerin requires other processes to result in a level of purification suitable for use in subsequent processes.

Given that the purification process does not fall within the scope of the production system analyzed in this study, the economic value assigned reflects the production of crude glycerin. Specifically, for each GJ of biodiesel, an additional 0.21 USD is obtained from the sale of crude glycerin.

The highest additional added values were obtained from the MRUS and UBIS scenarios. This is because both of these scenarios yielded additional economic value from the sale of the pericarp and tegument biomass, and seed cake, as well as from the sale of crude glycerin. Thus, in both MRUS and UBIS, an additional 16.15 USD of added value is obtained from each GJ of biodiesel produced.

3.1.6. Indicator 6. Employment

The jobs created in each of the three scenarios, categorized along the two dimensions skilled/unskilled and temporary/permanent, are depicted in Figure 9.

In the three scenarios collectively, the largest number of jobs were created during the oil extraction stage (549 jobs per TJ of biodiesel fuel) due to the fact that more processes are involved during that stage. The jobs created during the oil extraction and biodiesel production stages are for the most part skilled jobs, while the raw material stage involves the creation of temporary jobs and the utilization of unskilled labor.

3.2. Comparison of Scenarios in Terms of Sustainability Index

The results of the six sustainability indicators for the MR, MRUS, and UBIS scenarios in normalized values, as well as the weighted value for each indicator, are presented in Table 4. The sustainability index for each of the three scenarios is presented in Figure 10.

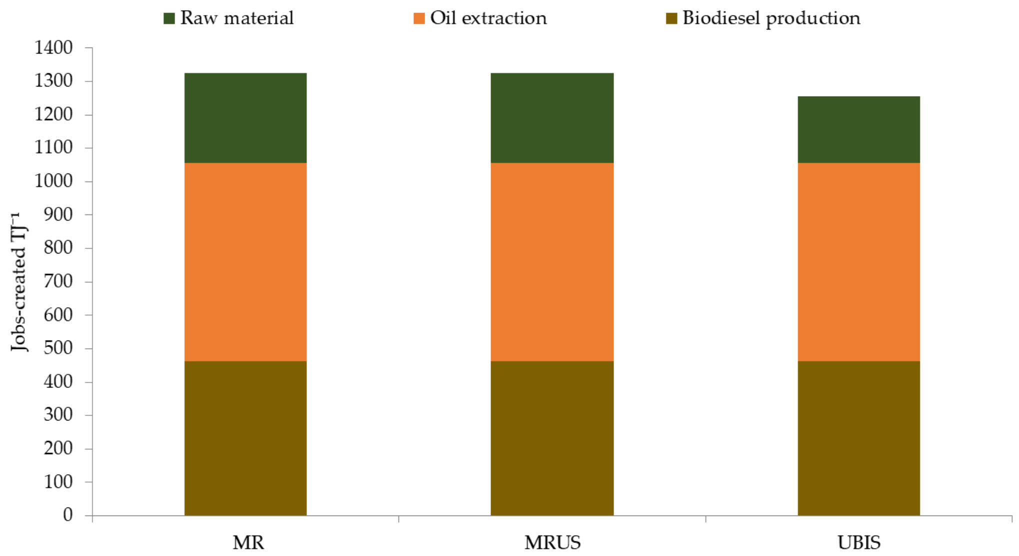

Figure 9. Jobs created from the production of one energy unit in the MR, MRUS, and UBIS scenarios.

Table 4. Normalized values of sustainability indicators and weighted level for the MR, MRUS, and UBIS scenarios.

Scenario	Normalized Values *						Weighted Value of Each Indicator
	GHG Emissions	Land Use	Energy Balance	Production Cost	Added Value	Employment	
MR	0.60	0.74	0.69	1	0.01	1	0.167
MRUS	1	0.74	1.0	1	1.00	1	
UBIS	0.42	1.0	0.65	0.8	1.00	0.95	

* indicators were normalized within a range from 0 to 1, with 1 representing the highest value in terms of sustainability.

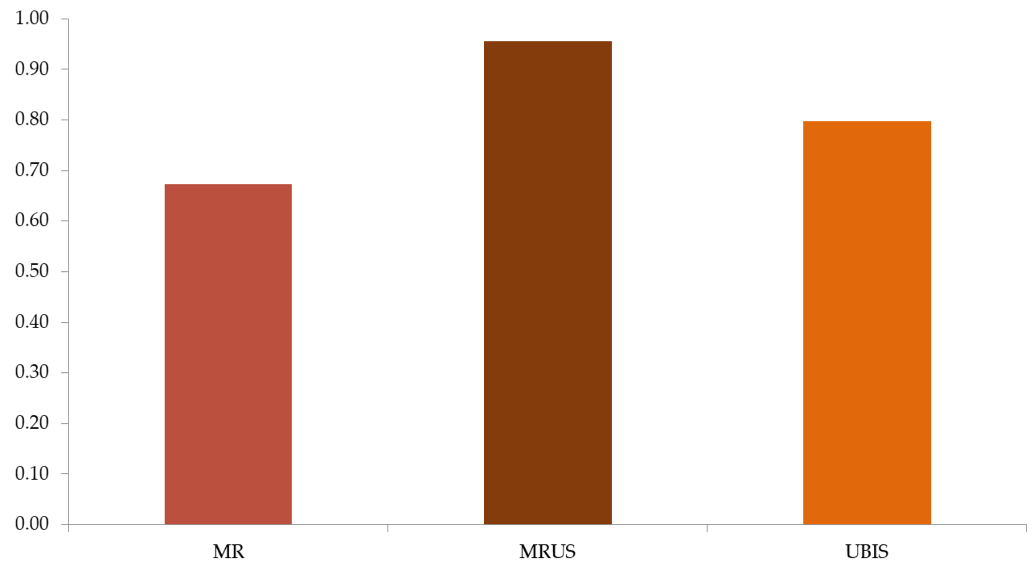

Figure 10. Sustainability index for the MR, MRUS, and UBIS scenarios.

The MRUS scenario resulted in the highest sustainability index—0.956; followed by UBIS—0.797. The MR scenario resulted in the lowest sustainability index—0.69.

The results show that a scenario such as MR, in which a variety of toxic *Jatropha curcas* is used primarily for biodiesel, and to a far lesser extent, for glycerin, has a lower degree of sustainability than the MRUS and UBIS scenarios, which also involve the utilization of other residual products such as seed cake and the residue products of both the pericarp and the tegument of NTJC. The utilization of these additional products translate into a relatively high level of additional added value. This means that the MRUS and UBIS scenarios offer substantial advantages over the MR scenario. It is especially noteworthy that NTJC has a natural advantage over toxic *Jatropha curcas,* the latter representing the majority of the plant's existing varieties. This advantage of the non-toxic variety is due to the fact that it allows the possibility of utilization of the seed cake without requiring an additional process to eliminate the seed's toxicity.

Furthermore, the results of this study show that the UBIS scenario, which involves improving conditions for the cultivation of NTJC through the application of biofertilizers and flood irrigation, does not yield any additional sustainability as compared to the MRUS scenario. This is due to the fact that even though the two additional measures improve the per-hectare seed production, this improved production does not compensate for the increases in GHG emissions, production cost per unit of GJ of biodiesel, or the poorer energy balance obtained in the MRUS scenario. For these reasons, other strategies to improve production should be studied that might avoid such undesired consequences. Despite these disadvantages, the UBIS scenario was shown to improve per-hectare seed production, and to have a higher degree of sustainability in comparison to the MR scenario.

4. Conclusions

The MRUS scenario was conceived for the purpose of increasing the economic value of biodiesel production systems based on the E2M NTJC under conditions of minimal resources and rural marginal soils. Furthermore, the MRUS condition provided added value through utilization of the pericarp and tegument biomass, and seed cake of the NTJC. In the present study, the MRUS scenario yielded a higher sustainability index than the other two conditions to which it was compared.

The UBIS scenario, which was conceived to improve sustainability, yielded a higher normalized value in the indicator "land use." However, the inputs to improve productivity in this scenario also result in an increase in GHG emissions, the quantity of fossil fuels utilized, and production costs. Furthermore, this increased resource utilization was not compensated by higher productivity yields. However, even with these disadvantages, the UBIS scenario had greater sustainability than the MR scenario.

These results demonstrate that the biodiesel production system utilizing non-toxic Mexican ecotypes of *Jatropha curcas* has a higher degree of sustainability because these ecotypes allow for a more integral use of the seed's residual products—most especially, of the seed cake—due to their non-toxic properties.

Future research should be directed at increasing productivity of E2M NTJC. The two key components of such increased production are: (1) a E2M NTJC seed improvement program; and (2) the use of more effective biofertilizers. Increasing production by these means will ensure the implementation of systems that are environmentally, socially, and economically viable (i.e., that have high sustainability) when implemented on marginal soils in poor rural areas.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14102746/s1, Table S1. Study site conditions of the experimental plantation of ecotype E2M of Mexican non-toxic *Jatropha curcas* and Table S2. Parameters, measurement periodicity, methodologies, and evaluation results of ecotype E2M of Mexican non-toxic *Jatropha curcas*.

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Abbreviations

The following abbreviations are used in this manuscript

GHG	Greenhouse Gas
GBEP	Global Bioenergy Partnership
IESEP	Index of Environmental Sustainability in Energy Products
LCA	Life-Cycle Assessment
MR	Minimal Resources
MRUS	Minimal Resources and Utilization of Sub-products
NTJC	Non-toxic *Jatropha curcas*
RSB	Roundtable of Sustainable Biomaterials
SI	Sustainability Index
UBIS	Utilization of Biofertilizers, Flood Irrigation, and Sub-products

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