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Assessing the sustainability of Brazilian oleaginous crops – possible raw material to produce biodiesel

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ABSTRACT

The aim of this paper is to make an emergy assessment of oleaginous crops cultivated in Brazil, available to produce biodiesel, in order to determine which crop is the most sustainable. This study evaluates conventional agro-chemical farms that produce rapeseed (canola), oil palm, soybean, sunflower and cotton. Rapeseed (canola) crop uses 40.41% of renewable energy and it is the most sustainable conventional oil crop; on the other hand, it is not widely produced in Brazil, probably due to climate restrictions or low market demand. The oil palm emergy indicators are contradictory: its emergy exchange ratio (EER) value is the lower, showing the possibility of fair exchange, and the low transformity value indicates high efficiency; however, it also has low renewability (28.31%), indicating a high dependency on agro-chemicals (basically fertilizers). Oil palm is a potential energy source due to its high agricultural productivity, but appropriate management is necessary to increase its sustainability and reduce the use of non-renewable resources.

1. Introduction

This paper reports part of a vast work on assessing the sustainability of Brazilian agricultural systems using the emergy methodology (Ortega et al., 2005; Takahashi et al., 2008). The subsystem studied in this paper is "Oleaginous crops", and was chosen mainly to contribute to the discussions about the sustainability of biofuels.

World-wide oil production from crops is estimated to be 144.8 million tonnes and Brazil is responsible for 8% of this amount (FAO, 2009). Only six oil crops are responsible for 90% of the vegetable oil used in the world: oil palm, soybean, rapeseed, sunflowers, peanuts and cotton in order of volume of oil production. Oil plants and the chemical products derived from them are an alternative to petroleum stocks (Carlsson, 2009). There are many debates about the consequences of the use of biofuels in particular regarding the impacts on climate, the emission of CO_2 and NO_x (Reijnders, 2006). The analysis of exhaust emission from the combustion of rapeseed biodiesel when compared with diesel showed that he use of biodiesel reduces emissions of CO_2 emissions but also increase of NO_x emissions (Krahl et al., 2009).

The projected rise of biofuels demand for transportation is expected to cause a significant increase in vegetable oils production. In Brazil, this increase in demand is projected to be of 260% by 2030, and worldwide it is of 900% in the same time span (Escobar et al., 2009).

Brazil is already a potential producer of biofuels, especially ethanol and biodiesel. The National Program for Production and Use of Biodiesel (PNBP) was launched in December 2004. Besides the economic objective of fostering biodiesel production, a major social objective was the regional development via promotion of small family agricultural units. The PNPB provided research incentives for projects associated with biodiesel and stimulated the market demand for biodiesel in the Brazilian energy matrix. Biodiesel is defined by PNPB as a "biofuel derived from renewable biomass for use in engines of internal combustion with ignition by compression or for generation of another type of energy that can partially or totally substitute fossil fuels" (Pousa et al., 2007).

Are oilseed crops for biodiesel renewable? In order to answer this question and verify the environmental impact caused by biodiesel production, various methodologies and indicators have been used, such as ecological footprint (Stoeglehner and Narodoslawsky, 2007), exergy analysis (Talens et al., 2007), carbon footprint (Holzman, 2008), emergy analysis (Ortega et al., 2005; Cavalett and Ortega, 2009; Comar et al., 2004) and life cycle assessment (LCA) (Yee et al., 2009).

LCA in agriculture focuses primarily on the environmental impact of emissions and non-renewable energy inputs in the product's life cycle, from the extraction of the natural resource to the use and disposal of the product. LCA does not include ecosystem services and products, and the final results of this analysis depend on subjective evaluation. For this reasons, Ulgiati

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et al. (2007) proposed the integration among methods that may be potentially complementary like LCA and energy evaluation (Pizzigallo et al., 2008).

Emergy methodology is able to evaluate environmental and economic products and services in a common basis called ‘‘solar emergy’’ (Scienceman, 1987) and it has already been applied to several agricultural systems to compare management and scale (see for example Martin et al., 2006; La Rosa et al., 2008; Bastianoni and Marchettini, 1996).

The aim of this paper is to evaluate the main oleaginous crops cultivated in Brazil using the emergy methodology to verify the sustainability of the possible raw materials used to produce biodiesel and thus determine which crop is the most sustainable for biofuel production. This is a very important task since raw materials contribute a major portion to the cost of biodiesel production (Sharma and Singh, 2009), and the choice of raw materials and the agricultural practices used have a great influence on the ecological impacts (Stoeglehner and Narodoslawsky, 2009).

1.1. Characterization of the oleaginous crops evaluated

Oleaginous plants are vegetable oil-producing plants, which have a wide range of chemical compositions. The crops evaluated in this study are cotton seed, soybean, canola, sunflower and oil palm. Among this group, cottonseed oil is the only non-edible oil. It is important to distinguish these types of oils because edible oils intended for food cannot be processed in the same industrial processing facilities as non-edible oils. Table 1 shows the main characteristics of the oleaginous plants assessed in this study.

The palm oil is the most produced oil in the world. Oil palm (*Elaeis guineesis*) is believed to be indigenous to West Africa, but today more than 80% comes from Southeast Asia, mainly Indonesia and Malaysia. Soybean oil is the second most produced oil in the world and Brazil is the second largest soybean producer (27%), just behind the US (33%) (FAO, 2009).

Rapeseed (*Brassica napus*) is the third largest oil crop with 12% of the world’s plant oil market; more than 60% is produced by Europe and China. The most popular type of rapeseed cultivated today is Canola. Sunflower oil accounts for approximately 9% of the world’s vegetable oil production; the main producers are Russia (20%) and Europe (19%) (Carlsson, 2009). Cotton (*Gossypium hirsutum*) produces non-edible oil, and the main producers are China (27%) and Australia (17%) (FAO, 2009). Table 2 shows the production of vegetable oil in Brazil.

1.2. Biodiesel

Biodiesel is a biofuel produced from vegetable oils, animal fats and even recycled cooking oil and is defined by PNPB as a ‘‘biofuel derived from renewable biomass for use in engines of internal combustion with ignition by compression or for generation of another type of energy that can partially or totally substitute fossil fuels’’ (Pousa et al., 2007).

PNPB stimulated the market demand for biodiesel in the Brazilian energy matrix encouraging the optional use of B2 (a diesel fuel with 2% biodiesel) until the beginning of 2008. Between 2008 and 2013, blends with up to 5% biodiesel can be used, and after this period, B5 will be mandatory. Since July 2008, Brazil has adopted blend B3, and it is forecasted to switch to the blend B4 by mid-2009 (ANP, 2009)

The world-wide production of biodiesel increased by 200% from 1995 to 2006, and the European Union was responsible for 75% of the global production of biodiesel in 2006 (Demirbas et al., 2009). The major producers of biodiesel and its main raw materials are shown in Table 3.

Brazil has a total of 65 industrial units of biodiesel producers with an annual capacity of 3.8 billion liters (ANP, 2009). The production of biodiesel in Brazil has grown rapidly in recent years, as shown in Fig. 1.

From 2004 to 2008, Brazilian biodiesel production increased from 404 million liters to 1.16 billion liters. In 2008, Brazilian diesel consumption amounted 44.6 billion liters, which represented a demand of 1.13 billion liters of biodiesel for the production of blend B2 (mandatory until June) and B3 (mandatory in July) (ANP, 2009). It is expected that the Brazilian government will make blend B4 mandatory by mid-2009 (Nachiluk and Freitas, 2009).

2. Materials and method

2.1. Emergy synthesis

The fundamentals of emergy synthesis can be found in the book Environmental Accounting (Odum, 1996). Emergy is defined as the sum of all inputs of energy directly or indirectly required in the process of producing a given product and is expressed in solar equivalent joules (seJ) (Odum, 1988; Scienceman, 1987). Emergy analysis considers inputs from nature (e.g., sun, rain, wind, soil nutrients) and from the economy (e.g., goods, services, machinery, fossil fuels). It is a powerful tool that can measure the real wealth of the work of nature and society and assess public policies aimed at sustainability and fair trade (Odum, 1996; Brandt-Williams, 2002; Ulgiati and Brown, 1998). Many published works related to agriculture and emergy analysis use this methodology to compare systems for different types of agricultural production and management and thus evaluate which is the most sustainable

Table 2
Vegetable oil production in Brazil in 2007 (FAO, 2009).

Vegetable oil	Production (tonnes)
Soybean oil	5,430,000
Cottonseed oil	242,000
Palm oil	190,000
Maize oil	75,000
Palm kernel oil	75,000
Sunflower oil	33,700
Rapeseed oil	30,000

Table 1
Characteristics of the oleaginous plants assessed in this study (Lora and Andrade, 2009).

Species	Origin of the oil	Content of oil (%)	Maximum efficiency cycle	Harvesting months	Oil yield (kg/ha)
Oil palm or ‘‘Dendê’’ (*Elacis guineensis*)	Nut	20	8 years	12	3000–6000
Sunflower (*Helianthus annus*)	Seed	38–48	Annual	3	500–1900
Canola (*Brassica campestris*)	Seed	40–48	Annual	3	500–900
Soy beans (*Glycine max*)	Seed	17	Annual	3	200–400
Cotton (*Gossypium hirsute*)	Seed	15	Annual	3	100–200

(Ortega et al., 2005; Martin et al., 2006; La Rosa et al., 2008).

The first step in an emergy diagnosis is to construct the diagrams that identify all inputs, outputs, components and their relationships. Fig. 2 shows a general diagram of the agricultural systems studied in this paper.

The next step is to evaluate the inputs and outputs of the system. Every energy inputs must be multiplied by a conversion factor (transformity) so that they can be expressed in solar equivalent joules. Transformity is defined as the emergy input per unit of available energy (exergy) output. For example, if 4000 seJ are required to generate a joule of wood, then the solar transformity of that wood is 4000 seJ per joule (or seJ/J) (Brown and Ulgiati, 2004b). The flows of emergy can then be aggregated according to their origin, as shown in Table 4, by considering the renewability fraction of each material and service (Ortega et al., 2005, 2002; Ulgiati et al., 1994; Agostinho et al., 2008).

Table 3
Main biodiesel producers in 2006 (Escobar et al., 2009; Demirbas et al., 2009).

Country	Production (billion liters)	Share of total production (%)	Raw material
Germany	2.80	46.70	Rapeseed
USA	0.85	14.20	Rapeseed
France	0.63	10.50	Soybean
Italy	0.57	9.50	Rapeseed
Brazil	0.07	1.17	Soybean

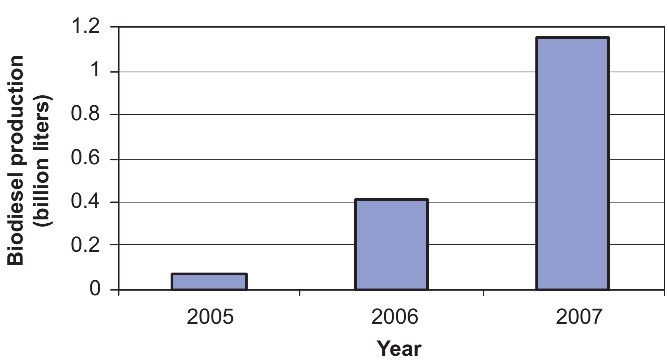

Fig. 1. Biodiesel production of Brazil (ANP, 2009).

The renewability fraction is very important to be considered because a fraction of the energy from some materials and services can be considered as renewable, such as seedlings, seeds and labor. The final stage includes a calculation of the emergy indices, as shown in Table 5.

2.2. Data collection for the emergy analysis

The data for emergy evaluation were obtained from AGRIANUAL (Agrianual, 2006), which is an important publication that provides data of the productivity and profitability of agricultural products in Brazil. Each crop has a different data set for different regions, management strategies and productivity levels. The emergy evaluation shown in this study considered the average of inputs for each crop, For canola, the average inputs of 3 canola systems were considered and for palm oil, soybean sunflowers and cotton, 1, 26, 4 and 15 systems, respectively, were considered.

3. Results and discussion

Tables 6–10 show the emergy table for cotton, soybean, canola, sunflower and oil palm, respectively.

Table 4
Emergy-aggregated flows.

Classification of inputs	Equation/ symbol	Description
Renewable resources from nature	R	Sun, rain, wind
Non-renewable resources from nature	N	Soil, biodiversity, people exclusion
Resources from nature	$I=R+N$	
Materials	$M=M_R+M_N$	
Renewable materials	M_R	Seeds, wood
Non-renewable materials	M_N	Fuels, chemicals
Services	$S=S_R+S_N$	
Renewable services	S_R	Manpower supported by renewable sources
Non-renewable services	S_N	Services such as external services, taxes, insurance
Feedback from economy	$F=M+S$	
Total emergy	$Y=I+F$	

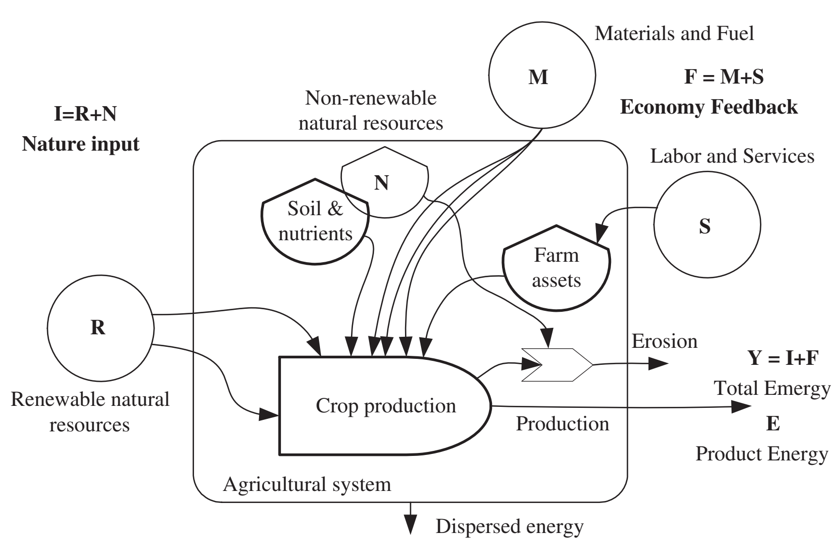

Fig. 2. General emergy diagram of an agricultural system (Based on Odum, 1996)

Table 6 shows the emergy table for cotton and the non-renewable resources that most impact the system are the limestone (11.81%) and soil loss (19.95%). These two non-renewable resources also have the most impact to the soybean system as shown in Table 7.

Table 8 shows the emergy table for canola and the non-renewable resources that most impact the system are the NPK fertilizer (15.30%) and soil loss (23.39%). The non-renewable resource that most impact the oil palm system is NPK fertilizer, which represents more than 39% of non-renewable emergy used by the system as shown in Table 9.

Table 10 shows the emergy table for sunflower and the non-renewable resources that most impact the system are the NPK fertilizer (12.60%) and soil loss (34.54%).

Table 5
Emergy indicators.

Indicator	Expression	Concept
Total emergy (Y)	$Y=I+F$	Total emergy
Energy of product (E)	E=caloric value of product	Energy
Transformity (Tr)	$Tr=Y/E$	Total emergy/energy
Renewability (%R)	$\%R=100\times(R+M_R+S_R)/Y$	Renewable inputs/total emergy
Emergy yield ratio (EYR)	$EYR=Y/(M_N+S_N)$	Total emergy/non-renewable from economy
Emergy investment ratio (EIR)	$EIR=(M_N+S_N)/(R+M_R+S_R+N)$	Non-renewable from economy/ renewable+non-renewable from nature
Environmental loading ratio (ELR)	$ELR=(M_N+S_N+N)/(R+M_R+S_R)$	Non-renewable/renewable
Emergy exchange ratio (EER)	$EER=Y/[(\$)\times(seJ/\$)]$	Total emergy/emergy received from the buyer
Renewable mobilization	$Benefit=R/F$	Renewable/feedback

3.1. Emergy analysis results for the crops investigated

The aggregated emergy flow and output data are shown in Table 11.

Fig. 3 shows the proportion of aggregated emergy used in each crop. It is notable that the emergy from materials increase with the productivity of the crop. In other words, the use of more emergy from materials (especially fertilizer) makes the productivity of crops increase but the proportion of renewable resources used decrease.

Oil palm is a special case due to the low net topsoil loss but the use of emergy from economy and services are high when compared with canola, sunflower and soybean. Fig. 4 shows the proportion of emergy from fertilizers compared with the total material emergy. Oil palm and cotton had worse emergy indices mainly due to the high use of chemicals.

The emergy indices of studied systems are shown in Table 12.

The transformity measures the efficiency of the system, in other words, how much of the emergy used is converted into net energy. The most efficient crops from high to low efficiency are oil palm, canola, sunflower, soybean and cotton. The high efficiency of oil palm was expected due to its high productivity (16800 kg/ha year).

Table 6
Emergy evaluation of cotton crop in Brazil (emergy flows in E+12 seJ/ha/year)

Code	Item	Renew. fraction	Unit	Quantity (unit/ ha year)	Transfomity (seJ/unit)	Renewable emergy flow	Non-renewable emergy flow	Total emergy flow	%
R1	Sun	1	J	1.51E+11	1	0.15	0.00	0.15	0.00
R3	Rain	1	J	7.05E+10	3.10E+04	2185.50	0.00	2185.50	15.68
N1	Soil loss	0	kg	24800.00	1.24E+05	0.00	2779.98	2779.98	19.95
M1	Seeds	0.2[a]	kg	18.78	1.68E+12	6.31	25.24	31.55	0.23
M2	Transgenic seeds	0	kg	7.48	1.68E+13	0.00	125.66	125.66	0.90
M6	Limestone	0	kg	980.00	1.68E+12	0.00	1646.40	1646.40	11.81
M23	Urea	0	kg	40.00	6.38E+12	0.00	255.20	255.20	1.83
M35	Herbicide	0	kg	8.23	2.48E+13	0.00	204.10	204.10	1.46
M36	Fungicide	0	kg	6.27	2.48E+13	0.00	155.50	155.50	1.12
M37	Insecticide	0	kg	7.06	2.48E+13	0.00	175.09	175.09	1.26
M38	Formicide	0	kg	0.00	2.48E+13	0.00	0.00	0.00	0.00
M50	Chemicals	0	kg	43.75	6.38E+11	0.00	27.91	27.91	0.20
M58	Other materials	0	US$	39.76	5.02E+12	0.00	199.60	199.60	1.43
M60	Depreciation	0	US$	4.60	5.02E+12	0.00	23.09	23.09	0.17
M61	NPK 4,16,0	0	kg	62.67	2.40E+12	0.00	150.42	150.42	1.08
N61	NPK 20,0,20	0	kg	146.67	2.03E+12	0.00	297.85	297.85	2.14
M61	NPK 4,16,15	0	kg	32.00	2.76E+12	0.00	88.46	88.46	0.63
M61	NPK 8,28,12	0	kg	111.18	4.57E+12	0.00	507.96	507.96	3.64
M61	NPK 33,00,01	0	kg	53.33	2.57E+12	0.00	137.31	137.31	0.99
M61	NPK 5,25,15	0	kg	90.00	4.02E+12	0.00	361.60	361.60	2.59
M61	NPK 4,30,16	0	kg	100.00	4.62E+12	0.00	461.83	461.83	3.31
M61	NPK 4,16,15	0	kg	156.00	2.76E+12	0.00	431.22	431.22	3.09
M65	Infrastructure	0	US$	286.69	5.02E+12	0.00	1439.18	1439.18	10.33
S4	Labor	0.6[a]	US$	56.85	5.02E+12	171.23	114.15	285.39	2.05
S8	Technical assistance	0	US$	6.48	5.02E+12	0.00	32.53	32.53	0.23
S9	Labor-management	0	US$	17.55	5.02E+12	0.00	88.10	88.10	0.63
S11	Taxes	0	US$	34.55	5.02E+12	0.00	173.44	173.44	1.24
S12	Telephone	0	US$	4.64	5.02E+12	0.00	23.29	23.29	0.17
S15	Other costs	0	US$	328.45	5.02E+12	0.00	1648.82	1648.82	11.83
	Total emergy					2363.19	11573.94	13937.13	100.00

Transformities references: R1, by definition; R3, Odum, 1996; N1, M23, Odum and Odum, 1983; M1, M2, Ortega et al., 2002; M6, Brandt-Williams, 2002; M35, M36, M37, M38, Brown and Ulgiati, 2004a; M50, Coelho et al., 2003; M58, M60, M61 and S4-S15, Ortega, 1998. Renewability fraction references:

[a] Ortega et al., 2005.

Table 7
Emergy evaluation of soybean crop in Brazil (emergy flows in *E*+12 seJ/ha/year)

Code	Item	Renew. fraction	Unit	Quantity (unit/ha year)	Transfomity (seJ/unit)	Renewable emergy flow	Non-renewable emergy flow	Total emergy flow	%
R1	Sun	1	J	1.50E+11	1	0.15	0.00	0.15	0.00
R3	Rain	1	J	72,500,000,000	3.10E+04	2247.50	0.00	2247.50	24.43
R9	Atmospheric nitrogen.	1	kg	60	7.73E+12	463.80	0.00	463.80	5.04
N1	Soil loss	0	kg	20,100	1.24E+05	0.00	2253.130	2253.130	24.49
M1	Seeds	0.2[a]	kg	32.12	1.68E+12	10.79	43.17	53.96	0.59
M2	Transgenic seeds	0	kg	30.27	1.68E+13	0.00	508.54	508.54	5.53
M6	Limestone	0	kg	703.85	1.68E+12	0.00	1182.47	1182.47	12.85
M35	Herbicide	0	kg	3.02	2.48E+13	0.00	74.90	74.90	0.81
M36	Fungicide	0	kg	0.91	2.48E+13	0.00	22.57	22.57	0.25
M37	Insecticide	0	kg	0.62	2.48E+13	0.00	15.38	15.38	0.17
M38	Formicide	0	kg	0.83	2.48E+13	0.00	20.58	20.58	0.22
M50	Chemicals	0	kg	1.45	6.38E+11	0.00	0.93	0.93	0.01
M58	Other materials	0	US$	1.92	5.02E+12	0.00	9.64	9.64	0.10
M60	Depreciation	0	US$	4.06	5.02E+12	0.00	20.38	20.38	0.22
M61	NPK 2,20,20	0	kg	265.38	3.25E+12	0.00	863.48	863.48	9.39
M61	NPK 0,20,20	0	kg	69.23	3.10E+12	0.00	214.56	214.56	2.33
M61	NPK 2,20,15	0	kg	30.77	3.13E+12	0.00	96.39	96.39	1.05
M65	Infrastructure	0	US$	103.41	5.02E+12	0.00	519.12	519.12	5.64
S4	Labor	0.6[a]	US$	1.65	5.02E+12	4.97	3.31	8.28	0.09
S8	Technical assistance	0	US$	3.51	5.02E+12	0.00	17.62	17.62	0.19
S9	Labor-management	0	US$	18.02	5.02E+12	0.00	90.46	90.46	0.98
S11	Taxes	0	US$	12.1	5.02E+12	0.00	60.74	60.74	0.66
S12	Telephone	0	US$	4.8	5.02E+12	0.00	24.10	24.10	0.26
S15	Other costs	0	US$	85.65	5.02E+12	0.00	429.96	429.96	4.67
	Total emergy					2727.21	6471.41	9198.62	100.00

Transformities references: R1, by definition; R3 R9, Odum, 1996; N1, M23, Odum and Odum, 1983; M1, M2, Ortega et al., 2002; M6, Brandt-Williams, 2002; M35, M36, M37, M38, Brown and Ulgiati, 2004a; M50, Coelho et al., 2003; M58, M60, M61, M65 and S4-S15, Ortega, 1998. Renewability fraction references:

[a] Ortega et al., 2005.

Table 8
Emergy evaluation of canola crop in Brazil (emergy flows in *E*+12 seJ/ha/year)

Code	Item	Renew. fraction	Unit	Quantity (unit/ha year)	Transfomity (seJ/unit)	Renewable emergy flow	Non-renewable emergy flow	Total emergy flow	%
R1	Sun	1	J	1.50E+11	1	0.15	0.00	0.15	0.00
R3	Rain	1	J	7.25E+10	3.10E+04	2247.50	0.00	2247.50	39.08
N1	Soil loss	0	kg	12,000	1.24E+05	0.00	1345.152	1345.152	23.39
M1	Seeds	0.2[a]	kg	4	1.68E+12	1.34	5.38	6.72	0.12
M35	Herbicide	0	kg	1.6	2.48E+13	0.00	39.68	39.68	0.69
M37	Insecticide	0	kg	0.63	2.48E+13	0.00	15.62	15.62	0.27
M50	Chemicals	0	kg	0.16	6.38E+11	0.00	0.10	0.10	0.00
M60	Depreciation	0	US$	6	5.02E+12	0.00	30.12	30.12	0.52
M61	NPK (8,20,20)	0	kg	236.67	3.72E+12	0.00	879.81	879.81	15.30
M61	NPK (21,0,0)		kg	76.67	1.62E+12	0.00	124.43	124.43	2.16
M65	Infrastructure	0	US$	36.35	5.02E+12	0.00	182.48	182.48	3.17
S4	Labor	0.6[a]	US$	24.88	5.02E+12	74.94	49.96	124.90	2.17
S8	Technical assistance	0	US$	7	5.02E+12	0.00	35.14	35.14	0.61
S9	Labor-management	0	US$	29	5.02E+12	0.00	145.58	145.58	2.53
S11	Taxes	0	US$	8.83	5.02E+12	0.00	44.33	44.33	0.77
S12	Telephone	0	US$	7.5	5.02E+12	0.00	37.65	37.65	0.65
S15	Other costs	0	US$	97.89	5.02E+12	0.00	491.41	491.41	8.55
	Total emergy					2323.93	3426.83	5750.76	100.00

Transformities references: R1, by definition; R3, Odum, 1996; N1, M23, Odum and Odum, 1983; M1, Ortega et al., 2002; M35, M37, Brown and Ulgiati, 2004a; M50, Coelho et al., 2003; M60, M61 and S4-S15, Ortega, 1998. Renewability fraction references:

[a] Ortega et al., 2005.

The renewability ratio (%*R*) is the percentage of renewable emergy used by the system. Canola has the highest renewability, followed by sunflower, soybean, oil palm and cotton. As shown in Fig. 3, the renewable emergy from nature is practically constant among the crops, and the variation on this indice refers to the use of non-renewable materials and services from economy. Thus, the canola crop is less dependent on non-renewable emergy.

The emergy yield ratio (EYR) is the ratio between total emergy and emergy value of economy purchased inputs. This ratio measures the ability of a process to exploit and make local

Table 9
Emergy evaluation of oil palm crop in Brazil (emergy flows in *E*+12 seJ/ha/year)

Code	Item	Renew. fraction	Unit	Quantity (unit/ha year)	Transfomity (seJ/unit)	Renewable emergy flow	Non-renewable emergy flow	Total emergy flow	%
R1	Sun	1	J	1.53E+11	1	0.15	0.00	0.15	0.00
R2	Rain	1	J	6.00E+10	3.10E+04	1860.00	0.00	1860.00	25.20
N1	Soil loss	0	kg	900	1.24E+05	0.00	100.886	100.886	1.37
M35	Herbicide	0	kg	1.62	2.48E+13	0.00	40.18	40.18	0.54
M50	Chemicals	0	kg	147.36	6.38E+11	0.00	94.02	94.02	1.27
M58	Other materials	0	US$	13.8	5.02E+12	0.00	69.28	69.28	0.94
M61	NPK(17,17,17)	0	kg	735.84	3.95E+12	0.00	2905.16	2905.16	39.37
M65	Infrastructure	0	US$	8.9	5.02E+12	0.00	44.68	44.68	0.61
S4	Labor	0.6	US$[a]	75.94	5.02E+12	228.73	152.49	381.22	5.17
S8	Technical assistance	0	US$	6	5.02E+12	0.00	30.12	30.12	0.41
S9	Labor-management	0	US$	10.8	5.02E+12	0.00	54.22	54.22	0.73
S11	Taxes	0	US$	24.45	5.02E+12	0.00	122.74	122.74	1.66
S12	Telephone	0	US$	7.8	5.02E+12	0.00	39.16	39.16	0.53
S15	Other costs	0	US$	326.25	5.02E+12	0.00	1637.78	1637.78	22.19
	Total emergy					2088.88	5290.68	7379.57	100.00

Transfomities references: R1, by definition; R3, Odum, 1996; N1, Odum and Odum, 1983; M35, Brown and Ulgiati, 2004a; M50, Coelho et al., 2003; M58, M61, M65 and S4-S16, Ortega, 1998. Renewability fraction references: [a]Ortega et al., 2005.

Table 10
Emergy evaluation of sunflower crop in Brazil (emergy flows in *E*+12 seJ/ha/year)

Code	Item	Renew. fraction	Unit	Quantity (unit/ha year)	Transfomity (seJ/unit)	Renewable emergy flow	Non-renewable emergy flow	Total emergy flow	%
R1	Sun	1	J	1.5264E+11	1	0.15	0.00	0.15	0.00
R3	Rain	1	J	8.15E+10	3.10E+04	2526.50	0.00	2526.50	31.14
N1	Soil loss	0	kg	25,000	1.24E+05	0.00	2802.400	2802.400	34.54
M1	Seeds	0.2	kg	1	1.68E+12	0.34	1.34	1.68	0.02
M23	Urea	0	kg	85	6.38E+12	0.00	542.30	542.30	6.68
M35	Herbicide	0	kg	3.05	2.48E+13	0.00	75.64	75.64	0.93
M37	Insecticide	0	kg	0.13	2.48E+13	0.00	3.22	3.22	0.04
M50	Chemicals	0	kg	15	6.38E+11	0.00	9.57	9.57	0.12
M60	Depreciation	0	US$	4	5.02E+12	0.00	20.08	20.08	0.25
M61	NPK (8,20,20)	0	kg	275	3.72E+12	0.00	1022.30	1022.30	12.60
M65	Infrastructure	0	US$	84.5	5.02E+12	0.00	424.19	424.19	5.23
S4	Labor	0.6	US$[a]	3.31	5.02E+12	9.97	6.65	16.62	0.20
S8	Technical assistance	0	US$	1.5	5.02E+12	0.00	7.53	7.53	0.09
S9	Labor-management	0	US$	15	5.02E+12	0.00	75.30	75.30	0.93
S11	Taxes	0	US$	8.75	5.02E+12	0.00	43.93	43.93	0.54
S12	Telephone	0	US$	3	5.02E+12	0.00	15.06	15.06	0.19
S15	Other costs	0	US$	104.96	5.02E+12	0.00	526.90	526.90	6.49
	Total emergy					2536.96	5576.40	8113.36	100.00

Transfomities references: R1, by definition; R3, Odum, 1996; N1, M23, Odum and Odum, 1983; M1, Ortega et al., 2002; M35, M37, Brown and Ulgiati, 2004a; M50, Coelho et al., 2003; M60, M61, M65 and S4–S15, Ortega, 1998. Renewability fraction references: [a]Ortega et al., 2005.

resources available by investing in outside resources, in other words, the measure of use of local resources. All the crops show small EYR values, indicating a high dependency on non-renewable resources for production. Energy intensive agricultural systems have EYR values lower than two (Odum, 1996; Ulgiati et al., 1994; Ortega et al., 2002; Panzieri et al., 2000). Sunflower crops have the highest EYR value (2.92), followed by canola (2.76), soybean (2.50), cotton (1.58) and oil palm (1.42). These results indicate that cotton and oil palm have a high dependence on non-renewable resources and sunflower, canola and soybean crops have better performances when compared with another intensive agricultural system. The EYR index may give the wrong impression that sunflower crops are better than the others crops since they use more natural resources ($R+N$). The use of non-renewable resources from nature, like soil loss and biodiversity loss, is not advantageous. Thus, it is recommended to measure the R/F ratio instead, which shows that canola uses more renewable natural resources (N) compared with the economic resources (F) required. Therefore, the high EYR value for sunflower is due to the extensive use of non-renewable resources from nature (N), specifically soil loss. Thus, crops that use more local and renewable resources from nature are canola (1.04), sunflower (0.91), soybean (0.48), oil palm (0.34) and cotton (0.24). This index clearly shows that canola crops use 4% more renewable emergy from nature than from economy resources.

The emergy investment ratio (EIR) measures the intensity of use of economic resources in agriculture. The calculation of this ratio allows the choice of a model for agriculture compatible with the economic and environmental concerns. Accordingly, this index is a good indicator to assist the development of a sustainable agricultural policy. The low value for the sunflower crop (0.52) and canola crop (0.57) is advantageous, as it reflects a low use of emergy from economic resources. Sunflower (1.08), soybean (0.85) and cotton (1.71) have a moderate use of emergy

Table 11
Average aggregated emergy flow and output data (aggregate emergy flows in E+12 seJ/ha/year).

Inputs	Cotton	Soybean	Sunflower	Canola	Oil palm
Renewable resources from nature (*R*)	2185.50	2711.30	2526.50	2247.50	1860.00
Non-renewable resources from nature (*N*)	2779.98	2253.13	2802.40	1345.15	100.89
I= *R*+*N*	4 965.48	4964.43	5328.90	3592.65	1960.89
Materials from economy (*M*)	6719.93	3602.88	2098.98	1 278.96	3153.30
Renewable materials (M_R)	6.31	10.79	0.34	1.34	0.00
Non-renewable Materials (M_N)	6713.62	3592.09	2098.64	1277.61	3153.30
Services from economy (*S*)	2251.57	631.16	685.33	879.00	2265.22
Renewable Services (S_R)	171.23	4.97	9.97	74.94	228.73
Non-renewable Services (S_N)	2080.34	626.19	675.36	804.06	2036.49
Feedback from economy (*F*)	8971.50	5595.59	2784.31	2157.96	5418.53
Feedback renewable (F_R)	177.54	15.76	10.31	76.28	228.73
Feedback non-renewable (F_N)	8793.96	4218.28	2774.00	2 081.68	5189.79
Total emergy (*Y*)	13 936.98	10 560.02	8113.21	5750.61	7379.41
Outputs					
Mass (kg/ha/year)	3375	2712	1700	1 542	16,800
Energy/mass (kJ/kg)	2640	15,170	26 016	22 907	18,409
Total energy (kJ/ha/year)	8.98E+6	4.11E+7	4.42E+6	3.53E+7	3.09E+8
Price (US$/kg)	0.440	0.194	0.253	0.250	0.065

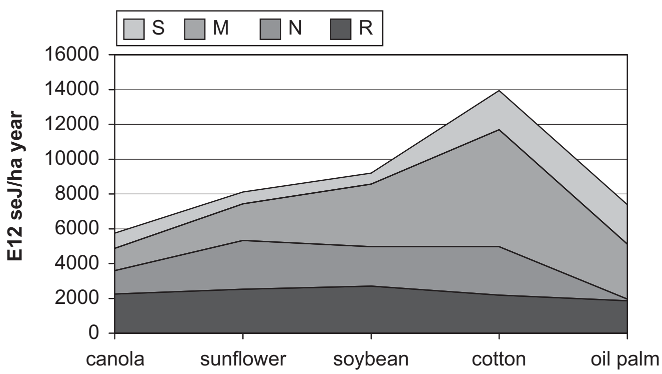

Fig. 3. Proportion of aggregated emergy of each crop.

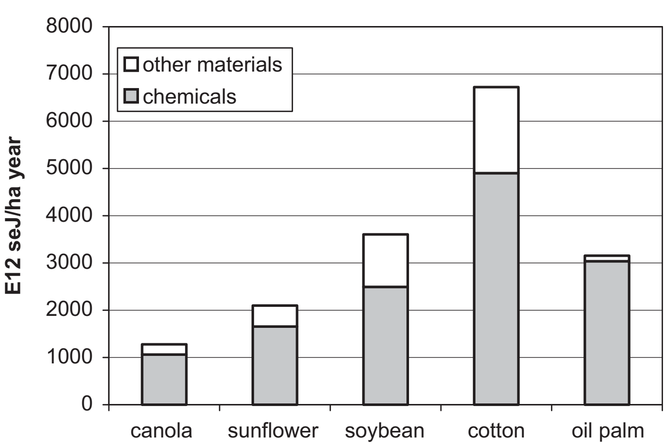

Fig. 4. Proportion of emergy from chemicals and another emergy from materials.

from the economy, while oil palm (2.37) uses the largest proportion of emergy from the economy, which reflects the highest EIR value.

The emergy exchange ratio (EER) would have a value of 1 to represent that all emergy spent to produce the product is returned to the producer by the money received. Generally for intensive commercial systems this value is greater than 1, i.e., the producer receives less emergy in the form of money than invested. The values of this indicator for vegetable oil crops from high to low are: sunflower (3.76), soybean (4,00), canola (2.97),

Table 12
Emergy indices of the crops in this study.

Indicator	Canola	Soybean	Sunflower	Oil palm	Cotton
Transformity (seJ/J)	4.37E+04	2.57E+05	1.83E+05	2.39E+04	1.56E+06
Renewability (%)	40.41	29.65	31.27	28.31	16.96
EYR	2.76	2.50	2.92	1.42	1.58
R/F	1.04	0.48	0.91	0.34	0.24
EIR	0.57	0.85	0.52	2.37	1.71
EER	2.97	4.00	3.76	1.35	1.87
ELR	1.47	2.37	2.20	2.53	4.90

cotton (1.87) and oil palm (1.35). Oil palm has the lower EER value among the crops, and this can be explained by the high productivity of oil palm (16,800 kg/ha year), which is 10.9 times higher than that of canola, 9.9 times higher than sunflower, 6.2 times higher than soybean and 4.9 times higher than cotton.

The emergy loading ratio (ELR) is an indicator of the pressure of agricultural systems on the environment and may be considered a signal of possible ecosystem stress. Canola crops have the best value (1.47) indicating a lower pressure when compared with the other systems.

The results from this study largely agree with the results from past studies. The renewability calculated for the sunflower crop in this work (31.6%) is close to the value reported for Italian systems (28.6%) (Bastianoni et al., 2008). The results for soybean crops are similar to those found in the literature (Ortega et al., 2005; Cavalett and Ortega, 2009).

Yee et al. (2009) used the LCA methodology of palm biodiesel and compared with rapeseed biodiesel. They conclude that palm biodiesel produced in Malaysia is more efficient than rapeseed biodiesel. The crop studied in Malaysia only uses 281 kg/ha year of fertilizer. In Brazil, the average use of fertilizer during 25 years of oil palm production is 735 kg/ha year and this reflects in a worse result for Brazilian oil palm crop.

The emergy indices show that canola crops are the most sustainable raw material for the production of biodiesel.

Oil palm proves to be a potential source of energy due to its high productivity, low transformity and low EER value; however, it has a high EIR value. In order to increase the sustainability, the use of non-renewable materials should be reduced through the use of appropriate management techniques to reduce the amount of chemical fertilizer, which currently represents over 39% of the total emergy used.

A study of soybean farming and industrialization showed that the industrial portion of production contributes a very small amount of non-renewable emergy when compared with the total emergy used for farming the crop (Cavalett and Ortega, 2009). High renewability (approximately 80%) can be achieved in agroecological soybean farms that use more renewable resources and less chemicals derived from petroleum (Ortega et al., 2002).

4. Conclusion

The emergy assessment of oleaginous crops indicates that the biodiesel produced by vegetable oil with conventional farming methods cannot yet be considered sustainable, as defined by the PNBP.

The main oil used in Brazil for biodiesel production is soybean oil. To produce pure biodiesel (B100), the renewable emergy used is smaller than 30% (in the case the soybean oil) as showed in the last section; this renewability index tends to fall during the processing chain with the incorporation of new non-renewable energy resources, and when the biodiesel (B100) is blended with diesel (petro fuel), this renewability falls further.

The crop with the best emergy indices is canola, a variety of rapeseed that is the main raw material used to produce biodiesel in Europe and North-America. Canola is not widely produced in Brazil, probably due to climate restrictions or low market demand.

The cultivation of oil palm must be researched due to its high productivity and oil yield. Palm oil is the third most produced vegetable oil in Brazil, and appropriate agroecological management can be used to reduce the dependency on non-renewable resources for its production. So that oil palm could be an important source of renewable energy. Thus, the Brazilian government should encourage the production of oil palm and support research aimed at reducing the use of chemical fertilizers.

This study did not consider natural renewable resources such as solubilized minerals, nutrients from the soil, environmental services and negative externalities. These materials should be evaluated and included in a future analysis to obtain more accurate emergy indices. However, these flows are difficult to account for, and there is still much debate about how to quantify environmental services and negative externalities.

The use of the LCA methodology integrated with the emergy methodology is a good suggestion proposed by Ulgiati et al., 2007 and it is recommended for future works. The results of such a study could contribute to the discussion of conventional oleaginous crops sustainability in Brazil.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2009.12.038.

References

Agostinho, F., Diniz, G., Siche, R., Ortega, E., 2008. The use of emergy assessment and the Geographical Information System in the diagnosis of small family farms in Brazil. Ecol. Model. 210, 37–57.

Agrianual, 2006. Anuário da agricultura Brasileira. Instituto FNP [Yearbook of Brazilian agriculture]. São Paulo, Brazil.

ANP, 2009 National Petroleum Agency. Available from: 〈http://www.anp.gov.br/petro/dados_estatisticos.asp〉; (accessed 05.10.09).

Bastianoni, S., Marchettini, N., 1996. Ethanol production from biomass: Analysis of process efficiency and sustainability. Biomass Bioenergy 11, 411-418.

Bastianoni, S., Coppola, F., Tiezzi, E., Colacevich, A., Borghini, F., Focardi, S., 2008. Biofuel potencial production form the *Orbetello lagoon* macroalgae: a comparison with sunflower feedstock. Biomass Bioenergy 32, 619–628.

Brandt-Williams, S.L., 2002. Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios. Folio No. 4 – Emergy of Florida Agriculture. Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville, p. 40. Available from: 〈http://www.emergysystems.org/downloads.php〉 (accessed 05.10.09).

Brown, M.T., Ulgiati, S., 2004a. Emergy analysis and environmental accounting. Encyclopedia Energy 2, 329–354.

Brown, M.T., Ulgiati, S., 2004b. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understandings systems. Ecol. Model. 178, 201–213.

Carlsson, A.S., 2009. Plant oils as feedstock alternatives to petroleum– – a short survey of potential oil crop platforms. Biochimie 91, 665–670.

Cavalett, O., Ortega, E., 2009. Emergy, nutrients balance, and economic assessment of soybean production and industrialization in Brazil. J. Cleaner Product. 17, 762–771.

Coelho, O., Ortega, E., Comar, V.,2003. Balanço de Emergia do Brasil (Dados de 1996, 1989 e 1981). (Emergy balance of Brazil. Statistics of 1996, 1989 e 1981). In: Engenharia Ecológica e Agricultura Sustentável (Ecological Engineering and Sustainable Agriculture). Organizer: Enrique Ortega. Available from: 〈http://www.fea.unicamp.br/docentes/ortega/livro/index.htm〉 (accessed 05.10.09).

Comar V., Tilley D., Feliz E., Turdera M., Chagas Neto M. Comparative emergy evaluation of castorbean (*Ricinus communis*) production systems in Brazil and the US. In: Ortega, E., Ulgiati, S. (Eds.), Proceedings of the IV Biennial International Workshop "Advances in Energy Studies", Unicamp, Campinas, SP, Brazil, June 16–19, 2004, pp. 227–237.

Demirbas, M.F., Balat, M., Balat, H., 2009. Potential contribution of biomass to the sustainable energy development. Energy Convers. Manage. 50, 1746–1760.

Escobar, J.C., Lora, E.S., Venturini, O.J., Yáñez, E.E., Castillo, E.F., Almazan, O., 2009. Biofuels: environment, technology and food security. Renewable Sustainable Energy Rev. 13, 1275–1287.

FAO, FAOSTAT. Available from: 〈http://faostat.fao.org〉 (2009) (accessed 05.02.09).

Holzman, D.C., 2008. The carbon footprint of biofuels can we shrink it down to size in time? Environ. Health Perspect. 6, 116.

Krahl, J., Knothe, G., Munack, A., Ruschel, Y., Schröder, O., Hallier, E., Westphal, G., Bünger, J., 2009. Comparison of exhaust emissions and their mutagenicity from the combustion of biodiesel, vegetable oil, gas-to-liquid and petrodiesel fuels. Fuel 88, 1064–1069.

La Rosa, A.D., Siracusa, G., Cavallaro, L., 2008. Emergy evaluation of Sicilian red orange production. A comparison between organic and conventional farming. J. Cleaner Prod. 16, 1907–1914.

Lora, E.S., Andrade, R.V., 2009. Biomass as energy source in Brazil. Renewable Sustainable Energy Rev. 13, 777–788.

Martin, J.F., Diemont, S.A.W., Powell, E., Stanton, M., Levy-Tacher, S., 2006. Emergy evaluation of the performance and sustainability of three agricultural systems with different scales and management. Agric. Ecosyst. Environ. 115, 128–140.

Nachiluk K. Freitas S.M., 2009. Evolução da Capacidade Instalada para produção de Biodiesel no Brasil e Auto-Abastecimento Regional. Análises e Indicadores do Agronegócio. v.4 n5.

Odum, H.T., 1996. Environmental Accounting, Emergy and Decision Making. John Wiley, New York 370 pp.

Odum, H.T., 1988. Self organization, transformity, and information. Science 242, 1132–1139.

Odum, H.T., Odum, E.C., 1983. Energy analysis overview of nations: concepts and methods. Working Paper, International Institute of Applied Systems Analysis, Laxenburg, Austria, 1983, 366 pp.

Ortega, E., 1998. Tabela de transformidades. Available from: 〈http://www.unicamp.br/fea/ortega/curso/transformid.htm〉 (accessed 05.10.09).

Ortega, E., Anami, M., Diniz, G., 2002. Certification of food products using emergy analysis. In: Proceedings of the III International Workshop Advances in Energy Studies, Porto Venere, Italy, pp. 227–237.

Ortega, E., Cavalett, O., Bonifacio, R., Watanabe, M., 2005. Brazilian soybean production: emergy analysis with an expanded scope. Bull. Sci. Technol. Soc. 25 (4), 1–11.

Panzieri, M., Marchettini, N., Hallam, T.G., 2000. Importance of the *Bradhyrizobium japonicum* symbiosis for the sustainability of a soybean cultivation. Ecol. Model. 135, 301–310.

Pizzigallo, A.C.I., Granai, C., Borsa, S., 2008. The joint use of LCA and emergy evaluation for the analysis of two Italian wine farms. J. Environ. Manage. 86, 396–406.

Pousa, G.P.A.G., Santos, A.L.F., Suarez, P.A.Z., 2007. History and policy of biodiesel in Brazil. Energy Policy 35, 5393–5398.

Reijnders, L., 2006. Conditions for the sustainability of biomass based fuel use. Energy Policy 34, 863–876.

Scienceman, D.M., 1987. Energy and emergy. In: Pillet, G., Murota, T. (Eds.), Environmental Economics: The Analysis of a Major Interface. Rolland Leimgruber, Geneva., pp. 257–276.

Sharma, Y.C., Singh, B., 2009. Development of biodiesel: current scenario. Renewable Sustainable Energy Rev. 13, 1646–1651.

Stoeglehner, G., Narodoslawsky, M., Applying ecological footprint in decision making processes on future local and regional energy supplies. In: Center for Business Relationships, Accountability, Sustainability and Society, University of Cardiff, Stepping Up the Pace. New Developments in Ecological Footprint Methodology, Policy and Practice, 8–10 May 2007, Cardiff. Available from: 〈http://www.brass.cf.ac.uk/uploads/fullpapers/Stoeglehner_Narodoslawsky_P27.pdf〉 (accessed 05.12.09).

Stoeglehner, G., Narodoslawsky, M., 2009. How sustainable are biofuels? Answers and further questions arising from an ecological footprint perspective. Bioresource Technol. 100, 3825–3830.

Takahashi, F., Ortega, O., Pires, A. Dynamic web page for evaluation of complex agricultural systems. In: Sixth Biennial International Workshop Advances in Energy Studies. Graz University of Technology, June2008.

Talens, L., Villablba, G., Gabarrell, X., 2007. Exergy analysis applied to biodiesel production. Resources Convers. Recycling 51, 397–407.

Ulgiati, S., Bargigli, S., Raugei, M., 2007. An emergy evaluation of complexity, information and technology, towards maximum poer and zero emissions. J. Cleaner Prod. 15, 1359–1372.

Ulgiati, S., Brown, M.T., 1998. Monitoring patterns of sustainability in natural and man-made ecosystems. Ecol. Model. 108, 23–36.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability. An emergy analysis of Italy. Ecol. Model. 73, 215–268.

Yee, K.F., Tan, K.T., Abdullah, A.Z., Lee, K.T., 2009. Life cycle assessment of palm biodiesel: revealing facts and benefits for sustainability. Appl. Energy 86, S189–S196.