Energy analysis of *Jatropha curcas* under irrigation and rainfed at the Southeast Brazilian humid subtropical

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Abstract: Jatropha (*Jatropha curcas* L.) is an oil seed species, adaptive to different climate and soil conditions. It is known due to its high-oil-content seed, being an option for biodiesel production and presenting competitive yields under irrigated condition. This study was developed in an experimental area located in a humid subtropical region of Brazil and the objective was to evaluate *Jatropha*'s energy balance under irrigation and rainfed condition during the first four years of its cycle. The input and output energy values were determined by multiplying the material amount by the related energy conversion factors. These values were used to determine the energy indices: energy balance (*EB*), and energy return on investment (*EROI*) for both conditions. Fertilizers had the highest contribution on energy input (42.58 GJ ha^{-1}, 37.7% in irrigated area and 45.9% in rainfed area) followed by fuel consumption (32.96 GJ ha^{-1}, 29.8% in irrigated area and 35.5% in rainfed area). Total energy input for the second, third and fourth years in the irrigated area was 114.58 GJ ha^{-1} (which 19.3% was due to the irrigation) and 92.51 GJ ha^{-1} in rainfed area. The output energy flows were 73.78 and 47.88 GJ ha^{-1} for irrigated and rainfed areas, respectively. In this study, negative value for *EB* and unviable *EROI* (<1) were obtained. However, *EROI* showed evolution when evaluated year-by-year, reaching values above 1 in the 4^{th} year for both systems, as expected from perennial crops. Considering just the period evaluated, this crop was not sustainable for energy production, but this is a long lifespan crop and for the following years it is expected yield levels like the last one and values positive of energy balance.

Keywords: biofuel, energy efficiency, sustainability, energy flow

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1 Introduction

For any human activity, energy is necessary and its total requirement has been intensified with constant population growth. Additionally, the dependence on petroleum as an energy source and its concentrated geographic distribution have motivated worldwide the search for alternative sources (Palacio et al., 2012; Ferrari et al., 2005). In this scenario, many energy crops have been studied, among them those high oil content, such as soybean (Ferrari et al., 2005; Pimentel and Patzek, 2005), castor bean (Sreenivas et al., 2011), palm oil (Al-Widyan and Al-Shyoukh, 2002), cotton (Nabi et al., 2009) and *Jatropha* (Achten et al., 2008; Lu et al., 2009).

Jatropha is a 5-7 meter-high tree that belongs to the *Euphorbiaceae* family. It presents some desirable characteristics such as high adaptability to different environments, long lifespan and high oil content seeds, from 32% up to 50% (Arruda et al., 2004; Saturnino et al., 2005).

Although biochemical process to transform *Jatropha* oil into biodiesel is well established, information about its

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sustainable aspects is still unknown. Even with the increase at the number of studies with this crop, there is a little information about the energy sustainability, especially those considering long-term production (Frigo et al., 2008a). Therefore, studies with energy balance in multiples growing seasons, considering especially from its establishment to the adult stages, are necessary to determine *Jatropha* crop productions and energy sustainability parameters (Frigo et al., 2008b).

Another component that is very important is the irrigation use either for the energy balance or for its effect in yield. Frigo et al. (2008a) analyzed the *Jatropha* energy balance only for first year using drip irrigation system and Frigo et al. (2011) found energy input values for *Jatropha* and corn intercropping system under irrigation and rainfed conditions. Diotto et al. (2014a) evaluated the embodied energy related to *Jatropha* production on different water management, such as drip, center pivot irrigation and rainfed. They showed that irrigation had high influence on the total energy input. In addition, some authors mentioned that irrigation must be performed as efficiently as possible to improve the energy efficiency (Frigo et al., 2008b; Pelizzi, 1992).

Energy sustainability can be determined using the energy flow methodology, which is calculated by the ratio between the total energy input and total output (Romanelli and Milan, 2005). Comprehending the energy flow allows to determine parameters to increase the energy efficiency in a specific system (Stanhill, 1984). In this context, energy balance should be used for crop selection for bioenergy purposes, since it includes the relationship between the energy input and the energy produced during the biofuel production chain (Feroldi et al., 2014).

Energy flow considers the energy input and output of all components used and can be divided by direct and indirect energy. Direct energy is the electricity and direct fuel consumption and the indirect energy is the embodied energy from fertilizers, seeds, machinery and other material used in the process. The embodied energy is usually calculated using the energy index pre-established that correlate the energy amount within a material by weighting unit (Pimentel, 1980).

Other indices can be used to express the energy sustainability in a system, such as the energy return on investment (*EROI*), which consider the energy available by the required energy in a process and it can be described as “energy profitability” (Romanelli et al., 2012). When this relationship is higher than one, the energy output is bigger than the energy input, showing energy feasibility in the process (Ulgiati, 2001; Cavalett and Ortega, 2010). The overall objective of this study was to determine the energy balance for *Jatropha* under center pivot irrigation and rainfed, from crop implantation to the fourth year of production.

2 Material and methods

2.1 Experimental area

This study was developed in an experimental area (22º41′57″ South, 47º38′38″ West and 530 m a.s.l.). According to Köppen climate classification, the climate of the region where the experimental area located is classified as a humid subtropical (Cfa) with precipitation concentrated at the summer season and dry winter. Soil was classified as loamy (57.1% clay, 20.9% silt and 22.0% sand), with 1.4% organic matter content, and density 1.4 g cm^{-3}. *Jatropha* seedlings were transferred to the experimental field in December 2011 in 3.0 m×4.0 m spacing. Treatments were divided into irrigated by center pivot and rainfed conditions, with a total area of 1.0 and 0.5 ha, respectively. Irrigation requirement was determined by two weighing lysimeters installed in each treatment, previously calibrated and used to perform *Jatropha* actual crop evapotranspiration.

2.2 Material and energy flow

Energy analysis in both water management was realized using the material flow as indicated by Romanelli and Milan (2010), which was necessary to compose the systemic diagram (Odum, 1996) (Figure 1). It was considered all data from the implantation stage to the fourth growing season of *Jatropha* (from mid-2011 to mid-2015) to perform the material flow in both conditions.

Energy flows were obtained from material flows, using the specific energy content of each input (Pimentel, 1980). Inputs considered were fertilizers, pesticides, direct fuel used in mechanized operations; irrigation systems; machinery and equipment depreciation and electricity (irrigation).

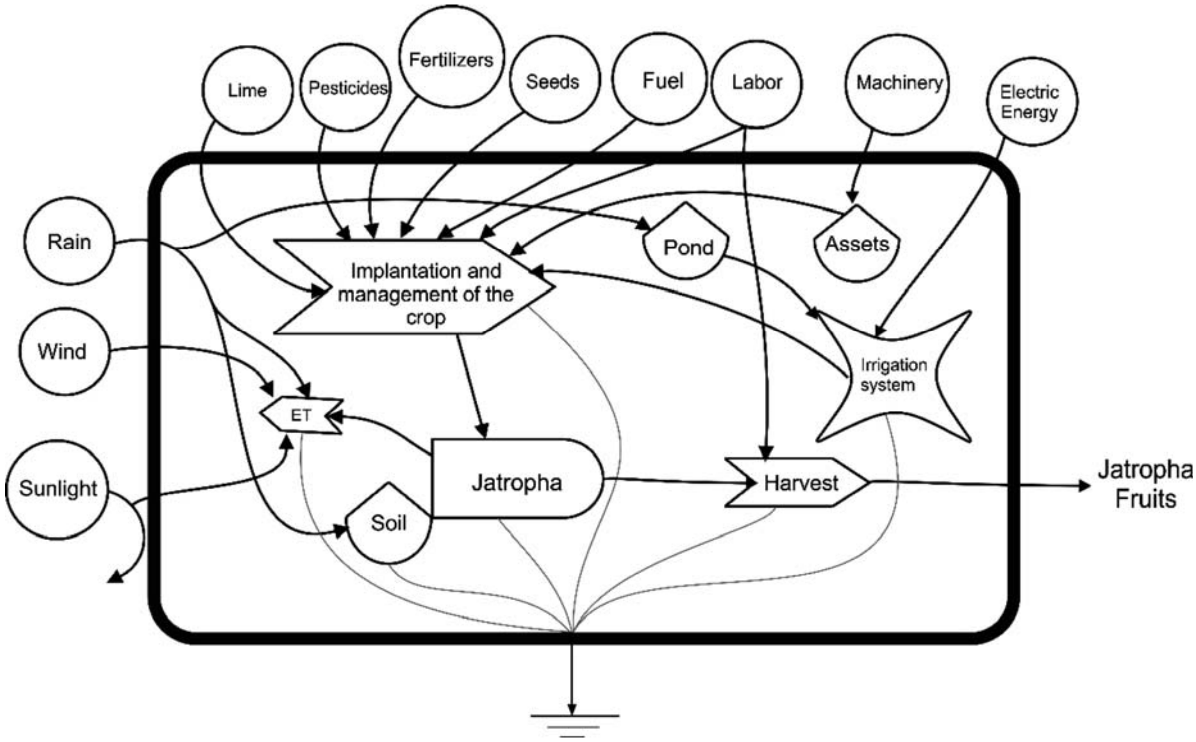

Figure 1 Systemic diagram of *Jatropha* production

Machinery and equipment mass depreciation were determined by Equation (1) (Romanelli and Milan, 2010) using the effective field capacity (area worked per time of each operation) and considering a tractor with 3,940 kg total weight, 55 kW of gross engine power and 12,000 h of equipment lifespan. The lifespan for the sprayer and the manual grass mower used in the weed control were considered 2,000 h and 1,500 h, respectively.

$$MD = M*EE_m/(EL*EFC) \quad (1)$$

where, MD (MJ ha^{-1}) is machinery depreciation; M (kg) is machinery mass; EE_m is the embodied energy of machinery (MJ kg^{-1}) – Table 1; EL (h) is machinery effective life (or lifespan), and EFC is effective field capacity (ha h^{-1}).

The fuel consumption for each field operation was calculated by Equations (2) and (3) (Romanelli and Milan, 2010).

$$C_{hour} = GP_{eng}*SC \quad (2)$$

$$E_c = \frac{C_{hour} * fcb * H_m}{A} \quad (3)$$

where, C_{hour} (L h^{-1}) is hourly consumption; GP_{eng} (kW) is engine gross power and SC is a consumption factor (0.163 L kW^{-1} h^{-1} for Molin and Milan (2002)); E_c is energy from fuel consumption (MJ ha^{-1}); fcb is fuel energy index (MJ L^{-1}) – Table 1; H_m is hours machines work in the year (h year^{-1}), and A is cultivated area (ha).

With regard to chemicals, the energy flow was calculated by Equations (4) and (5) (Romanelli and Milan, 2010). The amount of fertilizer used was based on the recommendation propose by Jongh (2010). Urea, simple phosphate, and potassium chloride were as the nitrogen, phosphorus, and potassium sources, respectively.

$$E_{li} = (E_{cl}*i_a*V_p*Q)/V_a \quad (4)$$

where, E_{li} (MJ ha^{-1}) is the enclosed energy on applied pesticides; Ecl (MJ L^{-1}) is the enclosed energy of a liquid input – Table 1; i_a (decimal) is the concentration of active ingredient in the commercial product; V_p (L) is the used volume of the commercial product; V_a (L) is the volume to be applied and Q (L ha^{-1}) is the application rate.

$$\underline{E_{si}} = Q_t*E_{cs} \quad (5)$$

where, E_{si} is the enclosed energy in solid inputs (MJ ha^{-1}); Q_t (kg ha^{-1}) is the quantity of input applied per hectare and Ecs (MJ kg^{-1}) is the energy content of a solid input – Table 1.

Different activities were performed during the years for weeds, insects, and diseases control. Weed control was performed by using herbicide glyphosate (SL) with a sprayed dose of 5 L ha^{-1}. For the control of pests and diseases it was used thiamethoxam (SC), abamectina (EC), thiophanate methyl (SC) and a mixture of azoxystrobin and cyproconazole (SC) in the doses of 160 mL ha^{-1}, 800 mL ha^{-1}, 800 g ha^{-1} and 600 mL ha^{-1}, respectively.

Energy related to human labor was determined using the Equation (6).

$$E_{labor} = (H_y * F_{labor})/A \quad (6)$$

where, E_{labor} (MJ ha^{-1}) is the embodied energy from human labor; H_y (h) is total hours from human labor; F_{labor} (MJ h^{-1}) is the hourly energy requirement for human labor (Table 1) and A (ha) is the area.

Table 1 Energy index for inputs applied for *Jatropha* crop system

Input	Embodied energy index (MJ unit^{-1})	Unit	Reference
Machinery	68.9	kg	Fluck and Baird (1982)
Fuel	38.55	L	Ulbanere and Ferreira (1988)
Urea	78.04	L	Ferraro Júnior (1999)
Simple phosphate	9.79	kg	Ferraro Júnior (1999)
KCl	7.19	kg	Ferraro Júnior (1999)
Lime	1.7	kg	Ferraro Júnior (1999)
Micronutrients	1.67	kg	Ferraro Júnior (1999)
Insecticides	184.7	L	Pimentel (1980)
Fungicides	97.13	L	Pimentel (1980)
Herbicide	454.2	L	Fluck and Baird (1982)
Labor	2.2	h	Serra et al. (1984)

Direct energy used to pump water for the irrigation system was calculated by Equation (7) (Romanelli and Milan, 2005).

$$E_{irr} = (C_{ee} * GP * H_d * N_d)/A \quad (7)$$

where, E_{irr} (MJ ha^{-1} year^{-1}) is the direct energy used by irrigation system; C_{ee} (MJ kW^{-1} h^{-1}) is the energy index of electric energy; GP (kW) is the electric engine gross power; H_d (h day^{-1}) is the hour used per day with the system on; N_d is the number of days with irrigation per year (day year^{-1}) and A is the irrigated area (ha).

The electric energy gross power requirement was estimated for 10 ha as 14.4 kW and the electric energy index was considered 11.8 MJ kW^{-1} h^{-1} (Pimentel, 1980). The indirect embodied energy from irrigation system was calculated by Equation (8) (Diotto et al., 2014b).

$$EE_{pivot} = \left(\frac{251.36 * A^{-0.501}}{UL}\right) + \left[\frac{(0.75 * Q + 0.0076) * L + 0.044 * P}{A}\right] \quad (8)$$

where, EE_{pivot} (GJ ha^{-1} year^{-1}) is the indirect embodied energy from center pivot; UL (year) is the irrigation system lifespan; Q (m³ s^{-1}) is the irrigation system total flow; L (m) is the main line length and P (kW) is the pump gross power.

To determine the indirect embodied energy from the center pivot system, it was considered the center pivot characteristic used at the experimental area with 20 years of lifespan. The irrigated area was 10 ha with 260 m long main line and the system flow was 0.01 m^3 s^{-1}.

Energy output was determined from the yield in each condition. It was considered the yield from second until fourth growing season. The first year was not considered due the absence of yield in this season. Harvest was performed manually between January and June of each growing season. To transform total yield to output energy, the energy index of 21.2 MJ kg^{-1} (Openshaw, 2000) was used for *Jatropha* fruit.

2.3 Energy efficiency indicators

To evaluate the energy balance and energy return on investment, the Equation (9) (Romanelli et al., 2012) and Equation (10) were used. Annually and total of four years were analyzed to quantify the total energy balance until the end of fourth year and the evolution among the years.

$$EB = E_o - \sum E_i \quad (9)$$

where, EB (GJ ha^{-1}) is the energy balance; E_o (GJ ha^{-1}) is the total energy output and E_i (GJ ha^{-1}) is the total energy input.

$$EROI = E_o / \sum E_i \quad (10)$$

where, $EROI$ – Energy Return On Investment (dimensionless).

2.4 Sensitivity analysis

Sensitivity analysis was performed to investigate the impacts of inputs (implantation, fuel, electricity, labor, machinery, pesticides, fertilizers and irrigation system) and output (*Jatropha* yield) on *EROI*. Thus, these parameters had their initial values increased with 10% and the differences were reflected in the *EROI* analysis (Diotto and Irmak, 2016).

3 Results and discussion

The total embodied energy for the field implantation was 19.6 GJ ha^{-1}. Implantation (first year) has peculiar characteristics compared to the following years, because there was all the area preparation such as weed control, soil fertilization and correction, soil tillage and planting. From this total 26.90% were related to direct energy used as fuel, 2.30% related to the labor, 3.60% related to machinery, and 67.20% related to agronomic input such as fertilizers, other chemicals and seedlings. *Jatropha* is a perennial plant and it can be cultivated for 20-year lifespan. However, the total embodied energy value at the first year was divided by the total following years or depreciated for the following years, so the annual embodied energy by the implantation was considered 0.98 GJ ha^{-1} $year^{-1}$.

All inputs were grouped and quantified per amount used per area in each growing season separately (Table 2). During the three growing seasons analyzed, the material flow by machinery used, fertilizer, pesticides, fuel, and labor were different, expressing the variation among the years on each activity. Comparing irrigated and rainfed systems, the annual material inputs were almost the same, except for the electricity used in irrigation. This was expected since both areas received the same crop management related to fertilization, weed, insect, and disease control.

Electricity considered on this study was just that related to irrigation. In the fourth year, the irrigation system was not allowed to be used due the water scarcity that occurred in 2014. The annual precipitation in the studied site was almost 50% below the historical average, so water supply was limited for irrigation and urban areas.

Table 2 Material flow from all input material used in the production system

Type	Input	Characteristic	Material flow (unity ha^{-1} $year^{-1}$)					
			Irrigated			Rainfed		
			Growing season					
			2nd	3rd	4th	2nd	3rd	4th
Direct	Fuel (L)	Diesel	161.4	381.4	117.4	161.4	381.4	117.4
		Gas	72.0	86.4	57.6	72.0	86.4	57.6
	Electric En. (kWh)		152.9	588.0	**	-	-	-
	Labor (h)		144.0	268.0	178.0	144.0	268.0	178.0
Indirect	Machinery (kg)	Sprayer	13.6	35.2	11.3	13.6	35.2	11.3
		Mower	6.6	11.6	3.3	6.6	11.6	3.3
		Manual mower	0.5	0.3	0.2	0.5	0.3	0.2
	Pesticides		1.2	4.8	1.2	1.2	4.8	1.2
			1.1	3.2	1.1	1.1	3.2	1.1
			30.0	50.0	20.0	30.0	50.0	20.0
			0.3	0.8	0.3	0.3	0.8	0.3
			1.1	4.0	1.1	1.1	4.0	1.1
	Fertilizers (kg)	Micronutrients	24.0	24.0	24.0	24.0	24.0	24.0
		Urea	75.5	153.0	229.0	75.5	153.0	229.0
		SS	55.0	105.0	160.0	55.0	105.0	160.0
		KCl	83.3	168.0	252.0	83.3	168.0	252.0

Note: SS – Simple Phosphate, ** Irrigation was not allowed to be done at this year.

The amount of fuel used in this study revealed the intense number of activities realized every year such as weed control by mowing or spraying herbicide, application of pesticides and fertilizer, and transportation of the seeds harvested.

The highest machinery mass incorporation (47.1 kg ha^{-1}) was obtained in the third year. It was caused by the higher number of operations during these years, represented mainly by the several weed controls as well as diseases and insects control.

The total amount of fertilizers applied increased from 237.8 to 665 kg ha^{-1} from second to fourth year following the plant nutrient requirement.

Each material has its specific energy index or energy content, therefore to compare just the amount of material used could not represent the amount of energy related with it. On Table 3 we had the energy input before transform each material in energy by their specific energy index (Table 1).

Total energy input during the four growing seasons was 134.15 and 112.08 GJ ha^{-1} for the irrigated and rainfed area, respectively. Even with the impossibility to run the irrigation system at the fourth growing season, it was possible to verify the impact of the irrigation used at the total energy input. Other authors have shown the same level of the impact in cantaloupe (Alexandrou et al., 2009), sugarcane (Karimi et al., 2008), corn (Diotto and Irmak, 2016) and *Jatropha* (Frigo et al., 2008a).

Table 3 Energy flow from all components used for *Jatropha* production

Input	Energy input (MJ ha^{-1})					
	Irrigated			Rainfed		
	Growing season					
	2nd	3rd	4th	2nd	3rd	4th
Implantation*	978.5	978.5	978.5	978.5	978.5	978.5
Fuel	8725.0	17708.7	6527.5	8725.0	17708.7	6527.5
Electric energy	1804.0	6938.4	**	-	-	-
Labor	316.8	589.6	391.6	316.8	589.6	391.6
Machinery	1425.6	3241.9	1022.3	1425.6	3241.9	1022.3
Pesticides	2027.7	3628.9	1391.9	2027.7	3628.9	1391.9
Fertilizers	7073.6	14216.1	21289.6	7073.6	14216.1	21289.6
Irrigation system	4444.2	4444.2	4444.2	-	-	-
Total	26795.4	51746.3	36045.6	20547.2	40363.7	31601.4

Note: * Implantation value is the total energy input at the first year divided by 20 years of lifespan; **Irrigation was not allowed to be done at this year.

The total energy input from fertilizer was 42.57 GJ ha^{-1} for both irrigated and rainfed areas, representing 37 and 46% of total, respectively. The high value of energy input from fertilizer is not just related to the quantity used but also to the energy index used (Table 1); especially for the nitrogen, that was 78 MJ kg^{-1}. The same level of energy input from fertilizer was also found by Jasper et al. (2010) that the values were around 44% of total energy input for crambe plant.

Both irrigated and rainfed areas presented higher relative energy input by the fertilizer and fuel consumption for all years (Figure 2). Chechetto et al. (2010), Jordan et al. (2012a), and Jordan et al. (2012b), also observed these results. The total energy input from fuel was 32.96 GJ ha^{-1}, representing 28.7% and 35.6% for irrigated and rainfed. According to Jordan et al. (2012b), high levels of fuel utilization showed a strong dependence from fossil fuel, and this fact was a problem which also presented by others crops used for biofuel production, such as sugar cane and soybean.

Even with several operations for weed, disease, and pest control, the energy input related with these pesticides was relatively low. The energy index of this materials is sometimes high (Table 1) but the quantity used was relatively low when compared with others such as fuel or fertilizers (Table 2).

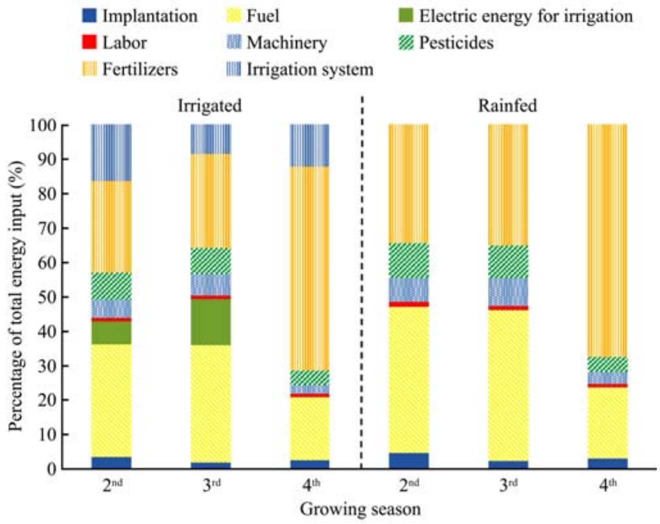

Figure 2 Distribution of total energy input for the several years of growing season with and without irrigation

The indirect energy associated with the irrigation system and the direct electric energy used to lift and pressurize the water explain higher energy demand at the irrigated area. From the total energy input in the irrigated area, 22.05 GJ ha^{-1} (19.3%) came from the irrigation system. The direct electric energy used by irrigation system represented 7.6% and indirect energy 11.63% of the total energy input. Frigo et al. (2011) found 9.0 % of total input was from indirect energy by the sprinkler irrigation system. The total energy input by irrigation system varies with the irrigation depth, especially the direct energy used as showing in sunflower (Jordan et al., 2012a), castor bean (Jordan et al., 2012b) and corn (Diotto and Irmak, 2016).

Pesticides portion was 6.1% and 7.6% of total energy input for irrigated and rainfed areas, respectively. These values were close to those found by Chechetto et al. (2010) in an experiment with castor bean. Frigo et al. (2011) found 2.95% and 3.33% for pesticides (herbicide and insecticide) used for *Jatropha* under irrigated and rainfed conditions, respectively.

The energy input from machinery was 5.0% for irrigated area and 6.1% for rainfed area. Chechetto et al. (2010) found values were even lower for castor bean, in which machinery energy input was only 0.5%. Jasper et al. (2010), analyzing the energy balance for crambe (*Crambe abyssinica* Hochst) under no tillage, found that machinery represented only 1% of total energy consumption. Variations in the machinery used are expected among different crops and even among different crop production system. The mechanization activities can be more or less intense for some crops, and other factor that can contribute in the differences is the machinery lifespan considered.

Labor required was mainly for manual harvesting and the labor associated with the machinery operation. Even we had relatively high number of hours of labor usage (Table 2), the energy input by labor had the lowest contribution to the total embodied energy in both areas, with 1.1% for irrigated area and 1.4% for rainfed. These values were similar to those presented by Chechetto et al. (2010) and Assenheimer and Campos (2009), with values below 1.0%.

Evaluating the total energy input among the growing seasons, the third one had the highest embodied energy in both systems (irrigated and rainfed). In this year, it was necessary higher numbers of crop management such as weed, disease and insect controls, requiring high amount of pesticides as well as mechanization. It was also observed that the indirect energy presented the highest input energy portion for all years analyzed. It is important to emphasize that we are not allowed to irrigate during the fourth growing season.

Differences between the embodied energy for irrigated and rainfed systems were 6.24, 11.38, and 4.44 GJ ha^{-1} for the second, third, and fourth growing seasons, respectively. These differences are explained by the irrigation system, which is responsible for indirect energy embodiment by the center pivot itself and direct energy use to lift and pressurize the water. During the fourth year, since it was not possible to perform irrigation, the difference was just the indirect energy related to the equipment depreciation.

It is possible to observe that the energy embodiment from the indirect inputs presented higher contribution in comparison to the direct inputs, representing at least 51.2% at the third year with irrigation and around 80% at the fourth year (no irrigation) (Figure 3). Therefore, the precise and reliable quantification of the components related to the indirect energy input should also to be considered when intent to do systems energy evaluation.

According to many authors, the agricultural phase or the on-farm activities present the highest energy consumption (Cavalett and Ortega, 2010; Macedo et al., 2008; Gomes et al., 2013), indicating the importance of improve the crop production system by improving the crop management such as fertilizer and water use efficiency.

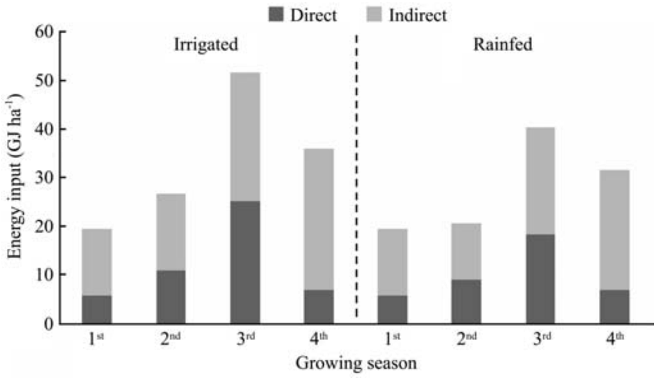

Figure 3 Direct and indirect *Jatropha* energy input for the growing seasons under irrigation and rainfed conditions

First yield was harvested at the second growing season because at the first year (establishment or year of implantation) there was not seed production. It was observed a crescent yield among the years starting with just 52 and 56 kg ha^{-1} respectively for rainfed and irrigated at the first harvesting, unto reach 1780.91 and 2685.75 kg ha^{-1} at the third harvesting. The fruit yield for all three years was 3290 kg ha^{-1} and 2140 kg ha^{-1} for irrigated and rainfed system, respectively.

We observed an increase in the *EROI* throughout the growing season for rainfed and irrigated (Figure 4). The moment that the invested energy is paid back happens when the output energy overpasses the amount of input during the fourth years. Higher values of *EROI* were observed at the irrigated area for the third and fourth growing season. Other authors such as Gomes et al. (2013), in a study with common bean, also observed that increment of *EROI* was promoted by the irrigation, and it was also directly affected by the irrigations depth. On the other hand, Jordan et al. (2012a) found *EROI* was decreased with the increase of irrigation depths for sunflower and Frigo et al. (2011) did not observe the differences on *EROI* values using irrigation.

Using the entire period of evaluation (four years) for calculation of total E_i and E_o, we had a total *EB* of –64.33 GJ ha^{-1} and –66.77 GJ ha^{-1} for irrigated and rainfed area, respectively (Table 4). The values presented in this study were different to those presented by Frigo et al. (2011) with *Jatropha* associated with corn production. The authors found 70.09 and 67.18 GJ ha^{-1} for irrigated and rainfed systems. However, it is important to mention that the authors included the total E_o from the corn and did not compute the outputs from the perennial crop (*Jatropha*), overestimating the results. Frigo et al. (2008b), studying *Jatropha* in rainfed condition, observed an *EB* of 0.32 GJ ha^{-1} and Sangaletti-Gehard et al. (2014) found negative *EB* values for biodiesel production only when the E_o from co-products were not considered. The improvement in E_i and E_o for the two water management were 19.70% and 54.10%, respectively, showing that the invested energy in irrigation was compensated by higher energy production (28.78%) (Table 4).

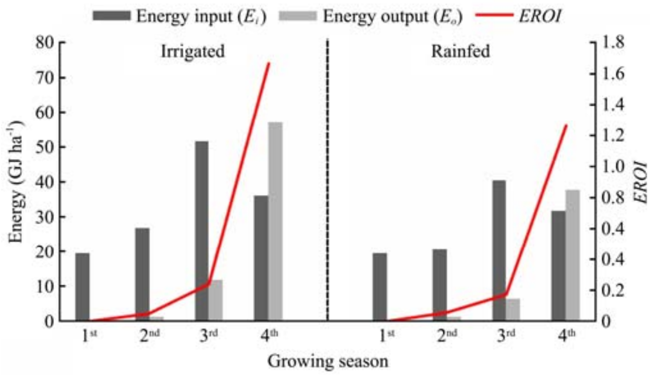

Figure 4 Energy flows and evolution of the energy return on investment (*EROI*) during the growing seasons

Table 4 Values of energy input and output for the total period evaluated, total energy balance and total energy return on investment

Indicator	Irrigated	Rainfed	Δ (%)
E_i (GJ ha^{-1})	134.16	112.08	19.70
E_o (GJ ha^{-1})	69.83	45.31	54. 10
EB (GJ ha^{-1})	–64.33	–66.77	–3.65
EROI	0.52	0.40	28.78

The residues (leaves and wood) not considered in this study could improve the system energy performance. According to Diotto et al. (2014a) for *Jatropha* crop production, it is required at least 4,270 and 1,500 kg ha^{-1} of fresh fruits to guarantee the energetic feasibility for irrigated and rainfed production system, respectively. Moreover, considering the co-products as source of output energy, theses authors described a reduction of a minimum yield to 3,880 kg ha^{-1} for irrigated and 1,370 kg ha^{-1} for rainfed. The co-products are also used in evaluation with other crops as presented by Diotto and Irmak (2016) for corn, when the co-products inclusion changed the values of *EROI* from negative to positive in different scenarios evaluated.

EROI results in both areas showed that *Jatropha* did not have energy gain when just the four first years were taken into account, presenting total *EROI* values of 0.52 and 0.40 for irrigated and rainfed conditions (Table 4). It can be associated with factors such as low *Jatropha* yield at the first year of production and the high amount of fertilizers and pesticides used. In addition, the co-products (branches after pruning for example) were not used as an energy output source. Prueksakorn et al. (2010) stated that *EROI* for 20 years old *Jatropha* plants was 1.4 and it may reach up around 6.0 if co-products are used as output energy. Frigo et al. (2008a), studying *Jatropha* under drip irrigation system, found *EROI* 0.36 in irrigated conditions whereas Frigo et al. (2008b) found *EROI* 0.25. These authors attributed the low values to the *Jatropha* yield at the growing stage evaluated. However, Odum and Barrett (2005) mentioned that *EROI* was more sensitive from the technology used (amount of fertilizer and crop management) than the final yield.

The largest differences in energy requirement between different productions systems came from different cultivation practices, such as irrigation, use of fertilizers and others intensive practices (Achten et al., 2008). However, it is important to consider these practices application in order to achieve higher yields even it does not always pay off in higher energy production (Achten et al., 2007). Therefore, energy balance and *EROI* of the systems analyzed in this study could be improved with the inclusion of wood from the annual pruning, leaves and husks from the *Jatropha* plants and the pressed cake from oil extraction as co-products able to generate energy.

Figure 5 showed the sensitivity analysis for the parameters used in the *EROI*. This analysis was performed to verify the influence of each parameter on *EROI*, contributing to indicate which improvements are necessary. The increase of 10% in the nine parameters related to operations in field produced different impacts on the *EROI*. All the inputs had negative impacts on *EROI*, where the highest variations were observed for fuel consumption and fertilizers application (mainly nitrogen fertilization). Fuel was responsible for the reduction of 3.5% on *EROI* in both water conditions, showing a large contribution of energy demand in production systems.

The greater participation of nitrogen is due to the great need for this element in the nutrition of the *Jatropha* in relation to the other nutrients, as well as to its high energy index (Diotto and Irmak, 2016). In rainfed conditions, the *EROI* variation was –4.40%, showing the lowest efficiency in the nitrogen utilization of the plants, in relation to the irrigated plants, where the variation was –2.25%. The adoption of modern techniques of nitrogen application can reduce the energy incorporated by its use (Patzek, 2004), such as the intercropping of legume species that contribute to the increase of the nitrogen input in the soil through the atmospheric fixation.

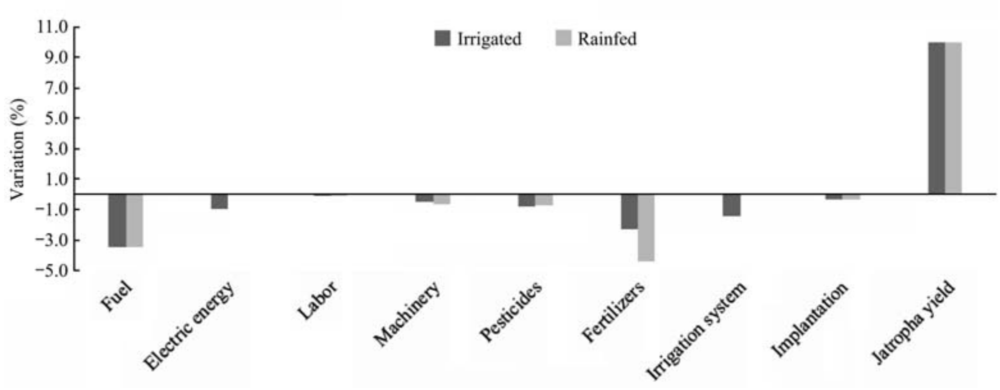

Figure 5 Sensitivity analysis for *EROI* increasing 10% in the on-farm operations

4 Conclusions

The energy balance for *Jatropha* crop system under irrigation and rainfed condition was negative when considered just the four first year, but showed evolution during the years reaching positive values at the last one. It is not possible to characterize this crop as sustainable for energy production using just the period evaluated, however for the following years it is expected yield levels like the last one and values positive of energy balance.

The highest component related to energy input was fertilizers following by fuel used at machinery operations, showing the importance of the on-farm practices.

The system under irrigation presented higher energy input, explained by the direct and indirect energy associated with the irrigation system. However, the energy balance and the *EROI* had improvement with the irrigation use.

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