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Assessing *Jatropha* Crop Production Alternatives in Abandoned Agricultural Arid Soils Using MCA and GIS

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Abstract: This paper discusses the assessment of various biofuel crop production alternatives on the island of Fuerteventura using *Jatropha* crops. It adopts an integrated approach by carrying out a multi-criteria assessment with the support of participatory techniques and geographical information systems. Sixteen production alternatives were analyzed for growing *Jatropha*, and the results suggest that the best alternative involves using typical torrifluvent soils irrigated with recycled urban wastewater using surface drip irrigation covering 100% evapotranspiration. It was also determined that a potential area of 2546 ha could be used for cultivation within a radius of 10 km from a wastewater treatment plant. This level of production would supply 27.56% of the biofuel needs of Fuerteventura, thereby contributing to the 2020 target of the European Commission regarding biofuels for land transport.

Keywords: *Jatropha* crops; arid soils; water and energy consumption; multi-criteria assessment; GIS; island-scale production feasibility

1. Introduction

The fuel used in the transport sector and particularly in road transport represents approximately a third of the total energy consumption in Europe [1,2]. This consumption has special relevance given the requirement imposed by the European Directive regarding the use of energy from renewable sources [3], with reference to the 2020 objectives(article 16): "a mandatory 10% minimum target to be achieved by all Member States for the share of biofuels in transport petrol and diesel consumption by 2020". This is mainly due to the fact that the transport sector is responsible for 21% of Greenhouse Gas Emissions (GGE), according to the European Commission's biofuels strategy [4].

In the last decades, biofuels have emerged as one of the most strategically sustainable fuel sources and are considered an important step in limiting greenhouse gas emissions, improving air quality, and finding new energy resources [5] with the potential to create new industry, raise farmer incomes, and restore degraded lands, all while promoting independence from oil imports and contributing to climate change mitigation [6]. With this in mind, an increasing number of developed and developing countries found biofuels key to reducing reliance on foreign oil, lowering GHG emissions, and meeting rural development goals [7].

Thus, for instance Spain's Royal Decree 459/2011 established objectives of 6.1%, 6.5%, and 7.0% for biofuels for 2011, 2012, and 2013, respectively. However, it will be extremely difficult for Spain to achieve the 20% target by 2020 imposed by the European Directive given that the current percentage of biofuel use is only 5%, unless studies like the one presented here on the feasibility and implantation of biofuels are encouraged.

Biofuels are broadly classified as primary and secondary biofuels [8]. First-generation liquid biofuels are liquid fuels generally produced from sugars, grains, or seeds and require a relatively simple process to produce the finished fuel product. First-generation fuels are being produced in significant commercial quantity in a number of countries. The viability of the first-generation biofuels production is, however, questionable because of the conflict with food supply. The rapid expansion of global biofuel production from grain, sugar, and oilseed crops has raised the cost of certain crops and foodstuffs. The dramatic rise in prices for food staples in 2008 was arguably related in part to farmers switching from food crops to biofuels [9]. A growing number of studies have been questioning the ecological and economic sustainability of biofuel energy [10–14]. In fact, taking into consideration the net energy analysis approach [15,16], biofuels might be considered as low net energy systems since the amount of energy being delivered in society through technology is lower than the total energy required to find, extract, process, and develop that energy in socially useful ways [15].

These limitations favor the search for non-edible biomass for the production of biofuels. Second-generation fuels refer to feedstocks that are dedicated to energy production, in contrast with first-generation feedstocks that are also consumed as food. *Jatropha curcas* L. (hereinafter *Jatropha*) is a hardy shrub claimed to be drought-tolerant and with the ability to reclaim land, prevent erosion, and respond better to organic manure compared to chemical fertilizers [17]. Inedible and toxic, *Jatropha* requires few inputs (e.g., irrigation or fertilizer) to survive in arid climates and infertile soil, and the seed generally contains a high proportion of oil (34% on average, by dry weight [18]. Its high oil content is comparable to palm oil and does not compete with food sources. Moreover, it can grow in semi-arid areas and thrive with fewer cultivation resources. Thus, it can avoid competing with other agricultural plantations for arable land [19].

Given these conditions, *Jatropha* has been chosen due to its adaptability to arid conditions and its effectiveness at recovering abandoned or marginal areas [20–23]. Also, the fact that it is not used for human consumption avoids generating competition in the food sector, with a resulting increase in prices, as is the case with first-generation biofuel crops such as soya or maize [24–29]. Additionally, *Jatropha*'s effects on the environment are limited [30–34]: it does not affect biodiversity as in the case of palm oil production, which requires extensive forest clearing [35]. However, some studies have presented concerns about the socioeconomic and ecological impacts of *Jatropha* crops. Thus, some authors [36] suggest that *Jatropha* cultivation favors resource-rich farmers, while possibly reinforcing the existing marginalization of small farmers from fieldwork on *Jatropha* plantations in Tamil Nadu (India); further research is thus required to improve *Jatropha* crop productivity and commercial viability. This is even more critical for feedstocks that are intended for use on marginal lands in the developing world [6].

In this context, it is clear that taking decisions regarding issues such as the implementation of biofuels in a territory involves multiple dimensions that cannot be avoided—from more technical aspects, such as agricultural procedures and financial revenues, to environmental impacts and social acceptance. This complexity requires integrated assessment approaches that also consider social, ethical, and other aspects difficult to quantify.

This article aims at evaluating the potential feasibility of *Jatropha* crop cultivation on an island scale to contribute to the sustainable development of Fuerteventura in the Canary Islands, Spain. It explores the technical challenges as well as some key economic and environmental consequences of the implementation of this crop.

Thus, the integrated assessment approach applied in this study is a holistic process in which knowledge about ecosystems, people, and public policies are linked with the aim of developing the tools and information necessary to improve decision-making processes [37].

2. Case Study

Fuerteventura (the Canary Islands) was selected by the research team to assess possible *Jatropha* crop cultivation due to the availability of large areas of abandoned farmland, the ongoing desertification process, and the semi-arid conditions of the island [38–40], together with socioeconomic difficulties. The island's abandoned farmland area is close to 95% of the total available [40]. This abandonment has been largely caused by a change in the economic model of the island towards the service and construction sectors associated with tourism, [41] with high unemployment rates in the last decade. Together with strong winds, this has led to 41.9% of the island's surface area being at a high or very high risk of suffering from wind erosion [40].

The case study consisted of a crop growth of seeds from Brazil and several combinations of irrigation techniques and soil qualities. Two experimental fields of 1200 m^2, each one with a different soil, designated TT and TH here, were chosen to cultivate *Jatropha*. Soil TT is a Typical Torrifluvents, with an average soil depth of 60–80 cm and a sandy-loam texture; soil TH is a Typical Haplocambids, with a mean depth of 90–100 cm and clay-loam texture [31].

In each of the two selected fields, eight experimental plots were created in a random block design with three replicates for each treatment. Treatments consisted of irrigation with two types of water: (i) recycled urban wastewater (RWW) and (ii) desalinated brackish groundwater (DBW), which is used in the island to irrigate conventional crops and was used in this case as a control treatment. It has been tested with two doses of irrigation (100% and 75% of the ETP) as well as both surface and buried drip irrigation. Irrigation lines were spaced 1 m apart and the pressure-compensating emitters with delivery rates of 2.3 $L\cdot h^{-1}$ were spaced 0.5 m apart. More information about the design and management can be found in [42,43]. The effects of the irrigation system, irrigation doses, type of soil, and quality of water on the *Jatropha* production were evaluated using a univariate analysis of variance. Statistical methods were implemented using SPSS (version 17.0) (IBM, Armonk, NY, USA), with a significance level of $p \leqslant 0.05$.

The fruit produced in each of the experimental plots was collected manually during the period of cultivation (2010–2013). Production was concentrated mainly during July–March and a total of 87 samplings were performed. The seeds were separated from the rest of the fruit by hand to determine their weight. Yield was expressed as the cumulative seed production per surface unit. In Figure 1 production results with different treatments during the years 2010–2013 are presented.

The statistical results indicate that production is not significantly affected by the irrigation system ($p = 0.926$), the irrigation dose ($p = 0.176$), or the type of soil ($p = 0.250$). However, with regards to the quality of irrigation water, there are significant differences ($p = 0.000$) in favor of RWW water. The maximum production was obtained with the TT RWW plot thicker texture. A better yield under application of wastewater is reported by different studies for different crops [32].

Bearing in mind that *Jatropha* productivity begins to stabilize at 4–5 years [33], these results reflect the potential of the crop under the study conditions. Seed yield values obtained in our study are close to the production range (2.0–3.0 $ton\cdot ha^{-1}\cdot year^{-1}$) suggested by Heller [34] and Tewari [44] for semi-arid areas.

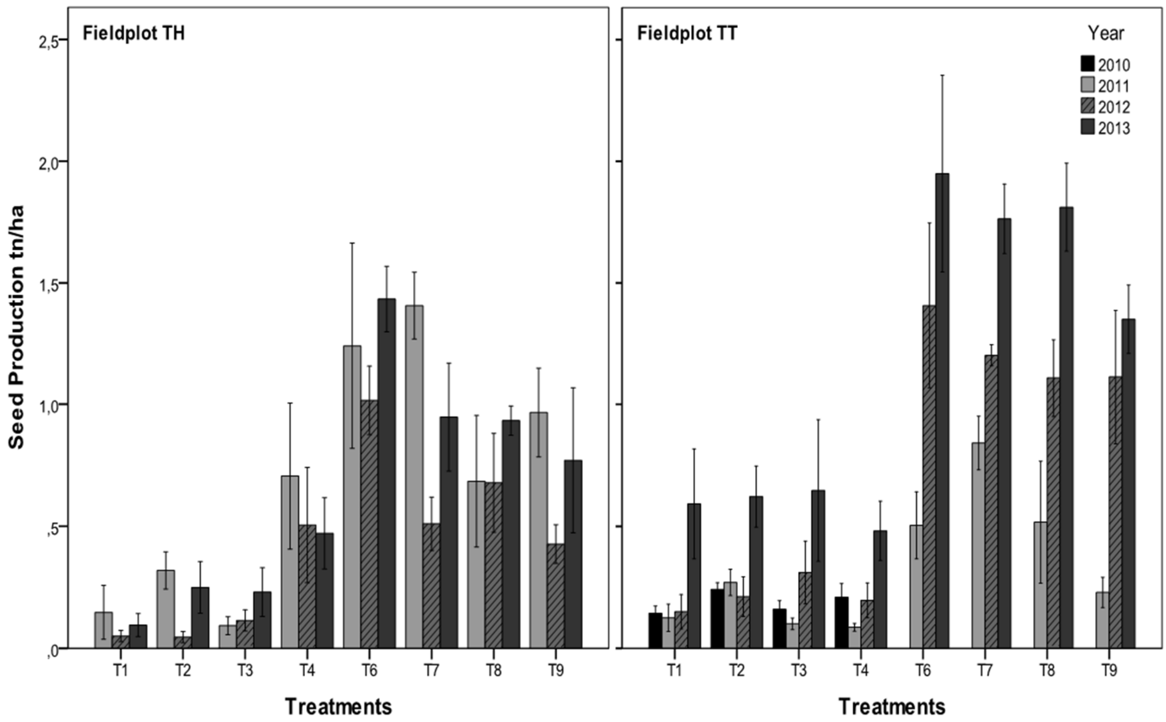

Figure 1. Annual seed yield under the different treatments and field plots; means ± standard error; *n* = 3. Treatments: T1: DBW, superficial, 100%; T2: DBW, subsurface, 100%; T3: DBW, superficial, 75%; T4: DBW, subsurface, 75%; T5: RWW, superficial, 100%; T6: RWW, subsurface 100%; T7: RWW, superficial, 75% and T8: RWW, subsurface, 75%.

3. Method: An Integrated Assessment Framework for *Jatropha* Crop Production

The integrated assessment approach applied here is mainly based on a participatory multi-criteria approach following previous research of De Marchi *et al.* [45], Corral Quintana [46], Munda [47], and Paneque *et al.* [48]. It consists of a combination of social techniques with multi-criteria ones to improve the understanding of the results and clarify the positions of the actors involved. This approach integrates formal and informal aspects that may be used later in the resolution of the problem. This focus can also be extended as a means to identify and design the social contexts where decisions are made or considered [49].

Specifically, it integrates participatory techniques and multi-criteria assessment methods, and the assessment results are represented using a geographical information system in order to extrapolate the results to an island-wide scale (see Figure 2) to facilitate a further analysis of the viability of production at such a scale.

The information obtained from the interviews and survey carried out, together with the scientific information collected, was used to define the alternatives and assessment criteria, which were incorporated into a multi-criteria model. As a result of the MCA a ranking of alternatives is determined, eliciting the positive and negative aspects of each alternative. This outcome that includes an integration of the social context—in which public policies are developed—promotes a better understanding of the social and economic interrelations in which decisions are taken.

In the present study, direct interviews with relevant individuals in public services related to water, energy, and agricultural management at the island level were carried out (see Table 1). These helped to determine if the initially proposed criteria were correct or if amendments, elimination, or additions were required. We also conducted a survey of the local population with a sample of 178 people (which corresponded to a 95% confidence level and an error margin less than 7%) from different island municipalities, age range, sex, education level, and professional sectors.

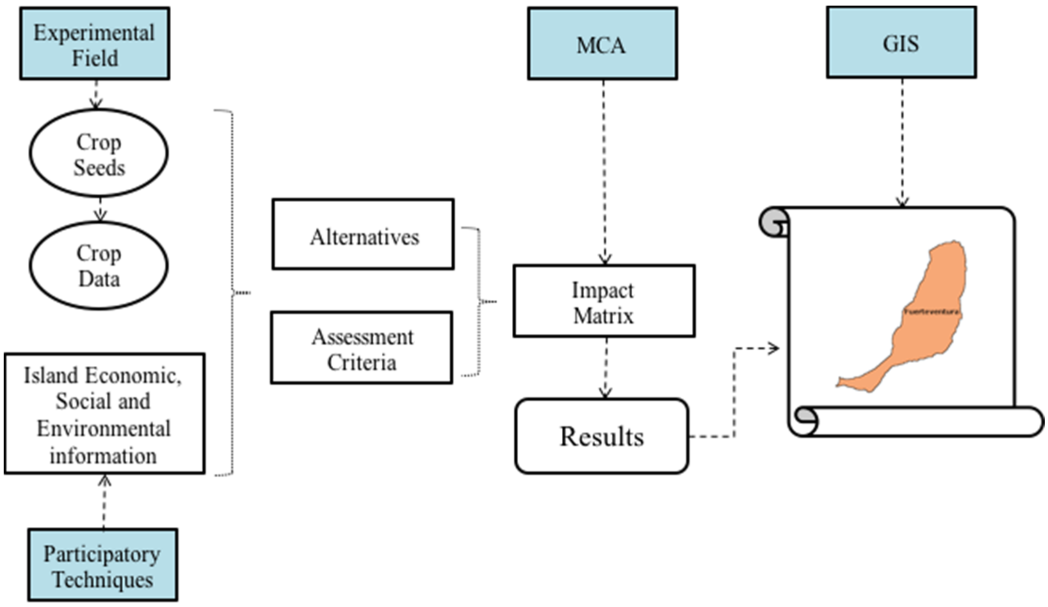

Figure 2. Representation of the assessment methodology.

Table 1. Interviewers and type of information gathered.

Institution	Field	Type of Information
Degremont—Water Treatment Plant (WTP)	Water (urban waste water)	WTP from Puerto del Rosario, treatments applied, water production, water quality, energy consumption
UNELCO—Electric Energy Generation Industry	Energy	Energy scene, issues, production, and consumption
CAAF—Fuerteventura Water Supplier Consortium	Water (desalted)	Water production, energy consumption
Antigua City-Hall	Agriculture	
Pozo Negro Experimental Farm	Agriculture (experimental *Jatropha* crop)	Experimental crop visit, technical agriculture issues, irrigation and pumping technics, harvesting procedures, *etc.*
Water Island Council	Water	Water issues, water distribution, water consumption, water desalination and depuration, natural water resources status, water uses at island scale
Cabildo de Fuerteventura (Island Government), Canarian Agriculture Agency local bureau (Agencia de Extensión Agraria de Fuerteventura)	Agriculture	1. Agriculture perspectives, issues involving agriculture and sheep breeding 2. Agriculture island conditions, farming land circumstances, biofuels and renewable energy entrepreneurship and perspectives
Puerto del Rosario City Hall Antigua City-Hall Tuineje City-Hall Betancuria City-Hall	Agriculture Agriculture Agriculture Agriculture	Agriculture local scene, water treatment availability, and abandoned farmed availability

The need to assure a balance between economic, environmental, and social aims in development processes cannot be satisfied with conventional policy-making approaches [50]. The inherent complexity of the systems concerned, the uncertainty regarding the consequences of alternative policy choices, the conflict between contradictory values, and the multiplicity of people involved in policy decisions advocate the use of other decision-making tools [46,48,49].

Multi-criteria assessment (MCA) is a methodology able to handle various dimensions of a system, integrating both qualitative and quantitative variables into the assessment with the purpose of achieving a decision-making hierarchy according to a range of assigned values. A range of MCA methods are currently available for using in a wide variety of decision-making situations. For a classification of MCA methods, revisit the classification proposed by Belton and Stewart [44].

Several literature reviews on the use of this methodology in the field of energy planning have been published *i.e.*, [51,52], which together analyzed over 90 studies. Thus, this methodology has been applied in the analysis of renewable energies and decision-making in energy planning [53]. Moreover, several studies have been conducted in the field of energy planning at a local scale in rural environments [54] and on energy planning in the transport sector in isolated island territories, although, in this case, it dealt with energy storage for use in electric vehicles [55]. Furthermore, SWOT methodologies have been combined with MCA for regional energy planning in Jaén [56].

However, there are very few references to the use of this methodology in the field of biofuels. Dinh and Guo [57] carried out an assessment of the sustainability of biodiesel production from several raw materials. In that case, the best environmental and economic performance was assessed regarding the material used and the quality of the fuel obtained. The study revealed that algae performed the best overall and *Jatropha* came second from last, above only rapeseed. However, this study did not take into account the competition effect on food in the case of rapeseed and soy or the effect on biodiversity of palm oil. Furthermore, the authors concluded that the study should be widened to include the feasibility of the crops and government support, two aspects that could affect the final findings. In this study, the Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) developed by Munda [58] has been used. It was selected because of its capacity to structure and process information generated by different sources, both qualitative derived from the implementation of social techniques, and quantitative from field experiments, statistics, or models' outcomes.

NAIADE includes the possibility of using different types of measurement, including crisp (e.g., 1, 20, 34), stochastic (e.g., probability functions), fuzzy (e.g., ambiguity of information), or linguistic information (e.g., good, not so good, bad) to evaluate the performance of alternatives. The assessment depends on the number of criteria in favor of a specific alternative and the intensity of the preference according to each criterion.

NAIADE provides a ranking of *Jatropha* production alternatives. That impact matrix assessment shows how alternatives are assessed according to an optimization criterion and a decision output is produced based on the pairwise comparison between alternatives and, therefore, the best alternative in relation to the assessment criteria [58]. Obtaining the final ranking is subsequently possible thanks to the concepts of strengths and weaknesses of one alternative in relation to another. Thus, an evaluation of scores assigned to the criteria in each *Jatropha* production alternative, namely an impact matrix, is possible with NAIADE.

Participative processes have been combined with multi-criteria on various occasions. Munda [47] defined the concept of Social Multi-criteria Evaluation (SMCE) by carrying out a review of how multi-criteria and participative methodologies in decision-making were intrinsically linked. Corral Quintana has put the integration of both methodologies into practice in various studies to assess the elaboration process of public policies [48,49]. Finally, in order to explore the viability of the production of biofuel at an island scale, the potential area for the location of JLC crops on Fuerteventura was determined applying Geographic Information Systems (GIS) based on the results obtained from the multi-criteria assessment in order to map the best alternative approximating the available potential cultivation area.

This assessment was aimed at providing the best compromise solution among environmental, technical, and economic aspects in the definition of policy actions with regard to an effective implementation of *Jatropha* as a source of biodiesel on Fuerteventura.

These three complementary assessments were driven by different objectives. In the first case, the assessment highlighted how crop production alternatives performed according to environmental and economic criteria. The second phase evaluation had two objectives, from a technical perspective, which aimed to optimize the oil extraction process from the seeds of the experimental crop. First, it aimed to find the best compromise between economic and environmental parameters. Second, the third phase assessment addressed the performance of biodiesel production from the oil extracted from the seeds, while at the same time considering the best compromise between the environment and the economy.

3.1. Alternatives of Analysis

In the first phase of the pilot project, a series of alternatives for the experimental *Jatropha* crop were proposed to identify agricultural parameters that could optimize production: soil type (TT or TH), type of drip irrigation (subsurface or surface), percentage of evapotranspiration cover (100% or 75%), and non-conventional water resources used (either recycled or desalinated).

The permutation of these parameters resulted in a total of 16 combinations that were considered as assessment alternatives (Table 2). The integrated assessment carried out was based on the results obtained over three years of cultivation of *Jatropha* on the experimental farm in Pozo Negro, Fuerteventura, as discussed in Section 2.

Table 2. Identified MCA alternatives.

Soil	Irrigation	ETP	Water
TT	Surface	100%	Recycled
			Desalinated
		75%	Recycled
			Desalinated
	Sub-Surface	100%	Recycled
			Desalinated
		75%	Recycled
			Desalinated
TH	Surface	100%	Recycled
			Desalinated
		75%	Recycled
			Desalinated
	Sub-Surface	100%	Recycled
			Desalinated
		75%	Recycled
			Desalinated

3.2. Assessment Criteria

With the aim of defining assessment criteria, a series of guided interviews were held with the most relevant stakeholders connected with water and agricultural management, energy production, and distribution on Fuerteventura, as well as experts in the field of biofuel production. Among the most relevant contributions, it is worth mentioning the following:

- "Fuerteventura is a system in a critical state from an energy perspective, and wind power is the most profitable renewable energy in the Canary Islands today" (electricity supplier UNELCO-ENDESA manager).
- "Water consumption data for the island and future strategies for piping treated water are key aspects to estimate the surface area that can be irrigated in the short and medium term" (Island Water Council of Fuerteventura manager).

- "The dependence on non-conventional water resources is obvious both for the population and agriculture" (Island Water Council of Fuerteventura expert). Moreover, it is worth highlighting the need to take advantage of recycled water, as currently, owing to the lack of water piping, a high percentage of this water is discharged directly into the sea.
- Regarding management and maintenance of desalination and wastewater treatment plants, it can be observed that even though they are two completely different types of infrastructures, in both cases the energy requirements for the production of industrial drinking water will increase costs (managers and technicians of water treatment plants).
- Finally, town hall agricultural technicians confirm the abandonment of the farming sector and the need to search for alternatives. They mention the need to take into account the goat-herding sector, which is of importance on the island, to avoid possible conflicts with the implementation of this project on an island scale.

After the consultation process and a prior data gathering process, a shortlist was prepared, classifying the resulting criteria according to three dimensions: economic, technical, and environmental criteria for each assessment phase. The selected criteria and their assessment values, based on both the literature review and the results obtained from the experiment carried out on the Pozo Negro farm, are shown in Table 1 (a detailed description is presented in a supporting document). Thus, the alternatives' assessment was carried out based on a set of economic and environmental criteria such as sapling purchase cost, initial investment, water cost, direct and indirect labor cost, fertilizer cost, energy cost, seed production, water consumption, and energy consumption.

Table 3 summarizes the list of quantitative criteria used for the assessment of alternatives, and shows how they were measured. Each dimension represents the highest hierarchical level of analysis, encompassing the criteria (a detailed description of the criteria using during the assessment may be found in the supplementary materials), the indicator used to measure them, and the desired direction of change.

Table 3. Criteria considered in this study.

Dimension	Criterion	Units	Score Type	Goal Type
ECONOMIC	Sampling purchase cost	€/ha	Numeric & Fuzzy	Minimize
	Initial investment	€/ha	Numeric	Minimize
	Water cost	€/month/ha	Numeric & Fuzzy	Minimize
	Direct labor cost	€/month	Numeric & Fuzzy	Minimize
	Indirect labor cost	€/month	Numeric & Fuzzy	Minimize
	Phytosanitary and fertilizer cost	€/unit	Numeric & Fuzzy	Minimize
	Energy Cost	€/month	Numeric	Minimize
TECHNICAL	Seeds Production (in a yearly basis)	Tn/ha	Numeric	Maximize
ENVIRONMENTAL	Water consumption	m^3/ha/month	Numeric	Minimize
	Energy Consumption	kWh/month/ha	Numeric & Fuzzy	Minimize

4. Results

Based on the alternatives and the assessment criteria, an impact matrix was built (see Table 4), using the knowledge provided by both the reviewed scientific literature and experts' opinions. The horizontal axis of the impact matrix represents the 16 alternatives, while on the vertical axis the evaluation criteria are presented. Meanwhile, each cell reflects how each alternative is influenced quantitatively by a selected criterion.

Table 4. Assessment impact matrix.

	PBDS100	PBDS75	PBDE100	PBDE75	PBRS100	PBRS75	PBRE100	PBRE75	GBDS100	GBDS75	GBDE100	GBDE75	GBRS100	GBRS75	GBRE100	GBRE75
Energy Consumption	2239.34	1650.97	2239.34	1650.97	744.36	656.80	744.36	656.80	2239.34	1650.97	2239.34	1650.97	744.36	656.80	744.36	656.80
Water Consumption	1452.00	965.58	1452.00	965.58	1452.00	965.58	1452.00	965.58	965.58	965.58	1452.00	965.58	1452.00	965.58	1452.00	965.58
Water Cost at WTP	871.20	579.35	871.20	579.35	435.60	355.79	435.60	289.67	871.20	579.35	871.20	579.35	435.60	289.67	435.60	289.67
Initial Investment	12540	12540	13410	13410	12540	12540	13410	13410	12540	12540	13410	13410	12540	12540	13410	13410
2011 Seed Production	0.125	0.1	0.27	0.086	0.504	0.517	0.841	0.183	0.147	0.093	0.319	0.706	1.241	0.684	1.407	1.064
2012 Seed Production	0.15	0.311	0.212	0.197	1.407	1.108	1.202	0.952	0.05	0.114	0.069	0.505	1.016	0.678	0.51	0.429
2013 Seed Production	0.592	0.647	0.622	0.481	1.949	1.811	1.763	1.354	0.095	0.231	0.249	0.471	1.434	0.933	0.947	0.863

Note: criteria units are shown in Table 3.

The values for the chosen criteria were calculated taking into account the data discussed in Section 3. So, it has to be noticed that some of the economic criteria were unchanged for all alternatives, such as the cost of the seedlings (2500 €· ha^{-1}), fertilizer costs (€343.75 per unit), direct labor costs (€1118 per month), and indirect labor costs (€300 per month). One of the economic criteria that did vary was the initial investment, as the alternative involving a subsurface irrigation system meant an extra cost of 13,018 €· ha^{-1} compared to the surface one of 12,008 €· ha^{-1}. As for monthly water consumption, this varied between 1472 m^3· ha^{-1} for those alternatives that covered 100% of the evapotranspiration (ETP) to 979 m^3· ha^{-1} for those that covered 75% of ETP. As for energy consumption, this depends on the quantity and origin of the water, since the greatest consumption arises from those alternatives that use desalinated water and those that cover 100% of the ETP (2231 kWh· ha^{-1} per month), whereas those with least consumption are the ones that use recycled water covering 75% of ETP (645.653 kWh· ha^{-1} per month).

However, energy costs remain the same for all the alternatives (€62.55 per month) as only the energy consumed during the water pumping process is considered, whereas the variation in energy consumption in water production is reflected in the water costs. In the latter, the cost of water varies depending on consumption, with desalinated water and alternatives that cover 100% of ETP being the highest (€883.20 per month) and the least being from recycled water covering 75% of ETP (€294.00 per month).

Finally, it should be noted that no investment costs of mechanization have been taken into account, nor the energy costs resulting from the use of such mechanization, as these criteria are strongly related to the cultivation area. In the current case study mechanization processes were not contemplated.

The results of the multi-criteria assessment—through the implementation of NAIADE—are shown in Figure 3.

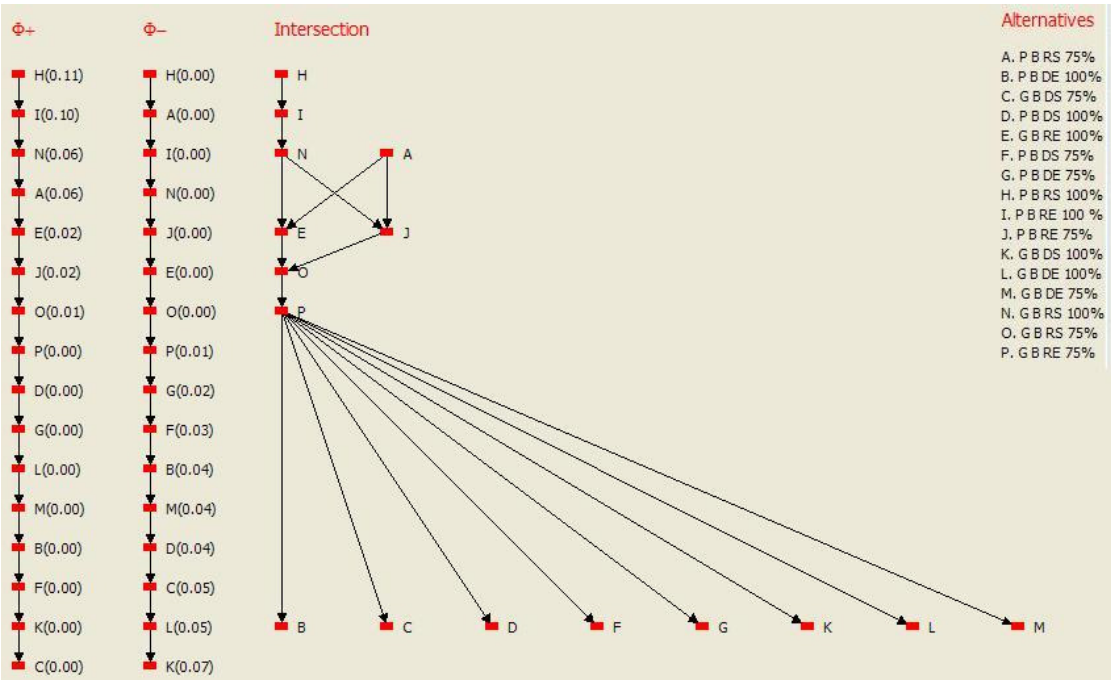

Figure 3. MCA of *Jatropha* seed production, 2011–2013.

Initially, the alternatives achieving the best compromise between the economy and the environment were those that use TT soil irrigated with RWW using surface drip irrigation covering 100% ETP (represented in Figure 3 by letter H). Next in the ranking were alternatives I, A, and N, corresponding to TT soil for the first two and to TH soil for the third, using surface irrigation and covering either 75% or 100%; in these three cases the water used for irrigation was also RWW; assuming that crop productivity remains similar, the 75% entails less water consumption and is therefore more sustainable (see Figure 1).

These results encouraged a further analysis, assessing the viability of JLC cultivation to an island scale to explore the potential surface area on which *Jatropha* could be grown on the island. In Fuerteventura, according to the available information, abandoned farming lands form 90% of the existing farming territories [40]. More specifically, the available abandoned lands with TT and TH soils—although TT soil provided the best conditions, as has been identified above, compared to TH soil, it should not be ruled out since its growing results are still better than the average obtained in other experiences—correspond to an amount of *circa* 9000 ha of abandoned farmland potentially available to plant *Jatropha* (see Figure 4).

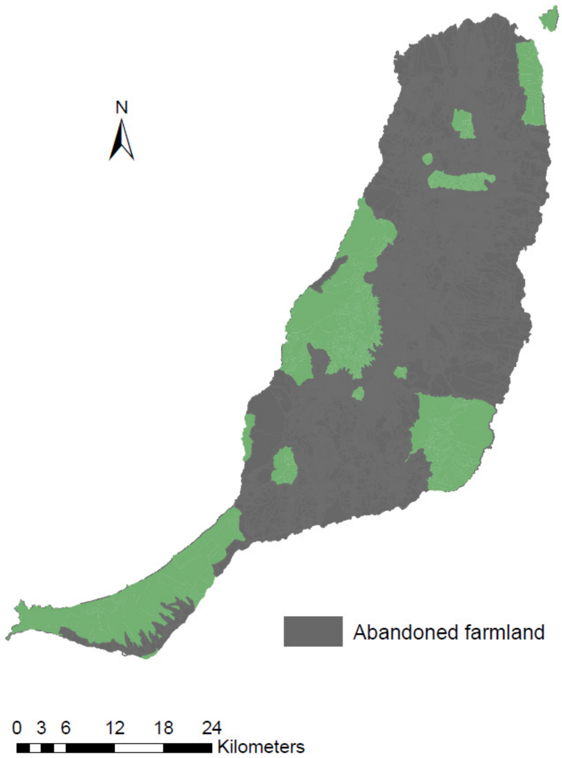

Figure 4. Abandoned farmland in Fuerteventura.

However, in order to consider *Jatropha* cultivation on the island of Fuerteventura a technically, socioeconomically, and environmentally feasible option, some considerations regarding water and energy sources have to be taken into account. According to the recent eco-management plan of the regional government for the production and distribution of water in the Canary Islands, 100% of Fuerteventura's potable water comes from desalination plants [59], which is mainly used for domestic consumption as its cost is too high for crop irrigation, despite being partially subsidized by the island government. Even though newly adopted technologies have helped reduce costs, this industrially produced water still consumes a substantial amount of energy (5 $kWh \cdot m^3$). In addition, European regulations require that wastewater must be treated before being discharged into the sea [60]. This RWW can be used for agricultural irrigation; in fact, *Jatropha* cultivation in Fuerteventura should be mainly based on treated water, due to the good growing results and the availability of this type of water.

The Wastewater Treatment Plant (WWTP) in Puerto del Rosario has a treatment capacity of 3200 m^3 per day. Currently, this RWW water is used as "Service Water" (irrigation of urban green areas, street cleaning, fire protection systems, industrial vehicle washing) by the local government. However, approximately 50% of this RWW is discharged into the sea. There are plans for a series of pipelines to distribute this water from the WWTP of Puerto del Rosario to the northeast part of the island, specifically in the areas known as Barranco de la Herradura—Guisguey, La Calderetilla, La Asomada, and Tetir [61]. According to estimations, it would provide an irrigated area suitable for cultivation of 72 ha [62]. If such a 72-ha area were devoted to the cultivation of *Jatropha*, an estimated biodiesel production of 35.32 tons per ha would be achieved based on current crop estimations.

Other island municipalities have similar prospects for future infrastructure development but are in a more preliminary stage. Again, using GIS with a buffer of 5 km and 10 km around a WWTP in areas of abandoned farmland where there are TH and TT soils in order to extrapolate the maximum potential area for cultivation, we find that there would be around 2500 ha within a 10-km radius and 1200 within for a radius of 5 km of a WWTP, respectively (see Figure 5).

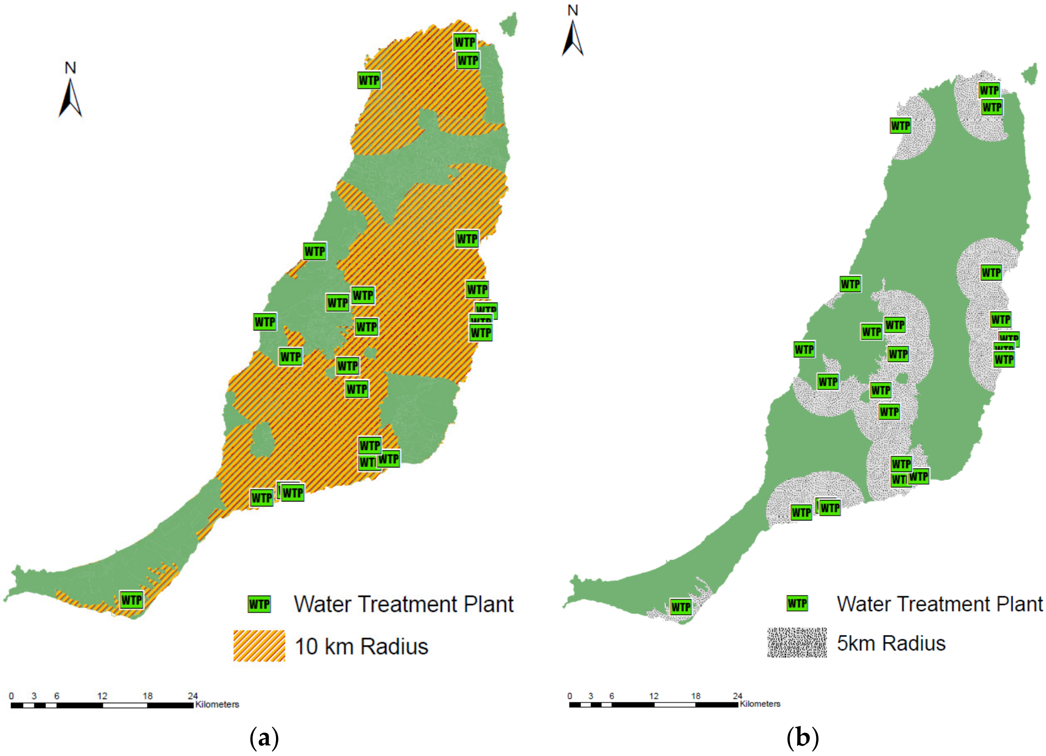

Figure 5. Potential farmland for *Jatropha* within a 10-km (**a**) or 5-km (**b**) radius of a WTP.

5. Conclusions

In this article, the main results of four years of analysis on the feasibility of growing *Jatropha* in Fuerteventura have been discussed. The integration of MCA and GIS has allowed us to determine the most feasible alternatives, but also to estimate the potential cultivation area on an island scale, based on data from an experimental crop currently being grown.

Several aspects should be highlighted in the integrated assessment. Not only technical data but also information from interviews with a range of experts has been gathered, providing important quantitative and qualitative data and considerations, which have been integrated with the technical data, as well as economic and environmental data, to carry out an assessment using MCA.

As pointed out, the levels of production obtained in the study fall within the ranges reported in the literature and demonstrate that *Jatropha* cultivation is feasible in marginal soils and under arid conditions with RWW irrigation [43]; however, in order to be sustainable, the crop production requires periodic cleaning operations to limit the gradual salinization of the soil.

The current abandonment of agricultural practices together with strong winds have led to 41.9% of the island's surface area being at a high or very high risk of suffering from wind erosion [40]. The process of abandonment of farmland has been caused by external and internal factors. In fact, the progressive abandonment of any agricultural practice—due to the impossibility of competing with more short-term profitable economic activities such as construction and tourism—have transformed Fuerteventura, in the last decades, into a territory affected by an aridity index (Pa/ETo) of 100%.

The results of the multi-criteria assessment on the alternatives and defined criteria show that the optimum solution is cultivation in TT soil with seeds from Brazil and using RWW to provide surface irrigation covering 100% of ETP. When ETP cover is only 75%, there is hardly any difference except that this might result in a slight economic saving in the final product without significantly affecting production.

On the other hand, using a Geographic Information System, the potential cultivation area for *Jatropha* consists of 2545.747 ha within a radius of 10 km of a WWTP, 1272.874 ha within 5 km, and 509.149 ha within a radius of 2 km of a WWTP. According to the European Directive on the promotion of the use of energy from renewable sources [63], there is a target of 10% of biodiesel to be used for land transport by 2020. Diesel consumption for land transport on the island of Fuerteventura in 2012 was 40,960 tons. Based on this figure, an estimate of vehicle growth was made to determine the likely biodiesel consumption by the year 2020, obtaining a figure of 45,318.30 tons of diesel.

Thus, *Jatropha* crop production might be considered a feasible alternative for the agricultural sector in Fuerteventura mainly because: (a) it is based on recycled urban wastewater (currently of no use in the island); (b) it presents acceptable crop growth rates in marginal abandoned lands, avoiding potential competition with other crops for available farmland; and (c) there is the possibility of using this crop production to cover, at least partially, the island's biofuels requirement enforced by current EU legislation, so there is a potential market available.

If the *Jatropha*-produced biodiesel is used for the island's own consumption to contribute to reducing fuel imports, the sustainability and energy self-sufficiency of the island would improve substantially. According to estimates of the area of farmland available for *Jatropha* cultivation, the biodiesel produced might vary from 5% to 30% of the island's total requirement within a 2–10 km radius.

Jatropha's extensive system of roots would have an additional positive effect on stabilizing the soil and preventing erosion [38,39,43]. At this stage, it might be concluded that the use of RWW is producing promising results in terms of the amount of *Jatropha* seed produced.

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