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A Three-Dimensional Sustainability Evaluation of Jatropha Plantations in Yucatan, Mexico

Julio C. Sacramento Rivero [1,*], Amarella Eastmond-Spencer [2], Javier Becerril García [3] and Freddy S. Navarro-Pineda [1]

[1] Faculty of Chemical Engineering, Universidad Autónoma de Yucatán, Periferico Norte km 33.5, Tablaje Catastral 13615, Col. Chuburna de Hidalgo Inn, Merida, Yucatan 97203, Mexico; fredonava@gmail.com
[2] Social Sciences Unit, Universidad Autónoma de Yucatán, Calle 61 x 66 No. 525, Centro, Merida, Yucatan 97000, Mexico; rillaeastmond@gmail.com
[3] Faculty of Economics, Km. 1 Carretera Mérida-Tizimín, Cholul, Merida, Yucatan 97305, Mexico; javier.becerril@correo.uady.mx
* Correspondence: julio.sacramento@correo.uady.mx; Tel.: +52-999-946-0956 (ext. 1129)

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Abstract: This paper presents a unique sustainability analysis of one of the first attempts to establish a biodiesel industry in Mexico. From 2008, several companies established medium to large-sized *Jatropha curcas* plantations in Yucatan, hiring local peasants to carry out the agricultural work. After five years, the plantations were abandoned due to poor seed yields and a lack of key knowledge for large-scale cultivation. Based on a multidisciplinary approach, we performed a three-dimensional sustainability evaluation of the potential biodiesel production chain, which included household interviews, a socioeconomic survey, and a life-cycle assessment (LCA). We identified both negative and positive effects in the three dimensions analyzed. Socially and culturally, the local peasant families understood sustainability as their ability to preserve their traditional lifestyle, and associated environmental services with their sense of identity. They therefore considered the jatropha plantations to be positive for sustainability, since they brought income, even though some perceived damage to the natural resources of the surrounding areas. Economically, peasants' annual household income increased by approximately $1080 USD due to the increased salaries paid by the jatropha companies. The LCA predicted large savings of greenhouse gas emissions (>50% compared to fossil diesel), but also potential negative impacts in some categories (human/ecological toxicity and eutrophication potentials) associated with the use of mineral fertilizers, insecticides, and pesticides applied during the cultivation stage. Biodiesel production would be potentially energetically self-sufficient, in addition to producing a 40% energy surplus. Finally, even though the sustainability indicators suggested a positive overall assessment, the reality was that the jatropha projects failed because they were predicated on unrealistically optimistic projections and poor agronomic knowledge of the plant.

Keywords: sustainability perception; propensity score matching; life-cycle assessment; biofuels; biodiesel

1. Introduction

In 2008, Mexico introduced the Law for the Promotion and Development of Bioenergy, thus creating a legal framework to foster a national industry of biofuels. The main drivers for this law were the national targets to reduce greenhouse gas (GHG) emissions, derived from Mexico's adherence to the Kyoto Protocol, and a promise of stimulating economic development in rural areas with high unemployment [1,2].

Based on the geography and climates of Mexico, the Ministry of Agriculture, Livestock, Rural Development, Fisheries, and Food (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, SAGARPA) identified a number of non-food crops, including *Jatropha curcas*, and provided subsidies to stimulate the plantation of these crops in low productivity soils, so as to avoid conflicts with food production [3].

Jatropha curcas L. (or simply "jatropha") is a perennial oilseed plant that belongs to the Euphorbiaceae family, considered to have originated in Mexico and continental Central America [4]. Traditionally, it has been used as a hedge plant and for medicinal uses. In recent years, tropical countries such as India, China, Malaysia, Indonesia, Mozambique, Brazil, and Mexico, among others, have explored the potential of the jatropha plant as a feedstock for biofuel production, mainly biodiesel [5]. The jatropha tree has been proposed as a potential feedstock for second-generation biofuels due to many attractive traits: toxic components (mainly phorbol esters) render it unusable for food use; it requires less inputs than other oleaginous crops; it is drought resistant; it can grow in soils with low nutrient content (arid and marginal), avoiding competition with food crops for land; and above all, the oil content in the seeds is very high, around 40%–60% [4,6].

Between 2008 and 2011, thousands of hectares were used for jatropha plantations in several states of Mexico, mainly Chiapas, Sinaloa, Michoacan, and Yucatan [7]. In Yucatan, jatropha plantations were owned by private companies who hired local peasants from nearby villages for their operation. However, after four to five years, companies and peasants alike realized that the projected seed yields (up to 10 tonnes per hectare per year) were greatly overestimated. Annual seed yields of 1 tonne per hectare or less were common throughout the world. As a result, many companies ceased operations, or sold or abandoned the plantations [5,8].

The Yucatan peninsula is comprised of three states: Yucatan, Campeche, and Quintana Roo. The Yucatan peninsula lies on a very large, porous limestone platform with almost no superficial water but with frequent sinkholes (known locally as *cenotes*) which give access to a plentiful underground water supply. The bedrock is covered by only a thin layer of poor, stony soil, making agriculture difficult and very difficult to mechanize, especially in the north. The climate is hot and humid, with an average annual temperature of 26 °C and marked dry and wet seasons. Yucatan lies within the seasonally dry tropical forest eco-region and the major vegetation type in the municipality of Tizimin (where the study was carried out) is medium-height (10 to 15 m) subdeciduous forest, rich in biodiversity [9].

This paper focuses on the jatropha plantations in the state of Yucatan. Jatropha plantations were established in the northeast, close to Tizimin, and in the east, close to Muna (see the map in Figure 1). The municipality of Sucopo was the focus of the social study, while the cities of Muna, Tizimín, and the municipality of Santa Elena were included in the socioeconomic study.

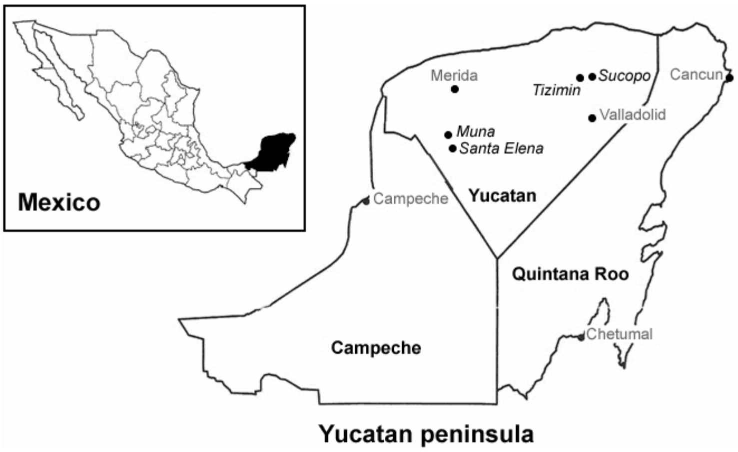

Figure 1. Map of the Yucatan peninsula and the study sites in the state of Yucatan.

In Yucatan, three private companies were responsible for the jatropha plantations. The following is a brief introduction to these three companies. Kuosol, a joint subsidiary of Mexican Keken and Spanish Repsol, chose to plant jatropha on 1500 ha near its intensive pig production unit, a few kilometers from Muna, in the eastern part of Yucatan, to take advantage of residual water from their biodigestors for irrigation purposes [10]. LODEMO, a Yucatecan corporation with its headquarters in Merida, is well established in the commercialization and distribution of fuel for transport in southeastern Mexico. In 2007 it created the subsidiary Biocom to position itself in the biofuel sector and also set up Agroindustria Alternativa del Sureste (now Jatronergy Bioenergéticos), with the ambitious project of developing 20,000 ha of *Jatropha curcas* plantations for the production of biodiesel. By blending biodiesel into its fossil fuels, the company hoped to get a foothold in the alternative energy sector and improve its environmental image [11]. It bought 2570 ha of farmland in the municipality of Tizimin and by 2011 had established 1500 ha of *Jatropha curcas* plantations. Global Clean Energy Holdings (GCEH) is a renewable energy company based in California, USA, focused on the production and commercialization of non-food-based feedstocks for biofuels [12]. They established in 2011 around 2000 ha of jatropha neighboring the LODEMO's plantations.

Currently it is well accepted that, even though there was an exaggerated hype over jatropha's potential as an oil source for biofuels and an international rush to plant extensive areas with a largely unknown wild plant, jatropha still holds great promise that must be unveiled through research [5,13]. Before this can happen, it is necessary to develop commercially exploitable varieties and agronomic management practices that present most of the above mentioned traits simultaneously [14,15]. Moreover, the availability of high-quality uniform planting material has been a major bottleneck for large-scale jatropha plantations [16]. In Yucatan, Mexico, only one out of the three companies that owned jatropha plantations (Agroindustria Alternativa del Sureste, now Jatroenergy Bioenergéticos) holds to this expectation, and conducts basic research on genetic selection and improvement of jatropha varieties, and on improving agricultural practices for increasing seed yield in experimental plantations.

Sustainability Assessment of Biofuels

The existing sustainability assessments for biofuel production consist of a set of principles and criteria. Principles are basic statements or truths associated with biofuel production while criteria are specific objectives that lead to the compliance of the principles [17,18]. Quantitative measurements of sustainability require that principles and criteria are translated into a set of indicators reflecting the issues considered by evaluators or stakeholders [17–19]. Commonly considered issues include global warming mitigation, food security, improved quality of life, biodiversity conservation, maintaining water quality, etc. [20]. A summary of the sustainability issues of biofuel included in these schemes and other sustainability frameworks can be found elsewhere [21].

Currently, the most important two international sustainability frameworks for biofuels are proposed by the Global Bioenergy Partnership and the Roundtable on Sustainable Biomaterials. The latter also offers a sustainability certification of supply chains for bio-based products, including biofuels. Other international initiatives propose voluntary standards and accreditations that have relevance for biofuel production. The reader is referred to other reviews [21,22] for a more complete description and comparisons of these programs.

In many cases, performance of biofuel production in the various criteria is measured against best practices, and historical data are scarce, or non-existent. Particularly in Mexico, insufficient data exist regarding GHG mitigation and other sustainability issues of biofuel production, such as water consumption or social welfare [23]. The current regulatory framework in Mexico for biofuels does not consider a full sustainability assessment, but rather proposes a voluntary scheme through a national norm project (PROY-NMX-AA-174-SCFI-2014) [24] that is heavily based on the RSB criteria and centers mainly on GHG mitigation for liquid biofuels. For this reason, for assessing the sustainability in three dimensions (social, economic, and environmental) of biofuel projects, a framework appropriate for the objectives of the evaluation must be selected first.

There is a growing literature on the social implications of biofuels. Recently, increasing attention has been paid to the livelihood and equity implications of changing land use to biofuel crop production, including such issues as food security and access to land [25,26]. This approach is important because it encourages researchers to take into account a large range of factors that can affect how people perceive the sustainability of their livelihoods [26] (p. 249). This is the framework that was selected to understand how Sucopo inhabitants perceived the impacts of the jatropha plantations on their way of life and community.

The improved salaries and increased income of workers for energy crops are often cited as a driver and potential benefit of first-generation biofuels [20]. However, this is rarely quantitatively measured to determine the real impact (if any) that increased salaries will have on the quality of life of local communities. To this end, the methodology of the propensity score-matching has been used in other countries [27], and in Mexico it has been applied to other industrial sectors [28]. This report is the first one applying the propensity score matching methodology to biofuel production projects in Mexico.

In general terms, life-cycle assessment has been by far the most used tool to measure environmental sustainability of the biofuel supply chain [29]. Several environmental LCAs of the biodiesel production from jatropha have been performed worldwide. A competent review can be found elsewhere [30]. However, these studies are heavily focused on the mitigation of the global warming potential. Martinez-Hernandez et al. [31] analyzed the GHG emissions from fossil primary energy use of a jatropha-based biorefinery in Mexico and, in a further work, they used a strategy for policy compliance of jatropha-based products in terms of economic and GHG emission savings [32]. This work expands the use of LCA for the calculation of the global warming mitigation potential, and other environmental impact categories.

This article describes a three-dimensional assessment of the jatropha plantations in Yucatan, Mexico, during the five-year period in which the project maintained an expectation of industrial production of oil for biofuels in Mexico. This is the first time that the integration of these three methodologies in a single sustainability evaluation is reported.

2. Methodology

The three dimensions of sustainability were analyzed separately using an appropriate instrument. In the social dimension, semi-structured interviews were conducted, designed to learn about the local community's perception of the plantations established nearby and the effect that the company and its activities had on their well-being, as well as on their lifestyle and environmental services. In the economic dimension, the effect of the jatropha plantations on annual household income in local communities was estimated using the propensity score matching methodology. Finally, the potential environmental impact of the biodiesel production chain was assessed using a life-cycle assessment (LCA). A more detailed description of these three methodologies follows.

2.1. Interviews and the Local Community's Perceptions

A qualitative anthropological approach was adopted to assess the social dimension of the sustainability analysis due to severe difficulties accessing official sources of data. Based on a case study research design, data were collected using semi-structured interviews with most respondents and unstructured in-depth interviews with key informants [33,34]. The originally planned sources of information were key stakeholders from the various sectors involved (national agencies, company executives and workers), as well as public information. However, by the time the analysis began, towards the end of 2012, most projects considering jatropha as a feedstock for biodiesel around the world had already collapsed [8], and local companies were thus not interested in commenting on them. Only very limited information was available from Mexican federal government departments responsible for different aspects of the jatropha projects, such as SAGARPA, the National Forestry Commission (Comisión Nacional Forestal, CONAFOR), and the Ministry of the Environment (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT).

The Maya village of Sucopo, 10 km east of Tizimin, where pre-Hispanic remains can still be found, was selected as the site for collecting data on the social dimension of the analysis because of its location next to the plantations belonging to Global Clean Energy Holdings Inc. (one of the three companies that invested in jatropha in Yucatan) and the large number of its inhabitants employed by the company. With a population of 1517 inhabitants, most of whom consider themselves Maya but who also speak Spanish, Sucopo is rated by the Mexican authorities as having a high degree of marginalization [35], indicating the highest level of poverty, low levels of formal education (19% of the population over 15 years of age have not completed primary school) and low salaries; i.e., over 50% of the population earn less than two minimum salaries [36]. Most of the older men in the village work their own small plots of land or are employed as agricultural laborers, while many of the younger ones migrate to the Caribbean coast to work in the construction and tourism industries where they can earn slightly more, returning home periodically to visit their families. Most women in Sucopo are housewives, but the younger ones increasingly work outside the home when the opportunity arises.

Semi-structured interviews were carried out in 60 households, selected from all four sections of the village by systematically contacting one out of every four houses along the main streets. Care was taken to include a balance of men and women of all ages over 18. Using an interview guide, the questions posed centered on the following themes: (1) perceptions about Sucopo, its importance for their cultural identity, and how people valued the place and its natural resources; (2) how the village and work opportunities had changed over the last 15 years and what expectations people had for the future; and (3) what perceptions people had about Global Clean Energy Holdings (GCEH) and the jatropha plantations, how the latter had impacted life in Sucopo in terms of job opportunities and future prospects and, finally, what effect, if any, the plantations had had on the natural resources surrounding the village. Longer and more informal conversations were carried out with community authorities and, most importantly, in order to understand the jatropha projects' impacts, with two key informants who provided critical insights into GCEH's plantations and their less visible social and ecological effects.

2.2. Propensity Score Matching

To estimate the effect of jatropha projects on the annual household income of workers, a total of three municipalities (Santa Elena, Muna, and Tizimin) in Yucatan were chosen as study sites. These localities were chosen because they have similar socioeconomic and cultural backgrounds, and because they are near to the jatropha plantations. The propensity score matching methodology [37] was employed, using the binomial Probit model in the statistical software STATA ©. This method compares the annual income of a worker on the jatropha plantations (JP), i.e., the *treatment*, against that of a counterfactual worker, who has the same socioeconomic profile, only differentiated by not working on the JP, i.e., the *control* group. An important issue when evaluating the impact that working on the JP has on income is the specification of the average treatment effect (Δ_i). Rosenbaum and Rubin [37] defined Δ_i in a counterfactual framework as:

$$\Delta_i = Y_i^B - Y_i^N \tag{1}$$

where Y_i^B and Y_i^N respectively denote the income of household i that works on the JP and the income of the same household i if it does not work on the JP. Because Y_i^N cannot be directly measured, it is approximated by the income of a counterfactual household with a set of features that are most similar to the treatment i. This is done by using the nearest-neighbor method (NNM), which matches the propensity score of individuals in the treatment and control populations. The propensity score is a measure of the probability of finding a subject with a given set of features, which are mathematically contained in the vector x. The features used in this study were defined at the individual and household levels. Examples of the individual features are sex, age, educational level, and languages. Examples of household features are number of family members, owns a home garden, owns a *parcela* (i.e., is a small farm with perennial crops, typically citrus, such as orange, bitter orange, grapefruit, and lime), owns a *milpa* (i.e., a larger farm with rotational crops, typically maize, squash, and various types of beans, which are maintained and harvested using the homonymous traditional farming system from Mesoamerica), public social-aid programs that they benefit from, number and types of environmental services used, number of rooms, access to utilities such as potable water and electricity, etc. A full list of included characteristics and the average values found in the populations studied are given in Table 1.

The instrument for gathering information about the socioeconomic characteristics in the three selected locations was a standardized survey [38], commonly employed in econometric studies and particularly useful for economy-wide analyses in small rural villages [28,39,40]. A total of 192 household surveys were conducted, representing a total of 907 individuals (4.7 members per household on average). Only adults (18 years and older) were included in the NNM algorithm.

2.3. Life-Cycle Assessment

An LCA quantifies the potential environmental impacts caused by all stages in the life cycle of a product, based on the inputs and outputs of energy and materials to and from each stage. The life cycle of a product is the sequence of all processes (or stages) needed to extract and transform all raw materials (in this case, jatropha fruits, fertilizers, pesticides, water, electricity, and others) into the final products (biodiesel and electricity), including the usage stage (i.e., burning the biodiesel in engines) [29,41]. The stages included in this analysis were (a) an agricultural stage, including the processes of land preparation, plant cultivation, and fruit harvest; and (b) the industrial stage, including the processes of materials transport and processing, product manufacturing, distribution and use, and end-of-life disposal or recycling (see Figure 2). For liquid biofuels, this is known as a well-to-wheels (or cradle-to-grave) system boundary [42]. For comparison purposes, two scenarios were assessed: first, a base scenario (S1) where the only valuable product is biodiesel produced from the jatropha oil, and the remaining streams are either considered by-products (such as the press cake, which is sold as a soil amender, and the crude glycerin, which is sold as it is after the chemical reaction process) or residues (hull and husks, which are lignocellulosic biomass left over from the extraction of the seed oil). In the alternative scenario (S2), all the lignocellulosic residues (husk and hull) and the press cake are transformed into steam and electricity, so that biodiesel production is energetically self-sufficient (i.e., without the need for external energy sources) and the excess electricity is injected into the public grid. In all cases, it was assumed that the plantations could maintain a constant seed yield of 2000 kg·ha^{-1}·a^{-1} for 20 years.

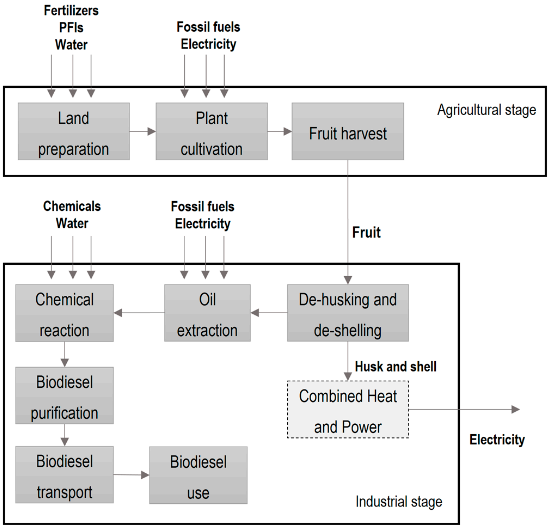

Figure 2. Process diagram of the two scenarios of the biofuel system based on *Jatropha curcas*. The dotted box corresponds to a process considered only in scenario S2. PFIs: Pesticides, fungicides, and insecticides.

The functional unit (calculation basis) for both scenarios was the production of 1 MJ of biodiesel (considering an average combustion heat of 40.64 $MJ \cdot kg^{-1}$), which is typical for biofuel LCA [29]. The inventory of material and energy flows in the agricultural stage was supplied directly from the company Agroindustria Alternativa del Sureste, which had 1500 ha of jatropha plantations at the time of this research. Since the industrial and distribution stages were not in place, the corresponding material and energy balances were estimated using the Aspen Plus © process simulator and validated with experimental data from the scientific literature. All characterization of the jatropha seeds (such as moisture content, oil content, chemical composition of the oil and press cake, etc.) was obtained experimentally from seeds provided by Agroindustria Alternativa del Sureste.

For the calculation of GHG emissions, direct land-use change (dLUC) was included (but not indirect land-use change) using the calculator developed by the Roundtable for Sustainable Biofuels [43]. This calculation considered that the plantation area changed from "managed grassland" to "cropland in a tropical moist zone", and assumed that the land change occurred in a cambisol soil type with no tillage and without using fire for clearing. The NH_3, N_2O, and NO_x emissions from the use of fertilizers were also calculated based on these guidelines assuming a plantation lifetime of 20 years. Emissions to the groundwater and soil, such as phosphates, nitrates and metals, were calculated following the metrics of the Agroscope Reckenholz-Tänikon Research Station [44].

The CML-IA 2000 methodology was used for the environmental impact assessment, considering all the baseline impact categories: Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming (GWP), Ozone Layer Depletion (OLDP), Human Toxicity (HTP), Fresh-Water Aquatic Ecotoxicity (FWAEP), Marine-Water Aquatic Ecotoxicity (MWAEP), Terrestrial Ecotoxicity (TEP), and Photochemical Ozone Creation (POCP) potentials. In addition to these categories, the energetic performance in the life cycle was assessed using the Fossil Energy Ratio (FER) indicator, which is the ratio of the total energy produced (in the form of biodiesel and electricity) to the fossil energy demanded by all processes in the life cycle. In the interpretation of the results, no allocation method was used. Instead, the emissions in all impact categories are considered to replace or substitute the emissions of a hypothetical reference system that produces the same amount of comparable products (i.e., electricity as per the electricity mix in Yucatan, and fossil diesel). This is known as consequential LCA [45].

3. Results and Discussion

3.1. Local Community's Perception

Gathering information from official sources of data proved to be a challenging task. Given the uncertainty surrounding jatropha's future worldwide and the collapse of most projects due to low on-site seed yields [10,46,47], private companies that had invested in jatropha refused all interviews on the grounds of confidentiality, and even the workers were reluctant to speak as they had all signed contracts which prohibited them from talking about their work. However, soon after initiating the study, two events occurred which provided valuable insights into the jatropha plantations. Firstly, Global Clean Energy (GCEH Mexico S.A.), a subsidiary of Global Clean Energy Holdings Inc. based in California, USA, was awarded a sustainable production certificate for its jatropha plantations in Yucatan (known locally as Asideros I and II), which was published on the internet [48] and contained useful basic information about the company; Secondly, a month later, local newspapers reported the dismissal of a large number of GCEH's workers in the Tizimin area [49]. Ex-employees of the company were suddenly more willing to talk about their experiences and perceptions of the plantations.

The certification evaluation report issued by SCS Global Services [48], based on the Roundtable on Sustainable Biomaterials (RSB) criteria, reveals that Global Clean Energy (GCEH Mexico) S.A. bought a total of 6054 ha (described as "abandoned cattle ranches") near Sucopo's ejido (common land) and applied for permission to plant 3393 ha of the land with jatropha. Although botanically a shrub, jatropha was classified as a tree by the Mexican government, making it eligible for a reforestation subsidy of $7300 MXN (approx. $558.96 USD at the time) per hectare for the first two years of establishment of the jatropha plantations. Interviews with SAGARPA personnel also revealed that the company obtained subsidies from this department amounting to some $300,000 MXN (approx. $22,970 USD) to purchase two tractors. Some 500 workers in total (at the peak of its operation) were hired by GCEH to work in the fields, mostly from Sucopo, but also from other nearby villages. The sustainability certificate states that GCEH provided social programs for the village and paid 195% of the rural minimum wage, which signified that its workers were getting higher salaries than those paid by most other companies in the area. It also mentions that, unlike many local businesses, the company fully complied with the Federal Labor Law (Ley Federal de Trabajo), meaning that its employees were all given access to medical services via the Instituto Mexicano del Seguro Social (IMSS), a mortgage from the National Housing Fund for Workers (Instituto del Fondo Nacional de la Vivienda para los Trabajadores, INFONAVIT), a pension scheme, as well as paid holidays and bonuses.

In response to the first group of questions regarding their perceptions about Sucopo, its importance for their cultural identity and how people valued the place and its natural resources, the people of Sucopo replied that they liked their village because it offered them tranquility and safety and, for most of them, it is where their Maya peasant roots lie. Everyone knows each other, all the families are poor and when someone is in need, neighbors and friends help. One can walk about the village without fear of being assaulted or that children might be harmed. Sucopo offers its inhabitants the possibility of living their lives according to their Mayan cultural values, their history, and their religious and spiritual traditions. Those who so wish can continue with their traditional shifting agriculture (*milpa*), based on a two-year cycle of maize, bean, and squash production, hunt wild deer, keep bees in the forest and raise domestic animals, such as chickens and pigs, in their backyard. Sucopo peasant farmers admit that today it is much harder than in previous times to obtain a good harvest from the land because of climate change, the increased incidence of agricultural pests and diseases, and the scarcity of old forest (*monte*) to cut for *milpa*. However, they still have access to land, which allows them to grow some of their own food when they have no other source of income.

Regarding the second group of questions that asked about how the village and work opportunities had changed over the last 15 years and what expectations people had for the future, there was a consensus amongst the interviewees that *milpa* agriculture had declined over the last few decades. They reported that families used to be able to live off their land by cultivating maize, beans and squash, raising animals, hunting and perhaps keeping bees or making hammocks [50]. However, they said that the days when Maya peasant families could be almost self-sufficient were gone, as yields had fallen far below what they used to be, sometimes resulting in no harvest at all, and many people had abandoned agriculture. Rainfall variability and timing were blamed for the recent bad harvests, compounded by a rise in pests and diseases. Population growth, farm division, and a decrease in the fallow period needed to allow the soil to recover its fertility, were also mentioned as contributing factors. It was remarked that only the older farmers still persisted today in eking out a living from their land. Some who have lost or sold their own plots of land work as day laborers tending other people's cattle. However, most of the young men have been forced out of agriculture, migrating to the Mayan Riviera in search of work in the construction and tourism industries. Not being able to find employment near their home is what Sucopo people regret the most. It is not surprising then that people jumped at the opportunity when GCEH arrived in the village promising them a job on their plantations for the next 15–30 years sustainably producing jatropha for biodiesel. Regarding gender-specific perceptions, women respondents appreciated the fact that GCEH employed females as well as males to work in their nurseries, since working in the field is traditionally seen as a man's job.

Finally, with reference to the perceptions people had about GCEH and the jatropha plantations, how the latter impacted life in Sucopo in terms of job opportunities and future prospects and what effect, if any, the plantations had on the natural resources, the people of Sucopo reported the following. Everyone spoke positively of GCEH as an employer. They confirmed that it paid better salaries than any other local company (including other companies planting jatropha), providing all the perks and benefits established in the Mexican Labor Law (which many other companies failed to provide), such as access to medical services, a pension, a housing loan, paid holidays, bonuses and items such as uniforms and work tools. The ex-employees were given very little technical information about the plantations (only the bare minimum in order to do their jobs), but they had no complaints about their working conditions. They were grateful to have had "such a good job" near their home and to be able to combine paid work with farming their own land after work hours. The sudden availability of employment near to the village had a huge impact on the quality of life in Sucopo because it brought stability and improved the economic conditions of so many families. At the height of their operations, GCEH employed over 500 field workers, many of whom were from Sucopo. It was reported that probably at least one member of each of Sucopo's approximately 400 households worked for GCEH at some point. However, during the third year, neighboring farmers and local newspapers reported that the jatropha leaves had turned yellow and that the yields had been reduced to a few kilograms per hectare. Despite flying in plant pathologists from the USA to give advice and spraying the plantations with pesticides, it was not possible to reverse the decline and finally all the workers were laid off and the whole operation was abandoned. Disappointment and gloom returned to Sucopo as people asked what had become of sustainable jatropha production. They had been led to believe that this time it would be different, but ultimately the jatropha plantations were just like any previous government project that ended in failure with no alternative plan or compensation (other than a month's salary) for the workers. Once again, Sucopo's inhabitants were forced to look for poorly paid work outside their village. When questioned about the future, many people expressed their wish that GCEH might one day return.

Regarding the perceived ecological impacts, little is known about the specific agricultural practices used by GCEH on its plantations as the workers were kept in the dark about most aspects of the operations. The certification evaluation report [48] states that 100% compliance with the RSB criteria was observed at the time of issuing the certificate on 20 November 2012. It specifically reports that GCEH's agricultural activities added no extra risk to soil, water, air, human, and land rights and that the company actually increased food security due to the large number of local people it had employed, and the free breakfasts it provided for schoolchildren. Some of Sucopo's inhabitants agreed or said they did not know. However, some of the older *milpa* farmers thought differently. One in particular, whose land was adjacent to the plantations, had seen small airplanes spraying products on various occasions and attributed losing half his bee colonies to these events. In addition, he pointed to the fact that the so-called "abandoned cattle ranches" that had been replaced by GCEH with jatropha had not been covered with grass, but by secondary growth, medium-height subdeciduous forest, with trees of 10 to 15 m, some of which were 50 years old. This key informant reported that the land had been inhabited by animals and used by the peasants for multiple purposes, such as hunting and bee keeping, as well as collecting firewood, building materials, fodder for their cattle, and medicinal plants. When the dry tropical forest was replaced with the monocrop jatropha, many species lost their habitat and sources of food, becoming pests to the neighboring farmers, whose *milpa* harvests were subsequently devastated.

3.2. Effect on Annual Household Income

The descriptive variables gathered from the survey in both the treatment and control populations are summarized in Table 1.

By looking at the large values of the standard deviations of practically all the non-binary descriptors, it is evident that there is a high heterogeneity among the surveyed population. The individual descriptors catalogued the interviewees as being between 30 and 50 years old, with an average education as far as primary school. Most people speak Mayan and very few speak English. All households maintain one type of land with crops for self-consumption, and the land area and number of crops vary widely. Also, almost all households obtain environmental services from surrounding woody areas, the most common being gathering wood for cooking and collecting wild fruits. Income from public social-aid programs varies widely, with an average of $7021.00 MXN

($537.60 USD, considering the December 2013 exchange rate). The majority of households (around 70%) receive health insurance from the public program *Seguro Popular*. This means that most people do not work for companies that offer the mandatory benefit of providing *Seguro Social* (the Mexican national health insurance service). Of the 192 household surveys, only 13 were found to have worked for the jatropha plantations (JP).

Table 1. Description and average values (n = 192 households) of variables included in vector **x** for characterizing individuals and gathered through the survey.

Variable Name	Description	Unit [1]	Average [2]
Individual descriptors			
Sex	1 = man, 0 = woman	b.	0.50 ± 0.50
Age	Current age in years	years	40.0 ± 15.4
Education	Completed years of formal education	years	5.8 ± 4.1
Maya	1 = speaks Mayan language	b.	0.87 ± 0.34
English	1 = speaks English language	b.	0.04 ± 0.19
Household descriptors			
Family	Number of family members in adult equivalent [3]	Adult eq.	4.6 ± 2.2
Home garden	1 = household has home garden	b.	0.8 ± 0.4
Home garden crops	Number of dissimilar crops in home garden	–	4.4 ± 2.8
Parcela	1 = household has a *parcela*	b.	0.18 ± 0.3
Parcela crops	Number of dissimilar perennial crops in *parcelas*	–	3.2 ± 2.0
Milpa	1 = household has *milpa*	b.	0.38 ± 0.49
Milpa crops	Number of dissimilar crops in *milpa*	–	2.0 ± 1.1
Total crops	Home garden crops + Parcela crops + Milpa crops	–	4.8 ± 3.8
Total parcelas	Total number of *parcelas*	–	1.2 ± 0.6
Land	Total land area owned by the household	ha	23.2 ± 22.9
Own house	1 = interviewee owns the house he/she lives in	b.	0.93 ± 0.25
Rooms	Number of rooms in the house	–	1.8 ± 0.8
Sewage	1 = household has a sewage system	b.	0.61 ± 0.49
Potable water	1 = household has potable water service	b.	0.97 ± 0.16
Electricity	1 = household has electricity	b.	0.98 ± 0.14
Gas cooker	1 = household has a gas stove	b.	0.05 ± 0.21
Wood cooker	1 = household cooks using wood	b.	0.74 ± 0.44
Owns car	1 = household owns a car	b.	0.03 ± 0.16
Owns motorcycle	1 = household owns a motorcycle	b.	0.32 ± 0.47
Owns bicycle	1 = household owns a bicycle	b.	0.68 ± 0.47
Owns TV	1 = household owns a TV	b.	0.88 ± 0.32
Owns PC	1 = household owns a PC	b.	0.09 ± 0.29
Landline	1 = household has a working landline (telephone)	b.	0.12 ± 0.33
Access to public social-aid program descriptors			
Procampo	1 = household is subscribed to the public program "Procampo"	b.	0.27 ± 0.44
65 y mas	1 = household is subscribed to the public program "65 y más"	b.	0.10 ± 0.31
Seguro Popular	1 = household is subscribed to the public health service "Seguro Popular"	b.	0.69 ± 0.46
PET	1 = household is subscribed to the public program "Programa de Empleo Temporal"	b.	0.02 ± 0.14
Oportunidades	1 = household is subscribed to the public program "Oportunidades"	b.	0.67 ± 0.47
PP income	Annual income from public social-aid programs	$MXN	7021 ± 8014
Environmental services descriptors			
ES trees	1 = household utilizes trees from surrounding woods	b.	0.09 ± 0.28
ES wood	1 = household collects wood from surrounding woods	b.	0.91 ± 0.28
ES fruit	1 = household collects wild fruits from surrounding woods	b.	0.44 ± 0.50
ES medicinal plants	1 = household utilizes medicinal plants from surrounding woods	b.	0.11 ± 0.31
ES Deer	1 = household reported hunting wild deer in surrounding woods	b.	0.14 ± 0.35

[1] Binary value, dimensionless; [2] average ± standard deviation; [3] Adult equivalent is a weighted-average unit of per capita consumption that uses age and sex of individuals as weighting factors.

These descriptors were fed into the Probit model in the software STATA © to calculate the propensity score of the individuals. Table 2 lists the regression parameters for a subset of 12 variables selected using economic theory. The shaded rows correspond to those variables that showed a statistically significant effect on differentiating individuals working on the JP (treatments) and individuals who did not (controls).

Most of the variables show the expected sign according to economic theory and are statistically significant, which indicates that the model is robust.

Table 2. Regression parameters of the binomial Probit model showing the 12 variables with a significant effect on the propensity score (shaded cells).

Variable	Coefficient	Std. Error	$\lvert z \rvert$-Value [1]
Sex	1.834	0.643	2.85
Age	–0.049	0.020	2.44
Education	–0.123	0.066	1.86
Family	–0.122	0.128	0.95
Total crops	0.064	0.053	1.21
Land	–0.038	0.019	1.98
Procampo	0.706	0.457	1.55
Seguro Popular	0.279	0.519	0.54
ES fruit	0.337	0.406	0.83
ES wood	–0.670	0.413	1.62
Owns motorcycle	1.006	0.437	2.30
Landline	1.108	0.755	1.47
Constant term	–0.563	1.283	0.44

n = 244 (working adults); pseudo-r^2 = 0.4086; Probability > $\chi^2(12)$; [1] A value of $\lvert z \rvert > 1.645$ (or $p < 0.05$) corresponds to a variable with statistical significance.

Once the propensity score was calculated, the evaluation of the impact of working on the JP on annual household income was estimated using the nearest neighbor method. The annual income of JP workers from salaries was found to be $14,123.08 MXN (approx. $1081.40 USD with $p < 0.05$) higher than the control population. This amount can be directly attributed to benefits from being hired by the JP companies.

These results are consistent with similar studies by Becerril et al. [51] applied to the manufacturing sector, where the income from salaries and other benefits paid by industries via formal employment translate into a significant positive impact. Of special relevance is the observed difference between the benefits which JP workers received from public programs ($537.60 USD) and the additional amount in their salaries ($1081.40 USD). This is evidence of the important influence that the JP had on the communities, albeit short-lived, which resulted in direct and indirect activation of the local economy; i.e., most JP workers consumed goods and services offered in the local and regional markets, mainly mobile phones, motorcycles, and televisions, thereby producing a multiplying effect on other sectors of the territorial economy.

3.3. Potential Environmental Impacts

When analyzing the sources of environmental impacts by stage (process) in the life cycle, it is evident that most of the emissions come from the agricultural stage. These are attributed to the production of fertilizers, and pesticides, fungicides, and insecticides (PFIs) used in the cultivation of the jatropha fruits. This agrees with the results of other studies [52,53]. Given the predominance of the agricultural stage, the corresponding impacts are shown in detail in Figure 3.

In the agricultural stage, PFIs constitute the largest contribution to the following impacts: ADP (40%), GWP (33%, excluding the dLUC effect), OLDP (96%), HTP (55%), FWAEP (42%), and POP (54%). On the other hand, production and use of fertilizers are the major contributors to AP (64%) and TEP (60%), while gasoline production contributes the most to the MAEP (39%) and POP (54%). Finally, the emissions derived from the nitrogen released by crop residues on the land are responsible for 53% of the EP.

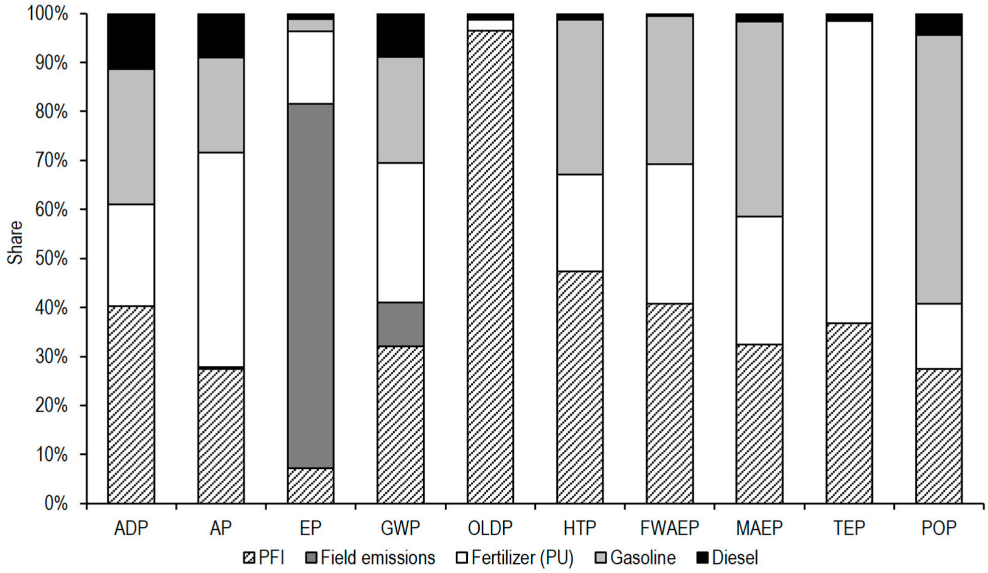

Figure 3. Distribution of the potential environmental impacts in the agricultural stage. The global warming (GWP) distribution does not include the direct land-use change (dLUC) effect. PFIs: Pesticides, fungicides, and insecticides. PU: production and use.

The potential reduction of environmental impacts of the biofuel system can be estimated by comparing them to the corresponding emissions of the reference system. The potential reductions (as a percentage) in all environmental impact categories are plotted in Figure 4. In this figure, relative emissions are expressed as a percentage of the fossil reference system; values lower than 100% indicate savings, while values higher than 100% occur when the emissions of the biofuel system are greater than those of the fossil system.

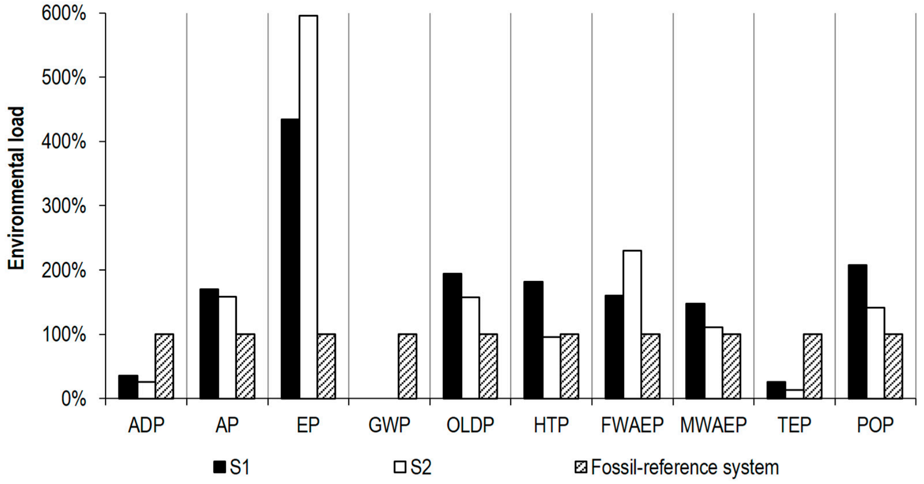

Figure 4. Emissions in the environmental impact categories of the scenarios analyzed using the fossil reference system as a basis for comparison (100%).

The largest reduction is observed in the GWP category, where the GHG emission savings are 23.86 and 27.79 g CO_2eq per MJ of biodiesel in S1 and S2, respectively. The dLUC contributes greatly to this result, because the considered land-use change (from managed grassland to cropland in a tropical moist zone) represents a gain in the carbon stock fixed as tree biomass. When the dLUC is not included in the calculation, the GWP increases to 14.54 and 10.61 g CO_2eq·MJ^{-1} (S1 and S2, respectively), which still translates to 57% and 79% reductions, respectively. Since the Roundtable on

Sustainable Biomaterials (RSB) requires a 50% reduction in GHG emissions compared to an emission factor of 83.8 g CO_2eq·MJ^{-1} for fossil-based fuels [54,55], both scenarios fulfill the RSB goal even when excluding the effect of direct land-use change. Furthermore, the seed yield could decrease to 447 and 403 kg·ha^{-1}·a^{-1} in the S1 and S2 scenarios, respectively, and still comply with the RSB target, although in such extreme cases the economics of the process would be prohibitive.

Regarding other impact categories, both scenarios reduce the ADP, GWP, and TEP. However, other impacts related to soil and water emissions (AP, EP, and FWAEP) increase, mainly due to the activities in the agricultural stage discussed previously. In general, this trade-off seems to be an implicit consequence of biofuel production [29]. It is worth noting that the assumed nitrogen and phosphorous doses for jatropha plants were taken from experimental plantations and therefore are most likely overestimated. More research is needed to find optimal doses of fertilizers and PFIs. Also, landfilling ash generated by biomass combustion causes larger EP and FWAEP impacts in S2 than in S1. These emissions could be avoided if some of this ash residue were used, for example, as an alternative construction material for filler in road embankments, cement-treated materials or non-structural concrete [56]. However, these alternatives require more research.

Figure 5 shows how the energy produced, or energy output (EO), is distributed among the energy products of the biofuel system (biodiesel and electricity). A second bar shows how the fossil energy demand, or energy input, is split between the two stages of the production process (agricultural and industrial). The third bar represents the fossil energy demand in the fossil reference system. The difference between the last two bars represents the savings that the biofuel system can provide with respect to the fossil alternative. The agricultural stage contributes the most to the fossil energy demand (66% in S2 and 75% in S1). The biodiesel represents the highest share of energy output. In fact, the energy provided by the biodiesel alone is enough to reach a FER of greater than 1. The FER values attained indicate that the proposed biofuel system returns about 2–3 times more renewable energy than the fossil energy it demands.

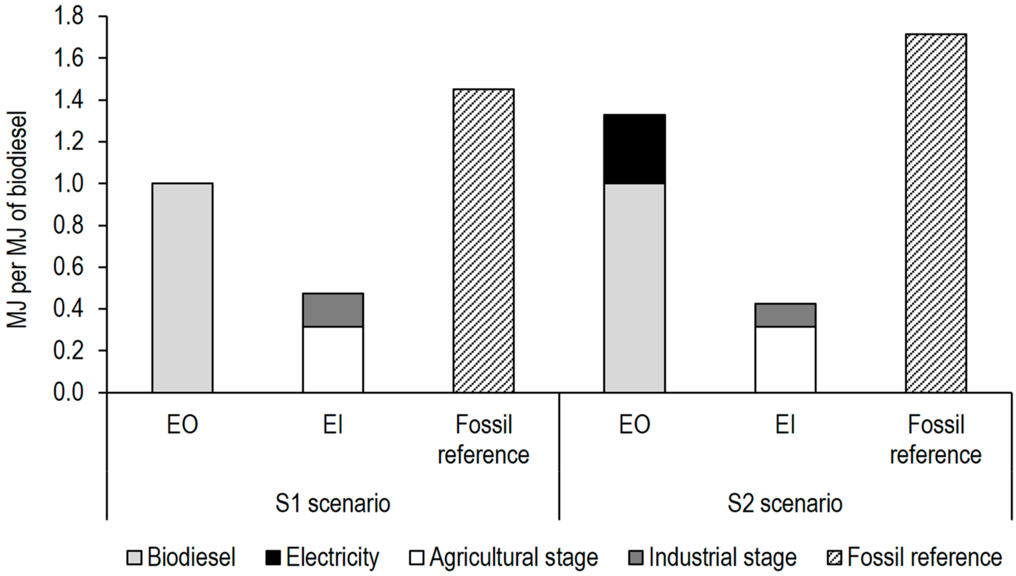

Figure 5. Energy output (EO), fossil energy input (EI), and fossil energy input demanded by the fossil reference.

Figure 6a shows the distribution of the fossil energy consumed by the agricultural stage. PFIs contribute the most to energy consumption (38%), followed by gasoline (29%) and fertilizers (21%). Other studies differ from these results in that they report that fertilizers are the major contributor to fossil energy consumption [53,57,58]. The difference arises because they considered both higher fertilizer requirements and lower or even null PFI inputs for the agricultural stage.

By estimating the water consumption of the scenarios analyzed it was found that the agricultural stage contributes about 99% of the total water consumption. Comparing this consumption to the water demand of the corresponding fossil reference system, it is around 15 times greater in the biofuel system. This trend is similar to the one reported in other works [59–61]. Tracing back the sources of water demand in the biofuel system, it was found that more than 80% of the water demand is used for irrigation, and the remainder is required for PFIs, fertilizer, and diesel production (see Figure 6b). This reflects the need to minimize the use of fertilizers and the irrigation of jatropha plants during cultivation without affecting the seed yield.

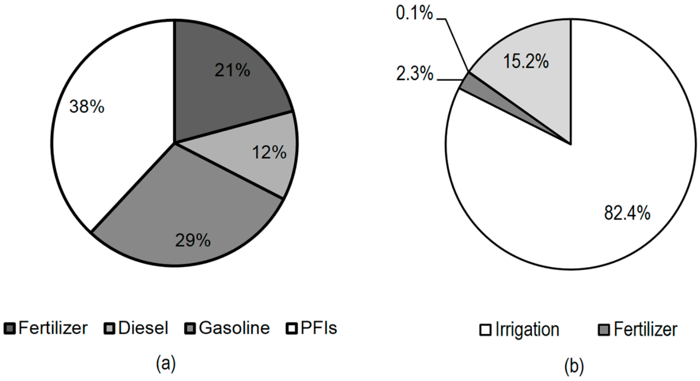

Figure 6. Distribution of (**a**) fossil energy; and (**b**) water consumed by the agricultural stage. PFIs: Pesticides, fungicides, and insecticides.

4. Conclusions

This paper describes a unique approach for evaluating the sustainability of a biofuel production project based on the cultivation of *Jatropha curcas*. In the social dimension, the perceptions of sustainability of inhabitants of villages near the plantations were gathered and reported; in the economic dimension, the effect on the annual household income was quantified; and in the environmental dimension, a life-cycle assessment of the proposed biodiesel value chain was conducted.

This evaluation was carried out in the context of jatropha plantations established in low-quality soils by private companies in Yucatan, using both endogenous and imported seeds. After four to five years, the average seed yields from the plantations were extremely low, which resulted in the companies deciding to close the projects. Local peasants were hired by three companies to establish and maintain the plantations. In the social interviews, it was reported that employees from Global Clean Energy Holdings (GCEH) obtained better salaries and benefits than they would normally have received for similar work. It is uncertain whether this holds true for employees from the other two companies. The evaluation of the economic dimension reflects the temporary positive impact on annual household income, ascending to an average of $1081.40 USD, almost twice the amount they received from public social-aid programs. The greatest disappointment for these people was getting fired after the closure of the projects despite being promised long-term contracts, and thus the economic benefits could not be sustained by this industry.

From the social interviews it was clear that the single most valued contribution from the jatropha projects was having what seemed to be a secure job that provided an increased salary and, in the case of GCEH, provided all the benefits they were entitled to by law. Also, the social evaluation captured the misalignment of sustainability definitions from the perspective of local communities (centered on job security, certain environmental services, and the ability to maintain their lifestyle) and those from the perspectives of companies and certification bodies. Life-cycle assessment (LCA) results indicate that there is a potential reduction of at least 57% in greenhouse gas (GHG) emissions compared to fossil alternatives, and if land-use change is considered, there is the potential for carbon capture (*negative* emissions). This is sufficient to certify reductions according to the Roundtable on Sustainable Biomaterials (RSB) international standard for sustainable biofuels. Savings are also observed in the Abiotic Depletion and Terrestrial Ecotoxicity impact categories. However, there are significant increases in other categories, especially in the Eutrophication potential, mainly due to the intensive use of fertilizers, pesticides, fungicides, and insecticides. These trade-offs are common to most biofuel feedstocks, having been extensively reported in the biofuel LCA literature [29], and they draw attention to the urgent need to minimize the consumption of these chemicals in the cultivation phase of energy crops. Moreover, these LCA results lack meaning for the current jatropha plantations in Yucatan, because the industry never materialized due to reasons already mentioned.

In light of these conclusions, the lessons learned about the sustainability of the jatropha projects in Yucatan and aspects that should not be overlooked are:

- *Jatropha curcas* is a wild species for which optimum cultivation conditions are still being studied worldwide, including in Mexico. Overoptimistic assumptions regarding seed yields in poor soils and the wide genetic diversity of the plant materials were the main causes for the collapse of the project. Further projects should work with elite, genetically selected and improved varieties that have been tested in the field to guarantee seed yields and low consumption of agricultural inputs.
- The RSB sustainability certification failed to reflect the problems with seed productivity. It also missed the fact that, over time, the so-called abandoned cattle ranches had come to offer valuable ecosystem services to the surrounding communities, which disappeared when the jatropha plantations were established. This leads to the conclusion that the sustainability of such interventions cannot be understood without a participatory process where local stakeholders can express what is most important to their living standards.
- Even though the GHG emission savings are considerable, using pesticides, fungicides, and insecticides on the plantations causes important impacts, especially on the eutrophication potential. These red flags should be further investigated in the local context (i.e., karstic soil, underground river flows, and *cenotes*) using an environmental impact assessment, in order to evaluate with greater accuracy the impacts that these new activities will have on the local environment. Furthermore, agronomic studies should be directed at minimizing the use of these substances without significantly decreasing seed yields.
- The economic benefits to jatropha workers were significant and positive for both household income and local economies. If the issues with seed productivity and plant management had been well thought out from the beginning of the projects, this aspect would have been of great value to local communities.
- These conclusions on the corresponding three dimensions of sustainability offer a snapshot of the projected and actual benefits of establishing a jatropha plantation on so-called marginal land in order to produce oil for biofuels. Although currently there are no active large plantations or any commercial production of jatropha oil in Mexico, several groups are still working on the genetic selection of *Jatropha curcas* accessions and on improving cultivation conditions to give fresh impetus to this activity. If successful, the lessons learned from this sustainability evaluation could be useful for improving the overall sustainability of jatropha oil production.

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Author Contributions: Julio C. Sacramento Rivero conceived and designed the research project, directed the environmental sustainability evaluation and consolidated the results in the final document; Amarella Eastmond-Spencer collaborated in the design of the research project, designed and directed the work on the social sustainability evaluation and contributed to the writing; Javier Becerril García collaborated in the design of the research project, designed and directed the work on the economic sustainability evaluation; Freddy S. Navarro Pineda performed the LCA and contributed to the writing.

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