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Integrated environmental assessment of biodiesel production from soybean in Brazil

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ABSTRACT

This paper presents the results of an environmental impact assessment of biodiesel production from soybean in Brazil. In order to achieve this objective, environmental impact indicators provided by Emergy Accounting (EA), Embodied Energy Analysis (EEA) and Material Flow Accounting (MFA) were used. The results showed that for one liter of biodiesel 8.8 kg of topsoil are lost in erosion, besides the cost of 0.2 kg of fertilizers, about 5.2 m^2 of crop area, 7.33 kg of abiotic materials, 9.0 tons of water and 0.66 kg of air and about 0.86 kg of CO_2 were released. About 0.27 kg of crude oil equivalent is required as inputs to produce one liter of biodiesel, which means an energy return of 2.48 J of biodiesel per Joule of fossil fuel invested. The transformity of biodiesel (3.90E + 05 seJ J^{-1}) is higher than those calculated for fossil fuels as other biofuels, indicating a higher demand for direct and indirect environmental support. Similarly, the biodiesel emergy yield ratio (1.62) indicates that a very low net emergy is delivered to consumers, compared to alternatives. Obtained results show that when crop production and industrial conversion to fuel are supported by fossil fuels in the form of chemicals, goods, and process energy, the fraction of fuel that can actually be considered renewable is very low (around 31%).

1. Introduction

The use of biofuels has been an increasingly important topic in worldwide discussions on energy resources. In the last decade they have gained wide acceptance among policy makers, scientists, environmentalists, agricultural entrepreneurs and the general public. Usually they are presented as a suitable option for energy supply, considering that if they are adequately supported, they could replace a portion of fossil fuels. The main reasons often presented to promote biodiesel production are: (a) It is a clean or "green" energy produced from renewable natural sources and, therefore, could supply a virtually infinite amount of energy for an infinite period of time; (b) It is often stated that biodiesel, by replacing oil products, would result in the reduction of greenhouse gases' emissions. It is supposed that the carbon emitted by biodiesel in the combustion phase is the one absorbed by the plant during its growth through photosynthesis, resulting in a carbon neutral budget; (c) Finally, biodiesel production is presented by the press to be a strategy for rural development.

However, when seeking an alternative source of energy, one must evaluate the whole production chain to correctly evaluate potential environmental benefits and disadvantages. If one takes a closer look at the complete biofuels production processes, the benefits are not so clear. In fact, biofuel production requires the use of fossil fuel energy, in the form of fertilizers, agrochemicals, machinery for both agricultural and industrial phases, as well as for transportation of raw materials, inputs and distribution of biofuel for final use. Moreover, depending on the biomass used, biofuels processing could require huge amounts of fossil fuels. The advantages in terms of reduction of greenhouse effect and national fossil fuel energy dependency are put into a different perspective, if one takes into account the entire picture and not only the end-of-pipe emissions. In order to do that, many different social and environmental factors should be taken into proper account, in addition to the energy yield, the carbon budget and the economic cost. There are several studies in the literature that evaluate one or other environmental aspect of biofuels production [1–6]. However it is necessary to make a comprehensive evaluation to explore different aspects of this debate, underlining the advantages and disadvantages of biomass cultivation to produce energy [7,8].

In order to obtain such a wider overview on the environmental impacts of the biodiesel production process in Brazil, a comprehensive assessment based on the parallel use of different evaluation methods was carried out. Soybean is the most important feedstock used to produce biodiesel in Brazil, where approximately 90% of biodiesel is produced from

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soybeans [9]. In this context, the objective of this study was to discuss global environmental impacts due to use of resources for biodiesel production from soybean in Brazil. Three environmental assessment methods proposed by Ulgiati et al. [10] were adopted for the assessment: (a) Emergy Accounting (EA), (b) Embodied Energy Analysis (EEA) and (c) Material Flow Accounting (MFA). These three approaches were chosen due to their larger space and time scale, while other methods are more process-oriented, such as Exergy Analysis (also suggested by Ulgiati et al. [10]) did not seem to be suitable for the goals of the present investigation.

2. Material and methods

The three approaches (EA, EEA, MFA) selected for the assessment, are believed to be effective in evaluating the environmental performance of biodiesel (both as a final product and as a process) from the supply-side perspective. They are able to reveal important aspects of sustainability and they have different scientific perspectives and system boundaries; the importance of natural resources are weighted differently by the three methods, which adds complementarity of viewpoints to our evaluation. A more detailed outline of the individual assessment methods is provided in the following paragraphs.

2.1. Material flow accounting

The Material Flow Accounting method [10–12] evaluates the environmental disturbance associated with the withdrawal or diversion of material flows of resources from their natural ecosystem pathways. In this method, appropriate Material Intensity Factors (MIF) (kg unit^{-1}) are multiplied by each input, respectively, accounting for the total amount of abiotic matter, water and air matter that is directly or indirectly required in order to provide that very same input to the system. The resulting material intensities of the individual inputs are then separately summed and assigned to the system's output as a quantitative measure of its cumulative environmental burden, intended as material resource withdrawal and depletion.

2.2. Embodied energy analysis

The Embodied Energy Analysis method [10,13,14] deals with the gross energy requirement of the analyzed system. The method accounts for the amount of commercial energy that is required directly and indirectly by the process for making a good or a service [14]. EEA was applied according to the IFIAS conventions, which were designed for quantifying the availability and use of stocks of fossil fuels (i.e. fossil and fossil-equivalent energy). Commercial energy is recognized in this analysis as all kinds of energies that require technological processing and that are sold at market price due to the processing needed (cost of labor and services) such as fossil fuels, nuclear and electricity. Electricity from the grid (including hydro and wind, if any) should therefore, be regarded as commercial, while free environmental services and direct renewables are not. Therefore, as the EEA of a product is concerned with the depletion of fossil energy, all the forms of material and energy that do not require the use of commercial resources to make them available are not accounted. For instance, resources provided for free by the environment such as rain, topsoil, spring water, human labor and economic services are not accounted by embodied energy analysis.

In this method, all the material and energy inputs to the analyzed system are multiplied by appropriate oil equivalent factors (kg oil unit^{-1}); the cumulative embodied energy requirement of the system's output is then computed as the sum of the individual oil equivalents of the input flows, which can be converted to energy units by multiplying by the standard calorific value of oil fuel (4.18E+07 J kg$^{-1}{}_{\text{oil fuel}}$). The CO_2 emissions can be roughly estimated by multiplying the embodied energy used by the stoichiometric CO_2 emissions of oil fuel ($\sim$3.2 kg CO_2 kg$^{-1}{}_{\text{oil fuel}}$).

2.3. Emergy accounting

The Emergy Accounting method [10,15,16] looks at the environmental performance of the system on the global scale, taking into account all the free environmental inputs such as sunlight, wind, rain, as well as the indirect environmental support embodied in human labor and services, which are not usually included in traditional embodied energy analyses. The Emergy Accounting methodology uses the solar energy embodied in the system's inputs as the measurement base. Emergy is defined as the total amount of solar energy that was directly or indirectly required to make a given product or to support a given flow, and is measured in solar equivalent Joules (seJ). The amount of emergy that was originally required to provide one unit of each input is referred to as its specific emergy (seJ unit^{-1}) or transformity (seJ J^{-1}). The renewability (%REN) is the percentage of renewable emergy used by the system. The Emergy Yield Ratio (EYR) is the

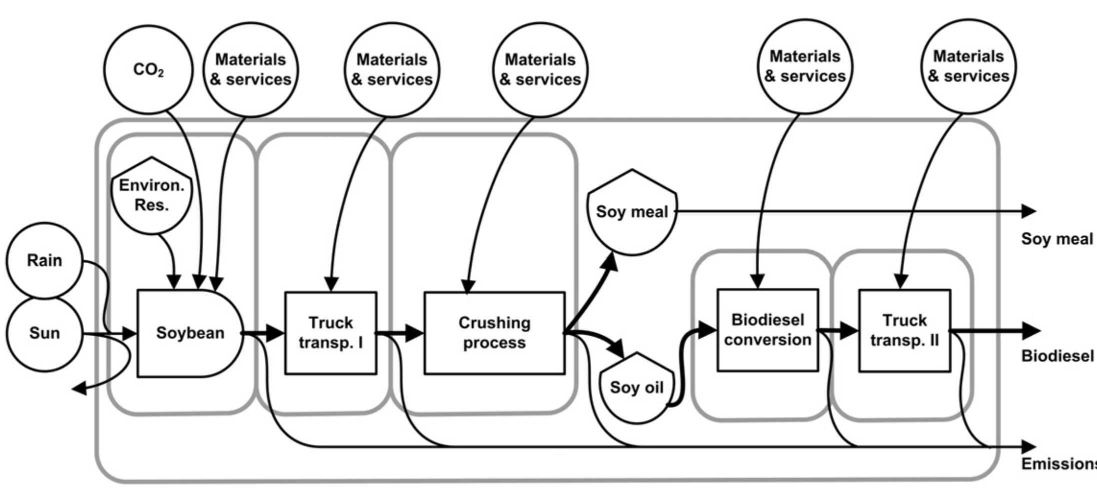

Fig. 1. Systems diagram of a biodiesel production process from soybean.

Table 1
Mass flows in the biodiesel production process.

Note	Description of flow	Unit	Amount ha^{-1} yr^{-1}	MIF abiotic (kg unit^{-1})	Ref[a]	Mass abiotic (kg)	MIF water (kg unit^{-1})	Ref.[a]	Mass water (kg)	MIF air (kg unit^{-1})	Ref.[a]	Mass air (kg)
	Agricultural phase											
	Renewable inputs											
1	Sunlight	J	(*)									
2	Rain water	kg	1.72E+07	0.00	[a]	0.00E+00	1.00	[a]	1.72E+07	0.00	[a]	0.00E+00
3	Deep heat	J	(*)									
4	N_2 fixed from atmosphere	kg	6.00E+01	0.00	[a]	0.00E+00	0.00	[a]	0.00E+00	0.00	[a]	0.00E+00
	Nonrenewable inputs											
5	Loss of topsoil	kg	1.70E+04	0.66	[a]	1.12E+04	0.30	[a]	5.10E+03	0.00	[a]	0.00E+00
6	Limestone	kg	3.75E+02	1.66	[c]	6.23E+02	9.70	[c]	3.64E+03	0.06	[c]	2.25E+01
7	Herbicides	kg	4.80E+00	1.10	[b]	5.28E+00	0.00	[b]	0.00E+00	0.00	[b]	0.00E+00
8	Insecticides and pesticides	kg	3.20E+00	1.10	[b]	3.52E+00	0.00	[b]	0.00E+00	0.00	[b]	0.00E+00
9	Seeds	kg	6.90E+01	4.62	[d]	3.19E+02	6060	[d]	4.18E+05	0.04	[d]	2.76E+00
10	Nitrogen in fertilizer	kg	0.00E+00	1.10	[b]	0.00E+00	0.00	[b]	0.00E+00	0.00	[b]	0.00E+00
11	Phosphorus in fertilizer	kg	3.38E+01	3.44	[c]	1.16E+02	23.30	[c]	7.87E+02	1.29	[c]	4.36E+01
12	Potash in fertilizer	kg	6.54E+01	11.32	[c]	7.40E+02	10.60	[c]	6.93E+02	0.07	[c]	4.58E+00
13	Diesel	kg	5.46E+01	1.36	[c]	7.43E+01	9.70	[c]	5.30E+02	0.02	[c]	1.04E+00
14	Electricity	kWh	(*)	2.09	[e]	7.09E+01	5.86	[e]	1.99E+02	0.37	[e]	1.25E+01
15	Steel for agricultural machinery	kg	2.50E+01	9.32	[c]	2.33E+02	81.90	[c]	2.05E+03	0.77	[c]	1.93E+01
16	Farm buildings	USD	(*)									
17	Local labor	yrs	(*)									
18	Extra labor	yrs	(*)									
19	Externalities	USD	(*)									
20	Annual services	USD	(*)									
	Products and by-products of agricultural phase											
21	Soybean produced	kg	2.83E+03	4.62	[d]	1.31E+04	6060.38	[d]	1.72E+07	0.04	[d]	1.04E+02
	Soybean transport											
	Row materials input											
21	Soybean	kg	2.83E+03	4.62	[d]	1.31E+04	6060.38	[d]	1.72E+07	0.04	[d]	1.04E+02
	Nonrenewable inputs											
22	Steel for transp. machinery	kg	1.98E+00	107.00	[c]	2.12E+02	927.00	[c]	1.84E+03	102.00	[c]	2.02E+02
23	Diesel for transport	kg	4.25E+00	1.36	[c]	5.78E+00	9.70	[c]	4.12E+01	0.02	[c]	8.07E-02
24	Labor	yrs	(*)									
25	Annual services	USD	(*)									
	Products and by-products of transport phase											
26	Soybean transported	kg	2.83E+03	4.70	[d]	1.33E+04	6061.04	[d]	1.72E+07	0.11	[d]	3.06E+02
	Crushing process											
	Row materials input											
26	Soybean	kg	2.83E+03	4.70	[d]	1.33E+04	6061.04	[d]	1.72E+07	0.11	[d]	3.06E+02
	Nonrenewable inputs											
27	Steel for plant machinery	kg	2.84E-01	9.32	[c]	2.65E+00	81.90	[c]	2.32E+01	0.77	[c]	2.19E-01
28	Cement in plant construction	kg	2.76E-01	1.33	[c]	3.67E-01	3.40	[c]	9.38E-01	0.04	[c]	1.21E-02
29	Iron in plant construction	kg	1.13E-02	21.58	[c]	2.44E-01	504.90	[c]	5.70E+00	5.08	[c]	5.73E-02
30	Diesel	kg	5.07E+01	1.36	[c]	6.89E+01	9.70	[c]	4.92E+02	0.02	[c]	9.63E-01
31	Electricity	kWh	(*)	2.09	[e]	6.24E-02	5.86	[e]	1.75E-01	0.37	[e]	1.10E-02
32	Water	kg	2.04E+03	0.01	[c]	2.04E+01	1.30	[c]	2.65E+03	0.00	[c]	2.04E+00
33	Hexane	kg	3.40E+00	1.00		3.40E+00	0.00		0.00E+00	0.00		0.00E+00
34	Labor	yrs	(*)									
35	Annual capital cost and services	USD	(*)									
	Products and by-products of crushing phase											

(*continued on next page*)

Table 1 (*continued*)

Note	Description of flow	Unit	Amount ha^{-1} yr^{-1}	MIF abiotic (kg unit^{-1})	Ref[a]	Mass abiotic (kg)	MIF water (kg unit^{-1})	Ref.[a]	Mass water (kg)	MIF air (kg unit^{-1})	Ref.[a]	Mass air (kg)
36	Total MI soybean crushed					1.34E+04			1.72E+07			3.09E+02
	Row soy oil	Kg	5.10E+02	9.35	[d]	4.77E+03	11980.09	[d]	6.11E+06	0.22	[d]	1.10E+02
	Soy meal	kg	2.30E+03	3.67	[d]	8.45E+03	4700.97	[d]	1.08E+07	0.08	[d]	1.95E+02
	Lecithin (gross)	kg	1.98E+01	9.35	[d]	1.85E+02	11980.09	[d]	2.37E+05	0.22	[d]	4.28E+00
	Biodiesel production											
	Row materials input											
36	Row soy oil	kg	5.10E+02	9.35	[d]	4.77E+03	11980.09	[d]	6.11E+06	0.22	[d]	1.10E+02
	Nonrenewable inputs											
37	Steel for machinery	kg	1.17E+00	9.32	[c]	1.09E+01	81.90	[c]	9.60E+01	0.77	[c]	9.05E-01
38	Cement in plant construction	kg	3.39E-01	1.33	[c]	4.51E-01	3.40	[c]	1.15E+00	0.04	[c]	1.49E-02
39	Iron in plant construction	kg	7.04E-03	21.58	[c]	1.52E-01	504.90	[c]	3.55E+00	5.08	[c]	3.57E-02
40	Diesel	kg	2.74E+01	1.36	[c]	3.72E+01	9.70	[c]	2.65E+02	0.02	[c]	5.20E-01
41	Methanol	kg	7.53E+01	1.67	[c]	1.26E+02	4.50	[c]	3.39E+02	3.87	[c]	2.92E+02
42	Catalyst	kg	5.44E+00	1.00	[a]	5.44E+00	0.00	[a]	0.00E+00	0.00	[a]	0.00E+00
43	Electricity	kWh	(*)	2.09	[e]	9.38E-01	5.86	[e]	2.63E+00	0.37	[e]	1.66E-01
44	Water	kg	2.60E+02	0.01	[c]	2.60E+00	1.30	[c]	3.38E+02	0.00	[c]	2.60E-01
45	Labor	yrs	(*)									
46	Annual capital cost and services	USD	(*)									
	Products and by-products of biodiesel production											
47	Biodiesel	kg	5.99E+02	8.26	[d]	4.95E+03	10189.2	[d]	6.11E+06	0.67	[d]	4.04E+02
	Glycerin	kg	4.42E+01									
	Soap stock	kg	2.72E+01									
	Biodiesel transport											
	Row materials input											
47	Biodiesel	kg	5.99E+02	8.26	[d]	4.95E+03	10189.2	[d]	6.11E+06	0.67	[d]	4.04E+02
	Nonrenewable inputs											
48	Steel for transp. machinery	kg	4.20E-01	107.00	[c]	4.49E+01	927.00	[c]	3.89E+02	102.00	[c]	4.28E+01
49	Diesel for transport	kg	8.99E-01	1.36	[c]	1.22E+00	9.70	[c]	8.72E+00	0.02	[c]	1.71E-02
50	Labor	yrs	(*)									
51	Annual services	USD	(*)									
	Products and by-products of transport phase											
52	Biodiesel transported	kg	5.99E+02	8.33	[d]	5.00E+03	10189.8	[d]	6.11E+06	0.74	[d]	4.46E+02

[a] References for Material Intensity Factors (MIF): [a] By definition; [b] After Ulgiati [8].; [c] Wurbs et al. [19]; [d] Calculated in this work. These values are calculated with the sum of the cumulative mass used up divided by the product output. e.g. The MIF abiotic for soybean in the field (Note #21) is: 1.31E+04/2.83E+03 = 4.62; [e] Hinterberger and Stiller [11].
(*) No Significant mass associated to this item within the local scale of investigation.

ratio of total emergy inflow to the emergy invested by the outside economy. The Emergy Loading Ratio (ELR) is the ratio of imported and locally nonrenewable emergy to the locally renewable one. At the core of an emergy evaluation of a given production system or process is a mass and energy flow inventory in which the flows are adjusted for energy quality using conversion factors (transformity, specific emergy, emdollar). Odum [15] and Brown and Ulgiati [16] provide a detailed explanation of the emergy accounting procedures for a variety of systems as well as a careful discussion of the meaning of emergy indicators.

2.4. Soybean biodiesel production system

Fig. 1 presents the system diagram of a biodiesel production process, showing the relations between input (natural and commercial) resources and the final product, accounting for all the material and energy flows involved in soybean biodiesel production process. The biodiesel production stages considered in this assessment were: the soybean agricultural production; transport to industry; the crushing process to produce soy oil and soy meal; trans-esterification of the soy oil to produce biodiesel and biodiesel transport to the final consumer.

The Appendix section provides footnotes describing in details the energy and material flows of the soybean agricultural cultivation, transport, extraction and conversion of soy oil into biodiesel, with calculation procedures and references for the inputs (e.g. diesel fuels, fertilizers, field operations, machinery) used in each processing phase.

Data used in the calculations were collected from field work and from scientific literature (see references for data collection in the

Table 2
Energy flows in the biodiesel production process.

Note	Description of flow	Units	Amount of input unit ha^{-1} $year^{-1}$	Oil equivalent per unit kg oil $unit^{-1}$	Ref. for oil equivalent[a]	Global oil demand kg oil equiv	Global energy demand (J)	Global CO_2 emissions (kg CO_2)
Agricultural stage								
Renewable inputs								
1	Sunlight	J	[b]					
2	Rain water	kg	[b]					
3	Deep heat	J	[b]					
4	N_2 fixed from atmosphere	kg	[b]					
Nonrenewable inputs								
5	Loss of topsoil	kg	1.70E + 04		[vi]			2.30E + 02
6	Limestone	kg	3.75E + 02	0.15	[iii]	5.64E + 01	2.36E + 09	1.80E + 02
7	Herbicides	kg	4.80E + 00	2.17	[i]	1.04E + 01	4.37E + 08	3.32E + 01
8	Insecticides and pesticides	kg	3.20E + 00	1.27	[i]	4.05E + 00	1.70E + 08	1.29E + 01
9	Seeds	kg	6.90E + 01	0.09	[iv]	6.21E + 00	2.60E + 08	1.98E + 01
10	Nitrogen in fertilizer	kg	0.00E + 00	1.77	[i]	0.00E + 00	0.00E + 00	0.00E + 00
11	Phosphorus in fertilizer	kg	3.38E + 01	0.31	[i]	1.05E + 01	4.39E + 08	3.34E + 01
12	Potash in fertilizer	kg	6.54E + 01	0.22	[i]	1.41E + 01	5.88E + 08	4.48E + 01
13	Diesel	kg	5.46E + 01	1.10	[i]	6.00E + 01	2.51E + 09	1.91E + 02
14	Electricity	J	1.22E + 08	6.97E − 08	[i]	8.53E + 00	3.57E + 08	2.72E + 01
15	Steel for agricultural machinery	kg	2.50E + 01	1.65	[i]	4.12E + 01	1.73E + 09	1.31E + 02
16	Farm buildings	USD	[b]					
17	Local labor	yrs	[b]					
18	Extra labor	yrs	[b]					
19	Externalities	USD	[b]					
20	Annual services	USD	[b]					
Products and by-products of agricultural phase								
21	Soybean produced	kg	2.83E + 03	0.07	[iv]	2.11E + 02	8.85E + 09	9.03E + 02
	Soybean produced	J	6.40E + 10					
Soybean transport								
Raw material inputs								
21	Soybean	kg	2.83E + 03	0.07	[iv]	2.11E + 02	8.85E + 09	9.03E + 02
Nonrenewable inputs								
22	Steel for transp. machinery	kg	1.98E + 00	1.65	[i]	3.27E + 00	1.37E + 08	1.04E + 01
23	Diesel for transport	kg	4.25E + 00	1.10	[i]	4.67E + 00	1.95E + 08	1.49E + 01
24	Labor	yrs	[b]					
25	Annual services	USD	[b]					
Products and by-products of transport phase								
26	Soybean transported	kg	2.83E + 03	0.08	[iv]	2.19E + 02	9.18E + 09	9.28E + 02
Crushing process								
Raw material inputs								
26	Soybean	kg	2.83E + 03	0.08	[iv]	2.19E + 02	9.18E + 09	9.28E + 02
Nonrenewable inputs								
27	Steel for machinery	kg	2.84E − 01	1.65	[i]	4.68E − 01	1.96E + 07	1.49E + 00
28	Cement in plant construction	kg	2.76E − 01	0.07	[i]	1.98E − 02	8.28E + 05	6.30E − 02
29	Iron in plant construction	kg	1.13E − 02	0.02	[iii]	1.78E − 04	7.45E + 03	5.67E − 04
30	Diesel	kg	5.07E + 01	1.10	[i]	5.57E + 01	2.33E + 09	1.77E + 02
31	Electricity	J	3.05E + 08	6.97E − 08	[i]	2.12E + 01	8.89E + 08	6.76E + 01
32	Water	kg	2.04E + 03	1.43E − 04	[v]	2.91E − 01	1.22E + 07	9.28E − 01
33	Hexane	kg	3.40E + 00	n.a.				
34	Labor	yrs	[b]					
35	Annual capital cost and services	USD	[b]					
Products and by-products of crushing phase								
					Total	2.97E + 02	1.24E + 10	1.18E + 03
36	Row soy oil	kg	5.10E + 02	0.21	[iv]	1.06E + 02	4.42E + 09	4.18E + 02
	Soy meal	kg	2.30E + 03	0.08	[iv]	1.87E + 02	7.84E + 09	7.41E + 02
	Lecithin (gross)	kg	1.98E + 01	0.21	[iv]	4.11E + 00	1.72E + 08	1.63E + 01
Biodiesel production								
Raw materials input								
36	Row soy oil	kg	5.10E + 02	2.07E − 01	[iv]	1.06E + 02	4.42E + 09	4.18E + 02
Nonrenewable inputs								
37	Steel for machinery	kg	1.17E + 00	1.65	[i]	1.93E + 00	8.08E + 07	6.15E + 00
38	Cement in plant construction	kg	3.39E − 01	0.07	[i]	2.43E − 02	1.02E + 06	7.74E − 02
39	Iron in plant construction	kg	7.04E − 03	0.02	[iii]	1.11E − 04	4.64E + 03	3.53E − 04
40	Diesel	kg	2.74E + 01	1.10	[i]	3.01E + 01	1.26E + 09	9.57E + 01

(*continued on next page*)

Table 2 (*continued*)

Note	Description of flow	Units	Amount of input unit ha^{-1} $year^{-1}$	Oil equivalent per unit kg oil $unit^{-1}$	Ref. for oil equivalent[a]	Global oil demand kg oil equiv	Global energy demand (J)	Global CO_2 emissions (kg CO_2)
41	Methanol	kg	7.53E + 01	0.60	[vi]	4.52E + 01	1.89E + 09	1.44E + 02
42	Catalyst	kg	5.44E + 00	n.a.				
43	Electricity	J	1.62E + 06	7.17E − 08	[i]	1.16E − 01	4.85E + 06	3.69E − 01
44	Water	kg	2.60E + 02	1.43E − 04	[v]	3.72E − 02	1.56E + 06	1.19E − 01
45	Labor	yrs	[b]					
46	Annual capital cost and services	USD	[b]					
Products and by-products of biodiesel production								
47	Biodiesel	kg	5.99E + 02	0.31	[iv]	1.83E + 02	7.66E + 09	6.65E + 02
	Glycerin	kg	4.42E + 01					
	Soap stock	kg	2.72E + 01					
Biodiesel transport								
Raw material inputs								
47	Biodiesel	kg	5.99E + 02	0.29	[iv]	1.83E + 02	7.66E + 09	6.65E + 02
Nonrenewable inputs								
48	Steel for transp. machinery	kg	4.20E − 01	1.65	[i]	6.92E − 01	2.90E + 07	2.20E + 00
49	Diesel for transport	kg	8.99E − 01	1.10	[i]	9.89E − 01	4.14E + 07	3.15E + 00
50	Labor	yrs	[b]					
51	Annual services	USD	[b]					
Products and by-products of transport phase								
52	Biodiesel	kg	5.99E + 02	0.31	[iv]	1.85E + 02	7.73E + 09	6.70E + 02

n.a. = Not available.
[a] References for oil equivalent per unit: [i] Biondi et al. [20]; [ii] By definition; [iii] Boustead and Hancock [21]; [iv] This work; [v] Smil [22]; [vi] After Ulgiati [8].
[b] No energy is associated to this item within the scale of investigation.

Appendix section) as representative of the soybean production and processing stages in Brazil, taking into consideration the most important management practices that are currently used in Brazil. In summary, it pertains to conventional non-tillage management with use of fertilizers and agrochemicals. In this survey, differences were considered in the input use, according to the production models adopted in the Southern and Northern regions, such as insolation, precipitation, field yield and use of fertilizers, limestone and agrochemicals, among others.

3. Results and discussion

Tables 1–3 show the material, energy and emergy flows for the biodiesel production process, respectively. Table 4 shows a summary of results of the three methods applied. The available set of indicators offer a way to evaluate the process sequentially (the agricultural step first, and then the industrial step).

The total demand of matter, embodied energy and emergy for the biodiesel production phases are reported in Fig. 2. This figure shows that agriculture is the most important phase as far as material and emergy demand are concerned. Embodied energy analysis is also very important in the agricultural phase, however soy oil trans-esterification uses a high amount of resources which should not be disregarded. Results indicate that agriculture is the stage that uses the largest amount of input flows. Such a finding calls for careful reorganization of cropping activities aimed at decreasing the amount of nonrenewable materials used in the process. Our findings reflect the situation of modern industrialized agriculture, mainly consisting of monocultures, being the major cause of exploitation of nonrenewable resources. In the last century, the use of industrial resources in soybean crops increased sharply, so that production is now strongly dependent on chemical inputs and high technology to ensure high crops yields. Most of these resources are directly or indirectly dependent upon the global availability of the fossil fuels and other minerals, both non-renewable resources. The excess and inadequate use of these resources, while ensuring the crop yield in the short-term perspective, also increases soybean production costs and generates high pressure on the environment as quantitatively shown by the indicators calculated in this study. This indicates that to produce biodiesel from soy oil is not an environmentally-friendly process and is not the best way to use such a feedstock.

Fig. 3 compares the relative importance of different types of input flows according to the three methods used to evaluate the biodiesel production process. This figure underscores the special importance of the emergy analysis because it also accounts for free environmental flows and human labor and services on the same accounting basis. On the other hand, the embodied energy method focuses on the commercial energy flows and the material flow accounting assigns more importance to the material flows. It shows the importance of use more than one approach of analysis.

Table 1 shows that some material flows required for biodiesel production are remarkably high on the global scale. For instance, about 8.88 kg of topsoil eroded, 0.2 kg of fertilizers and 7.33 kg of abiotic materials are needed per liter of biodiesel produced. Also, as expected, higher unit material, energy, land and labor demands are calculated for biodiesel than for soybean, due to further processing stages. Table 1 shows that soil loss is the most important contribution to the abiotic factor with around 80% of the total abiotic resources used for biodiesel production. Rain is the most important contribution to the water factor (almost 100%). Excluding rain, other important contributions to the water factor are soil loss, limestone and steel used in different process phases. Methanol is the most important contribution to the air factor with around 65% of the total abiotic resources used.

About 0.86 kg of CO_2 is released per liter of biodiesel produced. This figure translates into a release of 30.7 g CO_2 per MJ delivered. Commercial diesel production and use would release about 100 g CO_2 per MJ delivered [8]. Therefore, to use biodiesel instead of petroleum-based diesel would release 69.3% lower CO_2 emission according to our calculations. However, it is important to note that soybean biodiesel results showed that such a product is not totally climate neutral due to the inputs used in the production processes. Moreover, some authors claim that the production of commonly

Table 3
Emergy flows in the biodiesel production process.

Note	Description of flow	Units	Amount ha^{-1} yr^{-1}	Specific emergy seJ $unit^{-1}$	Ref. for specific emergy[a]	Emergy seJ ha^{-1} yr^{-1}
Agricultural phase						
Renewable inputs						
1	Sunlight	J	5.10E + 10	1.00E + 00	[a]	5.10E + 10
2	Rain water	J	5.25E + 10	3.06E + 04	[b]	1.61E + 15
3	Deep heat	J	3.00E + 10	1.01E + 04	[c]	3.04E + 14
4	N_2 fixed from atmosphere	kg	6.00E + 01	6.38E + 12	[d]	3.83E + 14
Nonrenewable inputs						
5	Loss of topsoil	J	4.61E + 09	1.24E + 05	[b]	5.72E + 14
6	Limestone	J	2.29E + 08	2.72E + 06	[b]	6.23E + 14
7	Herbicides	kg	4.80E + 00	2.48E + 13	[b]	1.19E + 14
8	Insecticides and pesticides	kg	3.20E + 00	2.48E + 13	[b]	7.94E + 13
9	Seeds	kg	6.90E + 01	2.73E + 12	[e]	1.88E + 14
10	Nitrogen in fertilizer	kg	0.00E + 00	6.38E + 12	[d]	0.00E + 00
11	Phosphorus in fertilizer	kg	3.38E + 01	6.55E + 12	[b]	2.21E + 14
12	Potash in fertilizer	kg	6.54E + 01	2.92E + 12	[b]	1.91E + 14
13	Diesel	J	2.43E + 09	1.11E + 05	[b]	2.68E + 14
14	Electricity	J	1.22E + 08	2.77E + 05	[c]	3.39E + 13
15	Steel for machinery	kg	2.50E + 01	1.13E + 13	[b]	2.83E + 14
16	Farm buildings	USD	4.74E + 01	3.70E + 12	[h]	1.75E + 14
17	Local labor	yrs	2.60E − 03	1.07E + 16	[b]	2.79E + 13
18	Extra labor	yrs	2.60E − 03	1.07E + 16	[b]	2.79E + 13
19	Externalities	USD	3.45E + 02	3.70E + 12	[h]	1.28E + 15
20	Annual services	USD	1.50E + 01	3.70E + 12	[h]	5.56E + 13
Products and by-products of agricultural phase						
21	Soybean produced	kg	2.83E + 03	2.27.E + 12	[e]	6.44E + 15
		J	6.40E + 10	1.01.E + 05	[e]	6.44E + 15
Soybean transport						
Nonrenewable inputs						
22	Steel for machinery	kg	1.98E + 00	1.13E + 13	[b]	2.24E + 13
23	Diesel	J	1.89E + 08	1.11E + 05	[b]	2.09E + 13
24	Labor	yrs	5.16E − 04	1.07E + 16	[b]	5.53E + 12
25	Annual services	USD	2.33E + 00	3.70E + 12	[h]	8.62E + 12
Products and by-products of transport phase						
26	Soybean transported	kg	2.83E + 03	2.29.E + 12	[e]	6.49E + 15
		J	6.40E + 10	1.01.E + 05	[e]	6.49E + 15
Crushing process						
Nonrenewable inputs						
27	Steel for machinery	kg	2.84E − 01	1.13E + 13	[b]	3.21E + 12
28	Cement in plant construction	kg	2.76E − 01	3.47E + 12	[b]	9.57E + 11
29	Iron in plant construction	kg	1.13E − 02	1.13E + 13	[b]	1.28E + 11
30	Diesel	J	2.25E + 09	1.11E + 05	[b]	2.49E + 14
31	Electricity	J	3.05E + 08	2.77E + 05	[c]	8.45E + 13
32	Process and cooling water	J	1.01E + 07	4.28E + 05	[f]	4.31E + 12
33	Hexane	kg	3.40E + 00	6.08E + 12	[c]	2.06E + 13
34	Labor	yrs	2.97E − 04	1.07E + 16	[b]	3.18E + 12
35	Annual services	USD	2.97E + 00	3.70E + 12	[h]	1.10E + 13
Products and by-products of crushing phase						
36	Oil	kg	5.10E + 02	1.35.E + 13	[e]	6.87E + 15
		J	2.02E + 10	3.40.E + 05	[e]	6.87E + 15
36	Meal	kg	2.30E + 03	2.98.E + 12	[e]	6.87E + 15
		J	3.58E + 10	1.92.E + 05	[e]	6.87E + 15
36	Lecithin (gross)	kg	1.98E + 01	3.47.E + 14	[e]	6.87E + 15
		J	7.85E + 08	8.75.E + 06	[e]	6.87E + 15
Biodiesel production						
Nonrenewable inputs						
37	Steel for machinery	kg	1.17E + 00	1.13E + 13	[b]	1.32E + 13
38	Cement in plant construction	kg	3.39E − 01	3.47E + 12	[b]	1.18E + 12
39	Iron in plant construction	kg	7.04E − 03	1.13E + 13	[b]	7.95E + 10
40	Diesel	J	1.22E + 09	1.11E + 05	[b]	1.35E + 14
41	Methanol	J	1.53E + 09	1.89E + 05	[g]	2.89E + 14
42	Catalyst	kg	5.44E + 00	2.48E + 13	[b]	1.35E + 14
43	Electricity	J	1.62E + 06	2.77E + 05	[c]	4.49E + 11
44	Water	J	1.29E + 06	4.28E + 05	[i]	5.51E + 11
45	Labor	yrs	1.80E − 04	1.07E + 16	[b]	1.93E + 12
46	Annual services	USD	4.32E + 00	3.70E + 12	[h]	1.60E + 13
Products and by-products of biodiesel production						
47	Biodiesel	kg	5.99E + 02	1.24.E + 13	[e]	7.46E + 15
		J	1.92E + 10	3.89.E + 05	[e]	7.46E + 15
	Glycerin	kg	4.42E + 01			
	Soap stock	kg	2.72E + 01			
Biodiesel transport						

(*continued on next page*)

Table 3 (*continued*)

Note	Description of flow	Units	Amount ha^{-1} yr^{-1}	Specific emergy seJ $unit^{-1}$	Ref. for specific emergy[a]	Emergy seJ ha^{-1} yr^{-1}
Nonrenewable inputs						
48	Steel for machinery	kg	4.20E − 01	1.13E + 13	[b]	4.74E + 12
49	Diesel	J	4.00E + 07	1.11E + 05	[b]	4.42E + 12
50	Labor	yrs	1.09E − 04	1.07E + 16	[b]	1.17E + 12
51	Annual services	USD	4.93E − 01	3.70E + 12	[h]	1.83E + 12
Products and by-products of transport phase						
52	Biodiesel transported	kg	5.99E + 02	1.25.E + 13	[e]	7.48E + 15
		J	1.92E + 10	3.90.E + 05	[e]	7.48E + 15

[a] References for Specific Emergy: [a] Definition; [b] Brown and Ulgiati [16] [c] Odum [15]; [d] Ortega et al. [23]; [e] This study; [f] Bastianoni et al. [24]; [g] After Ulgiati [8]; [h] Coelho et al. [25]; [i] Bastianoni and Marchettini [26].

used biofuels can contribute as much or more to global warming by considering the nitrous oxide emissions than cooling by fossil fuel savings [33].

Another important issue is the allocation of input flows to the products in the EEA and MFA. Results are strongly affected by the allocation procedure choice and this is a very significant calculation step. If co-products are accepted by the market, than an allocation mechanism can be used. If they are not, then all material and energy consumption must be allocated to the main product, because all the other products should be considered wastes. The results presented in Tables 1, 2 and 4 were obtained using energy allocation factors for the intermediate products of the crushing process phase. From this phase ahead only costs allocated to raw soy oil are accounted for as costs for the final product (biodiesel). This means that approximately 36% of the total material and energy used in the production, transport and crushing phases were allocated to the soy oil. The largest part of the resources (around 64%) were allocated to soy meal because this co-product has good market value as livestock feed in Brazil, the U.S. and Europe. This shows that even with a favorable allocation procedure, the environmental impacts of the biodiesel from soybean still are remarkably high. For example, if we consider no allocation to the soy meal in the crushing phase the releasing of CO_2 for biodiesel production is about two times higher, 62.4 g CO_2 per MJ delivered. On the other hand no allocation was made for energy and material for glycerin produced as co-product in the trans-esterification process because this is considered a non-desirable product for biodiesel production process. Furthermore, considering the increasing biofuels production, the overproduction of glycerin as a co-product will not find a good market value and can be considered to be an industrial waste, therefore, there is no reason to allocate materials and energy to produce waste.

Table 2 shows that agricultural and soy oil trans-esterification phases have the highest importance in the embodied fossil energy analysis, accounting for 41% and 42%, respectively, of the total energy inputs. The most important individual contributions were methanol (24.5%) and diesel fuel (16.3%) used in the trans-esterification phase, followed by diesel fuel used in the biodiesel production processes.

The Energy Return on Investment (EROI) is the amount of energy output divided by the energy invested by the economic system. They are calculated on the global scale and offer an interesting overall energy cost evaluation of the biodiesel production. About 0.07 kg of crude oil equivalent is needed to produce one kg of soybean, which translates into an energy return of about 7.24 J of soybean per Joule of fossil fuel invested. Instead, 0.27 kg of oil equivalent is globally required per liter of biodiesel produced, equal to an energy return of 2.48 J of biodiesel per Joule of fossil fuel invested. This value is higher than those calculated by Venturi and Venturi [17] (0.7–1.6) for biodiesel from soybean; by Janulis [18] (1.04–1.59) for biodiesel from rapeseed; and by Giampietro and Ulgiati [7] (0.98–1.21) for biodiesel from sunflower. However, the value obtained is lower than that calculated by Sheehan et al. [1] (3.2) for biodiesel from soybean. These great differences in the literature values may refer to different climate conditions, crop yields, inputs utilized, management practices, and allocation procedures. From the embodied energy perspective it is possible to realize that biodiesel uses a large amount of fossil fuel energy in the agricultural and industrial conversion stages. In some cases from the literature, the fossil fuel energy used for biodiesel production overcomes the energy available in the biodiesel delivered, which makes biofuels net releasers of greenhouse gases. Fossil fuels present much better energy return, between 10–15 and 1. Wind energy also presents very good energy returns, around 8–1 [8]. The lower net energy yield for biodiesel suggests that converting soy oil into a fuel may not be the most appropriate use for this product. The soybean biodiesel EROI calculated (2.48) easily translates into a Net-to-Gross Energy Ratio (NGER) of 0.60 (calculated: $NGER = 1 - 1/EROI$). This means that it is necessary to produce 1.68 l (calculated: 1/NGER) of biodiesel to deliver one liter of net biodiesel to the society, an important prerequisite if we foresee a biodiesel production process that is independent for fossil fuel inputs (a portion of biodiesel produced is feedback to support its production system). This would make demands upon production resources (e.g. land, materials, water) about 68% larger than those calculated in Table 2. Biodiesel production relies mainly on the large use of fossil fuels, especially in the soybean production phase (Fig. 2). Whether fossil fuels are used to enhance the productivity of

Table 4
Summary of matter, fossil energy and emergy indicators in soybean and biodiesel production.

Indicator	Soybean	Biodiesel	Unit[a]
Input			
Soil eroded	6.00	8.88	kg FU^{-1}
Oil equivalent demand	0.07	0.27	kg FU^{-1}
Gross fertilizers demand	0.139	0.206	kg FU^{-1}
Pesticides demand	0.003	0.004	kg FU^{-1}
Material intensity, abiotic factor	4.62	7.33	kg FU^{-1}
Material intensity, water factor	6060	8957	kg FU^{-1}
Material intensity, air factor	0.04	0.66	kg FU^{-1}
Total material input (including water)	6065	8975	kg FU^{-1}
Labor demand	0.005	0.01	hr FU^{-1}
Land demand	3.53	5.22	m^2 FU^{-1}
Output			
Total product	2.83E + 03	5.99E + 02	kg ha^{-1} yr^{-1}
Net energy yield	55181	11450	MJ ha^{-1} yr^{-1}
CO_2 released	0.238	0.864	kg CO_2 FU^{-1}
Industrial wastewater released	–	1.264	l FU^{-1}
Energy Output/Input	7.24	2.48	
Emergy indicators			
Transformity	1.01E + 05	3.90E + 05	seJ J^{-1}
Renewability	35.6%	30.7%	%
Emergy yield ratio	1.80	1.62	
Environmental loading ratio	1.81	2.26	

[a] Functional Unit (FU) for soybean is 1 kg and for biodiesel is 1 l.

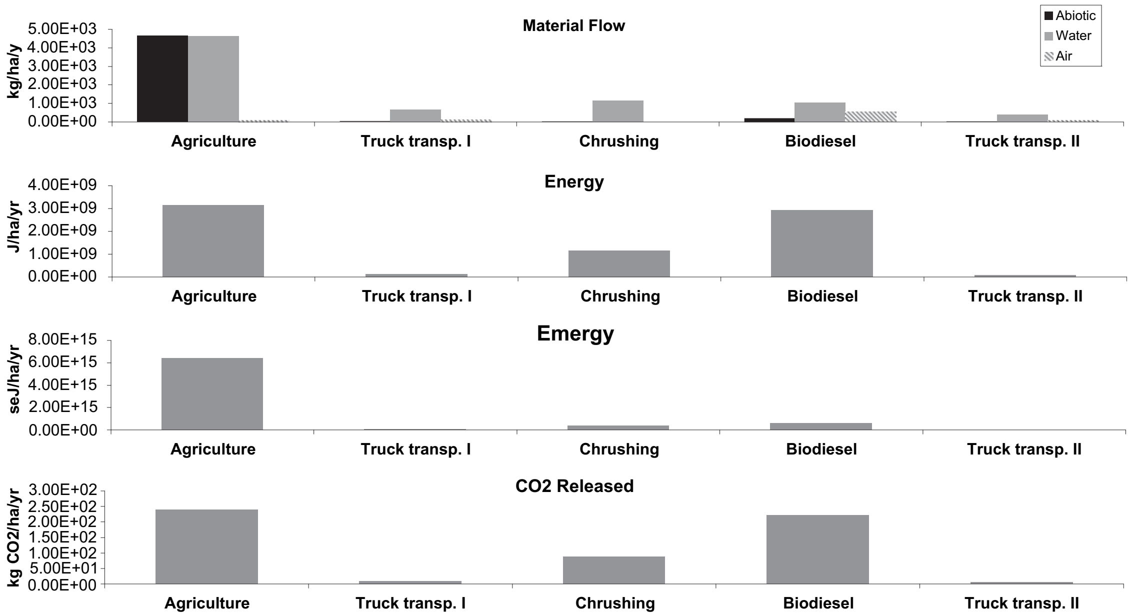

Fig. 2. Total demand of matter, embodied energy and emergy for the soybean biodiesel production phases.

the cropped area or a fraction of the biodiesel produced is reinvested, thus creating an amplification loop for land, water, and labor, we cannot escape the reality, that producing a high value, low entropy, vegetable oil requires a very large resource investment per unit, given the low efficiency of photosynthetic processes.

The Emergy method can properly account for and quantify the renewability of biodiesel since it includes not only inputs and services from the economy, but also resources from nature, usually not considered in conventional energy evaluations. Table 3 shows that renewable resources used in the agricultural phase account for only 30.7% of the total resources used by the biodiesel production processes. Rain is the main renewable input used. The great amount of non-renewable resources used by the production process indicates the strong dependency from economic resources and, therefore, its vulnerability to the input's market prices and to the availability of fossil fuels. The main non-renewable resources used from the economy are limestone (8.3%), topsoil loss by erosion (7.65%) and fertilizers (5.5%). Additional services that correspond to taxes and negative externalities produced by the production system accounted for 17.1% of the all resources used to produce biodiesel. The agricultural phase is responsible by the highest part of resources used (86.9%) flowed by the trans-esterification (7.9%) and the crushing (5.1%) phases.

The transformity of 1.01E+05 $seJ\,J^{-1}$ is calculated for soybean as such, in the field. Biodiesel is produced in the industrial phase, with a transformity of 3.90E+05 $seJ\,J^{-1}$. Transformities significantly

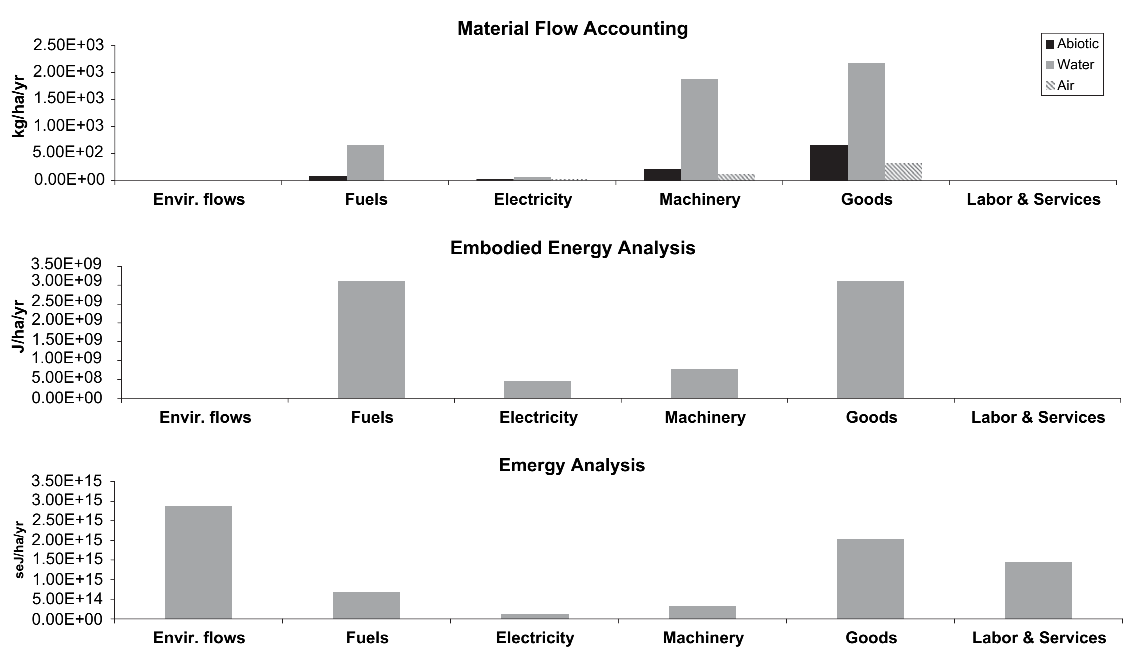

Fig. 3. Comparison of the relative importance of input flows according to the evaluation method applied.

increase from soybean to biodiesel due to the flows of emergy supporting the industrial steps. Emergy indicators presented in Table 3 show higher environmental loading of the whole biodiesel process compared to the agricultural step alone. Transformity can be used to compare different production systems generating the same product, helping to choose the better alternative. In order to compare the biodiesel transformity obtained in this work with the literature values it is necessary to exclude the contribution of additional services (taxes and negative externalities) because the transformities values selected from the literature were calculated without considering these inputs. Excluding additional services, the transformity of biodiesel from soybean calculated in this work is 3.18E+05 seJ J^{-1}. This value is higher than those obtained by Odum [15] for fossil fuels (coal: 6.70E+04 seJ J^{-1}; natural gas: 8.04E+04 seJ J^{-1}; oil: 9.05E+04 seJ J^{-1}; gasoline and diesel: 1.11E+05 seJ J^{-1}) and for other biofuels evaluated by Giampietro and Ulgiati [7] (Ethanol from sugarcane: 1.86E + 05–3.15E+05 seJ J^{-1}; Biodiesel from sunflower: 2.31E+05 seJ J^{-1}) and Bastianoni et al. [3] (Sunflower oil: 2.78E+05 seJ J^{-1}) indicating that soybean biodiesel presents larger demand for resources and therefore, a lower ability to convert resources into products than other energy sources considered in the literature. In summary, we might state that the natural processes producing fossil fuels have been globally more efficient than the human-driven process of soybean cropping for biodiesel.

From the point of view of renewability of resources, the non-renewable percentage of the emergy flow to the biodiesel production system is about 69%. This means that the biodiesel from soybean is less than one third renewable. However, such a result is still better than fossil fuels that are considered as totally non-renewable resources. The Environmental Loading Ratio shows that the non-renewable emergy is 2.26 times higher than renewable emergy for the soybean biodiesel. If we want to have a more sustainable process to produce biodiesel from vegetable oil, it is fundamental to find other procedures that allow increasing the system's renewability.

The emergy yield ratio (EYR) is a measure of the ability of the product to contribute with net emergy to the economic system by amplifying the resource investment. Biodiesel EYR is only 1.46, while it ranges from 3 to 7 for fossil fuels [15]. Therefore, based on these emergy accounting results, the investigated case of biodiesel from soybean does not easily compete with non-renewable energy resources. However, the biodiesel EYR can be increased by reducing the use of non-renewable resources by the system, mainly on the agricultural stage, which uses the major part of resources (Fig. 2). The usual soybean agricultural production methods in Brazil are characterized by intensive use of herbicides, fertilizers, agrochemicals, and agricultural machinery.

4. Conclusion

Results showed that in spite of a possible contribution to reduce the CO_2 emissions, soybean biodiesel is not a viable alternative taking into consideration materials, energy and emergy assessments performed in this study. The direct pollution (fertilizers, agrochemicals, pesticides) and other environmental impacts (soil loss, energy, material, water and land use) related to the net energy delivered to society as biodiesel indicate that soybean biodiesel produces a high pressure on the environment. The emergy accounting method showed quantitatively that biodiesel from soybean cannot be considered a totally renewable energy source. The soybean biodiesel production is strongly dependent on the use of non-renewable resources in the agricultural production, transport and industrial processing stages. When crop production and industrial conversion to fuel are supported by fossil fuels in the form of chemicals, goods, and process energy, the fraction of the fuel that is actually renewable is very low (around 30%). The biodiesel transformity is higher than those calculated for fossil fuels and for other biofuels indicating that biodiesel from soybean presents higher demand upon resources and therefore, a lower large-scale ability to convert resources into products than other energy sources selected from the literature.

The future of biodiesel is very likely to be linked to the ability of clustering biodiesel production with other agro industrial activities at an appropriate scale and mode of production to take advantage of the potential supply of valuable co-products. The agriculture production is the most important phase because it uses the largest amount of resources. Because of that the agricultural phase requires more attention from decision-makers for public policies toward a more sustainable soybean biodiesel production system. If the biodiesel production systems are not carefully designed according to a diversified small-scale perspective, the intensive exploitation of land and fossil fuel use for biodiesel production are more likely to generate environmental and social damages than to become a renewable energy source to society.

Acknowledgment

The authors wish to acknowledge the financial support of Capes. We are also grateful to Consuelo Pereira for the many ideas offered during the preparation of this paper.

Appendix 1. Footnotes for Tables 1–3.

	Agricultural phase			
1	Sun			
	Insolation	1.67E + 03	W-h/m2/yr	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi
	Albedo	15%		http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi
	Conversion	3.60E + 03	J/Wh	
	Insolation energy	5.10E + 06	J/m2/yr	
	Cropped area	1.00E + 04	m2/ha	
	Energy (J/yr) = (land area) (insolation)			
	Insolation energy	5.10E + 10	J/ha/yr	
2	Rain			
	Precipitation (Brazilian average 9 samples)	1.72E + 03	mm/yr or L/m2/yr	www.inmet.gov.br
	Cropped area	1.00E + 04	m2/ha	
	Density of water	1.00E + 00	kg/l	
	Mass of rain	1.72E + 07	kg/ha/yr	
	Fraction of water that is evapotranspired	6.20E − 01		www.inmet.gov.br
	Mass of rain evapotranspired	1.06E + 07	kg/ha/yr	

	Free energy of water = (Evapotranspired water)(Gibbs free energy of water)			
	Gibbs free energy of water	4.94E + 03	J/kg	[15]
	Energy of rain	5.25E + 10	J/ha/yr	
3	Deep heat			
	Heat flow through earth crust contributing to uplift replacing erosion.			
	Average heat flow per area	3.00E + 06	J/m2/yr	[15]
	Land area	1.00E + 04	m2/ha	
	Energy (J/yr) = (land area)(heat flow per area)	3.00E + 10	J/yr	
4	Nitrogen fixed from atmosphere			
	kg of N fixed from atmosphere	6.00E + 01	kg of N/ha/yr	
5	Soil loss			
	Soil loss (eroded)	1.70E + 04	kg/ha/yr	http://www.fea.unicamp.br/docentes/ortega/livro/C17-EAnaliseAl-JM.pdf
	Organic matter in topsoil used up = (total mass of topsoil) (% organic matter)			
	Ratio of the organic matter in the soil	4%		[15]
	Organic matter in topsoil used up	6.80E + 02	kg/ha/yr	
	Water content in organic matter	7.00E − 01		Average value
	Dry organic matter lost with erosion	2.04E + 02	kg/ha/yr	
	Energy content of dry organic matter	5.40E + 03	kcal/kg	Average value
	Energy = (kg/ha/yr) × (5400 kcal/kg) × (4186 J/kcal)			
	Energy loss	4.61E + 09	J/ha/yr	
6	Limestone			
	Mass of limestone used	3.75E + 02	kg/ha/yr	Estimated from field work
	Higher heating value	6.11E + 05	kg/ha/yr	[15]
	Total energy demand	2.29E + 08	J/ha/yr	
7	Herbicides			
	Mass of herbicides used	4.80E + 00	kg/ha/yr	From field work
8	Pesticides (includes pesticides and fungicides)			
	Mass of pesticides used	3.20E + 00	kg/ha/yr	From field work
9	Seeds			
	Mass of seeds used	6.90E + 01	kg/ha/yr	From field work
10	Nitrogen fertilizer			
	Total NPK fertilizer used	3.94E + 02	kg/ha/yr	From field work
	% N	0%		
	N = (Total fertilizer)(%N)(28 gmol N/132 gmol DAP)			
	Annual N consumption	0.00E + 00	kg N/ha	
11	Phosphate fertilizer			
	Total NPK fertilizer used	3.94E + 02	kg/ha/yr	From field work
	% P2O5	20%		
	P = (Total fertilizer)(%P2O5)(30 gmol P/70 gmol P2O5)			
	Annual P consumption	3.38E + 01	kg P/ha	
12	Potash fertilizer			
	Total NPK fertilizer used	3.94E + 02	kg/ha/yr	From field work
	% K2O	20%		
	K = (Total fertilizer)(%K2O)(78 gmol K/94 gmol K2O)			
	Annual K consumption	6.54E + 01	kg K/ha	
13	Fuels (includes diesel. gasoline. lubricants)			
	Volume used for farm machinery	6.50E + 01	l/ha/yr	[27]
	Density of diesel	8.40E − 01	kg/l	
	Mass used for farm machinery	5.46E + 01	kg/ha/yr	
	Higher heating value	4.45E + 07	J/kg	[8]
	Total energy demand	2.43E + 09	J/ha/yr	
14	Electricity			
	Electricity used general	3.40E + 01	kWh/ha/yr	From field work
	Conversion	3.60E + 06	J/kWh	
	Total energy demand	1.22E + 08	J/ha/yr	
15	Steel (assuming 10 year life spam)			
	Steel for agricultural machinery	2.50E + 01	kg/ha/yr	Average value
16	Farm buildings			
	Buildings area	9.00E − 02	m2/hr/yr	[20]
	Cost per m2	5.26E + 02	USD/m2	From field work
	Buildings cost	4.74E + 01	USD/ha/yr	
17	Local labor			
	Total applied labor	1.00E + 01	h/ha/yr	From field work
	working days per year (8 h/day)	1.25E + 00	day/ha/yr	
	working years (240 work yrs/year)	5.21E − 03	year/ha/yr	
	Labor cost	9.41E − 01	USD/h	From field work

	Total labor cost	9.41E + 00	USD/ha/yr	
18	Extra labor			
	Total applied labor	5.00E + 00	h/ha/yr	From field work
	working days per year (8 h/day)	6.25E − 01	day/ha/yr	
	working years (240 work yrs/year)	2.60E − 03	year/ha/yr	
	Labor cost	9.41E − 01	USD/h	From field work
	Total labor cost	4.70E + 00	USD/ha/yr	
19	Additional services			
	Externalities	345	USD/ha/yr	[23]
20	Production cost and annual services			
	Cost of production per hectare	498	USD/ha/yr	Average value
	Cost of production per ton	175	USD/ton	
	Taxes (2.3% of sells)	15	USD/ha/yr	
21	Agricultural phase output			
	Average soybean production	2.83E + 03	kg/ha/a	Average value
	Fraction moisture in soybean. at harvest time	1.20E − 01		FAO http://www.fao.org/es/ess/tcf.asp
	Higher heating value of residues	2.26E + 07	J/kg	Our previous calculations
	Total energy	6.40E + 10	J/ha/a	
	Average soybean market price	23.05	USD/kg	Average value from: Agromensal – ESALQ/BM&F (http://www.cepea.esalq.usp.br/agromensal/2003/06_junho/soja.htm#_II_-_Séries
	Gross income per ha	652.78	USD/ha/yr	
	Total residues in field	4.25E + 03	kg/ha/a	From field work
	Fraction moisture in residues. at harvest time	6.00E − 01		Our previous calculations
	Residues dry matter	1.70E + 03	kg/ha/yr d.m.	
	Higher heating value of residues	1.85E + 07	J/kg d.m.	
	Gross energy content of wet residues	3.14E + 10	J/yr	
Truck transport from farm to industry				
22	Steel for transport in heavy truck			
	Average soybean production	2.83E + 03	kg/ha/yr	
	Average loading of the heavy truck	2.00E + 04	kg/trip	From field work
	Number of trips	1.42E − 01	trip/ha/yr	
	Distance per trip (round way)	3.00E + 02	km/trip	Two times average distance estimated from [27]
	Total km allocated to transport	4.25E + 01	km/ha/yr	
	Average km run by the truck in its life	3.00E + 05	km/truck	Our assumption
	Fraction this transport is of total truck km	1.42E − 04	truck/ha/yr	
	Weight of an average truck	1.40E + 04	kg	Considering a loading factor of 70% from [27]
	Fraction of truck allocated to 1 ha of soybean	1.98E + 00	kg/ha/yr	
	Embodied energy machinery	8.00E + 07	J/kg mach.	[20]
	Total energy demand	1.59E + 08	J/ha/yr	
23	Fuel			
	Distance per trip (round way)	3.00E + 02	km/trip	Estimated from [27]
	Diesel demand per km	1.00E − 01	kg/km	[28]
	Mass of diesel oil used	3.00E + 01	kg/trip	
	Energy used per ton km	1.57E + 00	MJ/ton km	
	Higher Heating Value of diesel	4.45E + 07	J/kg	[8]
	Energy demand per trip	1.33E + 09	J/trip	
	Number of trips	1.42E − 01	trip/ha/yr	
	Mass of diesel oil used	4.25E + 00	kg/ha/yr	
	Total energy demand	1.89E + 08	J/ha/yr	
24	Labor			
	Labor per trip	7.00E + 00	h/trip	From field work
	Number of trips	1.42E − 01	trip/ha/yr	
	Total labor applied	9.91E − 01	h/ha/yr	
	Working days per year (8 h/day)	1.24E − 01	day/ha/yr	
	Working years (240 work yrs/year)	5.16E − 04	year/ha/yr	
	Labor cost	672	USD/h	Estimated from field work (Personal communication)
	Total labor cost	666	USD/ha/yr	
25	Production cost and annual services			
	Cost of the truck	86000	USD/truck	Estimated from field work (Personal communication)
	Fraction this transport is of total truck km	1.42E − 04	truck/ha/yr	See above
	Cost of truck allocated to this transport	12.2	USD/ha/yr	
	Mass of diesel oil used	3.00E + 01	kg/trip	
	Density	8.40E − 01	kg/l	See above
	Number of trips	1.42E − 01	trip/ha/yr	
	Diesel price	0.79	USD/l	From field work
	Total diesel cost	4.00	USD/ha/yr	
	Fees	10.00	USD/trip	From field work

	Number of trips	1.42E − 01	trip/ha/yr	
	Total fees cost	1.42	USD/ha/yr	
	Labor	6.66	USD/ha/yr	From field work
	Total transport cost per ha	24.25	USD/ha/yr	
	Taxes (35% of labor cost)	2.33	USD/ha/yr	
26	Products and by-products of transport phase			
	Soybean transported	2.83E + 03	kg	See above
Crushing process phase				
27	Steel for plant machinery			
	Mass allocated per kg soybean processed per year	1.00E − 04	kg/kg	[29]
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total allocated per year	2.84E − 01	kg/ha/yr	
28	Cement in plant construction			
	Constructed area	3.00E + 03	m2	[29]
	Perimeter of the constructed area	2.19E + 02	m	
	Height of the wall	3.00E + 00	m	Our assumption
	Walls area	6.57E + 02	m2	
	Total constructed area = (Floor area) + (Walls area)			
	Total constructed area	3.66E + 03	m2	
	Mean thickness of cement	2.00E − 01	m	Our assumption
	Volume of cement	7.31E + 02	m3	
	Density of cement	2.40E + 03	kg/m3	(McGraw-Hill Encyclopedia of Science and Technology) http://hypertextbook.com/facts/1999/KatrinaJones.shtml
	Mass of cement	1.76E + 06	kg	
	Life spam	3.00E + 01	years	
	Mass of cement per year	5.85E + 04	kg/yr	
	Annual soybean processing capacity of the plant	6.00E + 08	kg	
	Total cement allocated per kg soybean	9.74E − 05	kg/kg	
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total allocated per year	2.76E − 01	kg/ha/yr	
29	Iron in plant construction			
	Iron reinforcement in concrete (floor and wall)	3.50E + 01	kg/m3	[30]
	Volume of cement	7.31E + 02	m3	See above
	Mass of iron in floor and wall	2.56E + 04	kg	
	Iron sheet in roof. 1.25 mm thick	1.00E + 01	kg/m2	[30]
	Roof area	3.00E + 03	m2	
	Mass of iron in roof	3.00E + 04	kg	
	Total mass of iron	5.56E + 04	kg	
	Life spam	3.00E + 01	years	
	Mass of iron per year	1.85E + 03	kg/yr	
	Annual soybean processing capacity of the plant	6.00E + 08	kg	
	Total iron allocated per kg soybean	3.09E − 06	kg/kg	
	Average soybean production	3.66E + 03	kg/ha/yr	
	Total allocated per year	1.13E − 02	kg/ha/yr	
30	Fuel			
	Total diesel needed per kg soybean	1.79E − 02	kg/kg	[29]
	Average soybean production	2.83E + 03	kg/ha/yr	
	Mass of diesel used	5.07E + 01	kg/ha/yr	
	Higher Heating Value of diesel	4.45E + 07	J/kg	[8]
	Total per ha per year	2.25E + 09	J/ha/yr	
31	Electricity			
	Energy used per kg of soybean	2.99E − 02	kWh/kg	[29]
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total per ha per year	8.47E + 01	kWh/ha/yr	
	Conversion	3.60E + 06	J/kWh	
	Total energy demand	3.05E + 08	J/ha/yr	
32	Water			
	Water demand per kg of soybean	7.19E − 04	m3/kg	[29]
	Conversion	1.00E + 03	kg/m3	
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total water demand	2.04E + 03	kg/ha/yr	
	Free energy of water = (Evapotranspired water)(Gibbs free energy of water)			
	Gibbs free energy of water	4.94E + 03	J/kg	
	Energy of water	1.01E + 07	J/ha/yr	
33	Hexane			
	Hexane demand per ton of soybean	1.20E − 03	kg/kg	[29]
	Hexane demand per kg of soybean	1.20E + 00	kg/ton	
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total per ha per year	3.40E + 00	kg/ha/yr	
	Higher Heating Value of hexane	4.48E + 07	J/kg	http://www.chrismanual.com/H/HXA.pdf#search = %22hexane%20j%2Fkg%22
	Total energy demand	1.52E + 08	J/ha/yr	

34	Labor			
	Total applied labor per kg of soybean	2.01E − 04	h/kg	[29]
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total per ha per year	5.70E − 01	h/ha/yr	
	working days per year (8 h/day)	7.13E − 02	day/ha/yr	
	working years (240 work day/year)	2.97E − 04	year/ha/yr	
35	Production cost and annual services			
	Buildings and equipments per kg of soy	0.06	USD/kg	[29]
	Average life spam	3.00E + 01	years	
	Buildings and equipments	0.002	USD/kg	
	Operation costs per kg of soy	0.014	USD/kg	[29]
	Labor cost	0.003	USD/kg	[29]
	Total cost	0.016	USD/kg	
	Average soybean production	2.83E + 03	kg/ha/yr	
	Total per ha per year	46.5	USD/ha/yr	
	Taxes (35% of labor cost)	2.97	USD/ha/yr	
36	Crushing phase output			
	Average soybean production	2.83E + 03	kg/ha/yr	
	Fraction of meal (+hulls)	81.30%		FAO http://www.fao.org/es/ess/tcf.asp
	Mass of meal	2.30E + 03	kg/ha/yr	
	Higher Heating Value of soy flour	1.55E + 07	J/kg	[31]
	Total energy	3.58E + 10	J/ha/yr	
	Fraction of oil	18.00%		FAO (16–20%) http://www.fao.org/es/ess/tcf.asp
	Mass of oil	5.10E + 02	kg/ha/yr	
	Higher Heating Value of soy oil	3.96E + 07	J/kg	[31]
	Total energy	2.02E + 10	J/ha/yr	
	Fraction of lecithin gross	0.70%		FAO http://www.fao.org/es/ess/tcf.asp
	Mass of lecithin gross	1.98E + 01	kg/ha/yr	
	Higher Heating Value of lecithin	3.96E + 07	J/kg	Estimated from [31]
	Total energy	7.85E + 08	J/ha/yr	
Biodiesel conversion				
37	Steel for plant machinery			
	Total steel allocated per kg soy oil per year	2.30E − 03	kg/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total allocated per year	1.17E + 00	kg/ha/yr	
38	Cement in plant construction			
	Constructed area	4.18E + 02	m2	[32]
	Perimeter of the constructed area	8.18E + 01	m	
	Height of the wall	1.22E + 01	m	Our assumption
	Walls area	9.97E + 02	m2	
	Total constructed area = (Floor area) + (Walls area)			
	Total constructed area	1.42E + 03	m2	
	Mean thickness of cement	2.00E − 01	m	Our assumption
	Volume of cement	2.83E + 02	m3	
	Density of cement	2.40E + 03	kg/m3	(McGraw-Hill Encyclopedia of Science and Technology) http://hypertextbook.com/facts/1999/KatrinaJones.shtml
	Mass of cement	6.79E + 05	kg	
	Life spam	3.00E + 01	years	
	Mass of cement per year	2.26E + 04	kg/yr	
	Soy oil capacity of the biodiesel plant	3.40E + 07	kg/yr	
	Total cement allocated per kg soy oil	6.66E − 04	kg/kg oil	
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total allocated per year	3.39E − 01	kg/ha/yr	
39	Iron in plant construction			
	Iron reinforcement in concrete (floor and wall)	3.50E + 01	kg/m3	[30]
	Volume of cement	2.83E + 02	m3	(See above)
	Mass of iron in floor and wall	9.91E + 03	kg	
	Iron sheet in roof. 1.25 mm thick	1.00E + 01	kg/m2	[30]
	Roof area	4.18E + 02	m2	
	Mass of iron in roof	4.18E + 03	kg	
	Total mass of iron	1.41E + 04	kg	
	Life spam	3.00E + 01	yr	
	Mass of iron per year	4.70E + 02	kg/yr	
	Soy oil capacity of the biodiesel plant	3.40E + 07	kg/yr	
	Total iron allocated per kg soy oil	1.38E − 05	kg/kg of oil	
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total allocated per year	7.04E − 03	kg/ha/yr	
40	Fuel			
	Total diesel needed per kg soy oil processed	5.37E − 02	kg/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Mass of diesel used	2.74E + 01	kg/ha/yr	
	Higher Heating Value of diesel	4.45E + 07	J/kg	[8]
	Total allocated per year	1.22E + 09	J/ha/yr	
41	Methanol			

	Methanol demand per kg of soy oil	1.87E − 01	l/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Methanol demand	9.54E + 01	l/ha/yr	
	Methanol density	7.90E − 01	kg/l	(http://www.autoindustry.co.uk/articles/01-06-06)
	Methanol mass	7.53E + 01	kg/ha/yr	
	Higher Heating Value of methanol	1.60E + 07	J/l	(http://www.autoindustry.co.uk/articles/01-06-06)
	Energy content	1.53E + 09	J/ha/yr	
42	Catalyst			
	Catalyst demand per kg of soy oil	1.07E − 02	kg/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total catalyst demand	5.44E + 00	kg/ha/yr	
43	Electricity			
	Energy used per kg of soy oil	8.82E − 04	kWh/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total per ha per year	4.50E − 01	kWh/ha/yr	
	Conversion	3.60E + 06	J/kWh	
	Total energy demand	1.62E + 06	J/ha/yr	
44	Water			
	Water demand per kg of soy oil	5.11E − 01	m3/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total water demand	2.60E + 02	kg/ha/yr	
	Free energy of water = (Evapotranspired water)(Gibbs free energy of water)			
	Gibbs free energy of water	4.94E + 03	J/kg	
	Energy of water	1.29E + 06	J/ha/yr	
45	Labor			
	Total applied labor per kg of soy oil	6.77E − 04	h/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total allocated per ha per yr	3.45E − 01	h/ha/yr	
	working days per year (8 h/day)	4.32E − 02	day/ha/yr	
	working years (240 work day/year)	1.80E − 04	year/ha/yr	
46	Production cost and annual services			
	Total cost per kg of soy oil	0.053	USD/kg oil	[32]
	Soy oil processed	5.10E + 02	kg/ha/yr	
	Total allocated per ha per yr	27.00	USD/ha/yr	
	Taxes (ICMS 16%)	4.32	USD/ha/yr	
47	Biodiesel process output			
	Soy oil processed	5.10E + 02	kg oil/ha/yr	
	Biodiesel volume produced	6.81E + 02	L/ha/yr	[32]
	Biodiesel density	8.80E − 01	kg/L	http://www.autoindustry.co.uk/articles/01-06-06
	Biodiesel mass	5.99E + 02	kg/ha/yr	
	Higher Heating Value of biodiesel	3.20E + 07	J/kg	http://www.autoindustry.co.uk/articles/01-06-06
	Total energy	1.92E + 10	J/ha/yr	
	Mass fraction	90.5%		
	Glycerin	4.42E + 01	kg/ha/yr	[32]
	Higher Heating Value of glycerin		J/kg	[31]
	Total energy	0.00E + 00	J/ha/yr	
	Mass fraction	5.9%		
	Soap stock	2.72E + 01	kg/ha/yr	[32]
	Higher Heating Value of soap stock		J/kg	[31]
	Total energy	0.00E + 00	J/ha/yr	
	Mass fraction	3.6%		
Biodiesel transport				
48	Steel for transport in heavy truck			
	Average soy oil production	5.99E + 02	kg/ha/yr	
	Average loading of the heavy truck	2.00E + 04	kg/trip	Our estimative from field work
	Number of trips	3.00E − 02	trip/ha/yr	
	Distance per trip (round way)	3.00E + 02	km/trip	Two times average distance estimated from field work
	Total km allocated to transport	8.99E + 00	km/ha/yr	
	Average km run by the truck in its life	3.00E + 05	km/truck	Our estimative from field work
	Fraction this transport is of total truck km	3.00E − 05	truck/ha/yr	
	Weight of an average truck	1.40E + 04	kg	Considering a loading factor of 70% from [27]
	Fraction of truck allocated to 1 ha of soybean	4.20E − 01	kg/ha/yr	
	Embodied energy machinery	8.00E + 07	J/kg mach.	[20]
	Total energy demand	3.36E + 07	J/ha/yr	
49	Fuel			
	Distance per trip (round way)	3.00E + 02	km/trip	Estimated from [27]
	Diesel demand per km	1.00E − 01	kg/km	[27]
	Mass of diesel oil used	3.00E + 01	kg/trip	
	Energy used per ton km	7.42E + 00	MJ/ton km	
	Higher Heating Value of diesel	4.45E + 07	J/kg	[8]
	Energy demand per trip	1.33E + 09	J/trip	
	Number of trips	3.00E − 02	trip/ha/yr	

	Mass of diesel oil used	8.99E − 01	kg/ha/yr	
	Total energy demand	4.00E + 07	J/ha/yr	
50	Labor			
	Labor per trip	7.00E + 00	h/trip	Our estimative from field work
	Number of trips	3.00E − 02	trip/ha/yr	
	Total labor applied	2.10E − 01	h/ha/yr	
	Working days per year (8 h/day)	2.62E − 02	day/ha/yr	
	Working years (240 work yrs/year)	1.09E − 04	year/ha/yr	
	Labor cost	6.72	USD/h	Estimated from field work
	Total labor cost	1.41	USD/ha/yr	
51	Production cost and annual services			
	Cost of the truck	86000	USD/truck	Estimated from field work
	Fraction this transport is of total truck km	3.00E − 05	truck/ha/yr	
	Cost of truck allocated to this transport	2.58	USD/ha/yr	
	Mass of diesel oil used	3.00E + 01	kg/trip	
	Density	8.40E − 01	kg/l	See above
	Number of trips	3.00E − 02	trip/ha/yr	
	Diesel price	0.79	USD/l	Estimated from field work
	Total diesel cost	0.85	USD/ha/yr	
	Fees	1000	USD/trip	Our estimative from field work
	Number of trips	3.00E − 02	trip/ha/yr	
	Total fees cost	0.30	USD/ha/yr	
	Labor	1.41	USD/ha/yr	
	Total transport cost per ha	5.13	USD/ha/yr	
	Taxes (35% of labor cost)	0.49	USD/ha/yr	
52	Products and by-products of transport phase			
	Biodiesel transported	5.99E + 02	kg	See above
		1.92E + 10	J	

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