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RENEWABLE RESOURCES • CASE STUDY

Lifecycle assessment of fuel ethanol from sugarcane in Brazil

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Abstract
Background, aim, and scope This paper presents the lifecycle assessment (LCA) of fuel ethanol, as 100% of the vehicle fuel, from sugarcane in Brazil. The functional unit is 10,000 km run in an urban area by a car with a 1,600-cm^3 engine running on fuel hydrated ethanol, and the resulting reference flow is 1,000 kg of ethanol. The product system includes agricultural and industrial activities, distribution, cogeneration of electricity and steam, ethanol use during car driving, and industrial by-products recycling to irrigate sugarcane fields. The use of sugarcane by the ethanol agribusiness is one of the foremost financial resources for the economy of the Brazilian rural area, which occupies extensive areas and provides far-reaching potentials for renewable fuel production. But, there are environmental impacts during the fuel ethanol lifecycle, which this paper intents to analyze, including addressing the main activities responsible for such impacts and indicating some suggestions to minimize the impacts.

Materials and methods This study is classified as an applied quantitative research, and the technical procedure to achieve the exploratory goal is based on bibliographic revision, documental research, primary data collection, and study cases at sugarcane farms and fuel ethanol industries in the northeast of São Paulo State, Brazil. The methodological structure for this LCA study is in agreement with the International Standardization Organization, and the method used is the Environmental Design of Industrial Products. The lifecycle impact assessment (LCIA) covers the following emission-related impact categories: global warming, ozone formation, acidification, nutrient enrichment, ecotoxicity, and human toxicity.

Results and discussion The results of the fuel ethanol LCI demonstrate that even though alcohol is considered a renewable fuel because it comes from biomass (sugarcane), it uses a high quantity and diversity of nonrenewable resources over its lifecycle. The input of renewable resources is also high mainly because of the water consumption in the industrial phases, due to the sugarcane washing process. During the lifecycle of alcohol, there is a surplus of electric energy due to the cogeneration activity. Another focus point is the quantity of emissions to the atmosphere and the diversity of the substances emitted. Harvesting is the unit process that contributes most to global warming. For photochemical ozone formation, harvesting is also the activity with the strongest contributions due to the burning in harvesting and the emissions from using diesel fuel. The acidification impact potential is mostly due to the NOx emitted by the combustion of ethanol during use, on account of the sulfuric acid use in the industrial process and because of the NOx emitted by the burning in harvesting. The main consequence of the intensive use of fertilizers to the field is the high nutrient enrichment impact potential associated with this activity.

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The main contributions to the ecotoxicity impact potential come from chemical applications during crop growth. The activity that presents the highest impact potential for human toxicity (HT) via air and via soil is harvesting. Via water, HT potential is high in harvesting due to lubricant use on the machines. The normalization results indicate that nutrient enrichment, acidification, and human toxicity via air and via water are the most significant impact potentials for the lifecycle of fuel ethanol.

Conclusions The fuel ethanol lifecycle contributes negatively to all the impact potentials analyzed: global warming, ozone formation, acidification, nutrient enrichment, ecotoxicity, and human toxicity. Concerning energy consumption, it consumes less energy than its own production largely because of the electricity cogeneration system, but this process is highly dependent on water. The main causes for the biggest impact potential indicated by the normalization is the nutrient application, the burning in harvesting and the use of diesel fuel.

Recommendations and perspectives The recommendations for the ethanol lifecycle are: harvesting the sugarcane without burning; more environmentally benign agricultural practices; renewable fuel rather than diesel; not washing sugarcane and implementing water recycling systems during the industrial processing; and improving the system of gases emissions control during the use of ethanol in cars, mainly for NOx. Other studies on the fuel ethanol from sugarcane may analyze in more details the social aspects, the biodiversity, and the land use impact.

Keywords Acidification · Ecotoxicity · Fuel ethanol · Global warming · Human toxicity · Lifecycle assessment (LCA) · Nutrient enrichment · Ozone formation · Renewable energy · EDIP · Environmental impacts · Brazil

1 Background, aim, and scope

Instigated by our current energy supply problems and by the implementation of the commitments in the Climate Change awareness, the world is looking for renewable fuels harnessed with environmental qualities. One of the alternatives for engine fuel can be fuel ethanol from sugarcane.

Sugarcane has been one of the most important agricultural activities in Brazil since 1532, occupying around eight million hectares in 2008 (Ministry of Agriculture, Livestock and Supply 2007). The annual production in 2008 comprises 558.14 million tons of sugarcane; 30.8 million tons of sugar; 22.2 million cubic meter of alcohol (Ministry of Agriculture, Livestock and Supply 2007); and around 664.12 MWh of electricity (Ministry of Mines and Energy 2007).

There are a number of reasons to assess the fuel ethanol from Brazilian sugarcane, for instance, fuel ethanol made from sugarcane is based on renewable resources in contrast to other types of fuel; many activities in the lifecycle of Brazilian fuel ethanol have been the same for a long period of time and the improvement potentials may be substantial; it is possible to cogenerate electricity (renewable) from the solid waste (biomass) of some lifecycle activities, and this renders relevant the system's perspective inherent in Lifecycle Assessment (LCA); there are a number of potential improvements of the environmental interactions among the fuel ethanol lifecycle activities, such as recycling of waste fractions within the product system.

Sugarcane is one of the foremost financial sources in the rural areas of Brazil, notwithstanding many environmental impacts created by the lifecycle should be analyzed and reduced. The conventional fuel ethanol production model adopted in Brazil is based mostly on a plantation system with extensive use of agricultural land, intensive use of fertilizers and pesticides, high water consumption, burning of sugarcanes prior to harvesting, and others. It is, thus, very timely to include environmental concerns in planning the lifecycle of Brazilian agricultural products—to optimize it and reduce negative impacts on humans and on the environment—to develop more sustainable products.

To this end, LCA is a powerful methodology for studying the interactions between human activities and the environment and for developing and producing assets in an environmentally prudent and farsighted manner.

The goal of this paper is to present the LCA of the fuel ethanol from sugarcane in Brazil, assessing the environmental impact potentials, in order to designate the focus activity of the fuel ethanol lifecycle from Brazilian sugarcane, which causes the main impacts. Also, some guidelines for environmental improvements are indicated.

The function of the product is to be used as 100% fuel in urban area vehicles. The functional unit is 10,000 km run by a 1,600-cm^3 car with fuel hydrated ethanol and the corresponding reference flow is 1,000 kg of ethanol. The product system includes nine unit processes (Fig. 1): (1) soil preparation; (2) sugarcane plantation; (3) chemical application; (4) harvesting; (5) fuel ethanol industrial process; (6) electrical energy cogeneration; (7) irrigation; (8) ethanol distribution; (9) use of fuel ethanol in cars. The boundaries of the ethanol product system are drawn around the unit processes, applying cutoff criteria for inputs lower than 0.05% of the total material resource consumed, which represents 80 kg for each resource in each unit process, including significantly relevant environmental aspects. The production of calcium carbonate ($CaCO_3$) used for liming the soil is, thus, included in the product system because the input is more than 80 kg/unit process. The production of phosphorous fertilizer (P_2O_5) and diesel are included

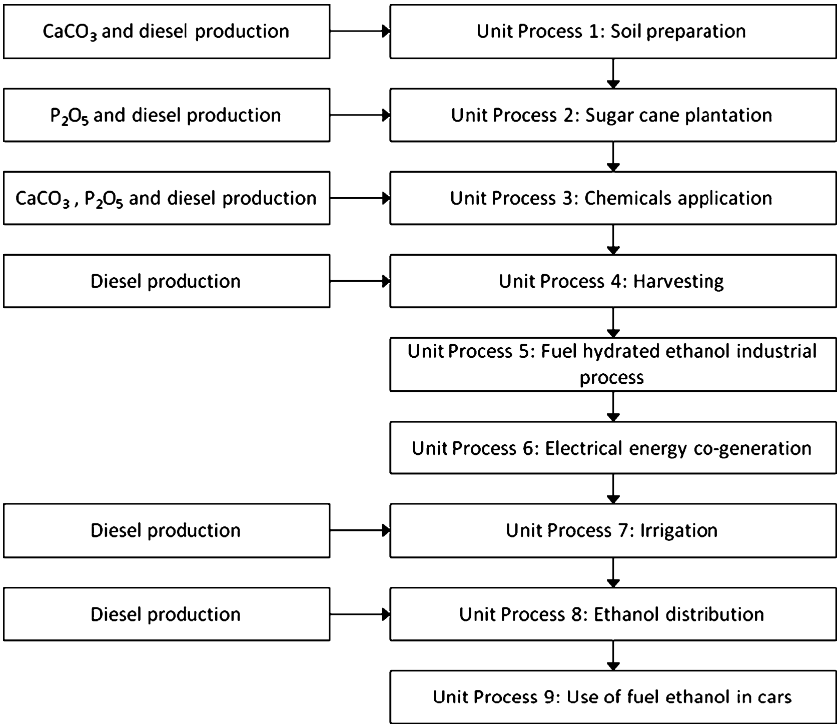

Fig. 1 Fuel ethanol product system

because of their environmental relevance. The primary data has been collected from 2001 to 2008 in the northeast of São Paulo State, illustrative of traditional up-to-date technology used in Brazil to produce ethanol.

2 Materials and methods

This study is classified as an applied quantitative research, for which the technical procedure to achieve the exploratory goal is based on bibliographic revision, documental research, primary data collection and study cases at sugarcane farms and fuel ethanol industries in the northeast of São Paulo, Brazil. The methodological structure for this LCA study is in agreement with the International Standardization Organization (ISO), ISO 14040 (ISO 1997), ISO 14044 (ISO 2006), and the method used is the environmental design of industrial products (EDIP; Wenzel et al. 1997; Hauschild and Wenzel 1998). The inventory analysis is based mainly on primary data from sugarcane farms, industries, distributors, and ethanol-fuelled cars in the northeast of São Paulo, Brazil collected from 2001 to 2008. There are also data from technical literature, specialists, and database—all cited in the lifecycle inventory (LCI) results (Tables 1, 2, 3, 4, 5, 6, 7, 8, 9). The process of conducting an inventory analysis is iterative, and the results constitute the input to the lifecycle impact assessment (LCIA). The LCIA of this study is in accordance with the EDIP method, covering the following emission-related impact categories: global warming, ozone formation,

Table 1 Unit Process 1: Soil preparation

Inputs		**Outputs**	
Non renewable resources	**Quantity (kg/10.000 km)**	**Emissions to air**	**Quantity (kg/10.000 km)**
Calcium Carbonate ($CaCO_3$)	80,00	CO_2 (from diesel and $CaCO_3$)	1,84 (SimaPro Database 2003)
Diesel	2,92		
Crude oil IDEMAT (from diesel)	0,33 (SimaPro Database 2003)	**Emissions to water**	
Pesticides	0,09		
Renewable resources		Cl^- (from diesel and $CaCO_3$)	0,00077 (SimaPro Database 2003)
Water (from $CaCO_3$ and diesel)	7069,11 (SimaPro Database 2003)	Pb (from diesel and $CaCO_3$)	0,00053 (SimaPro Database 2003)
		SO_4^{-} (from diesel and $CaCO_3$)	0,00052 (SimaPro Database 2003)
Energy consumption	**Quantity (MJ/10000 km)**		
Unspecified energy (from diesel)	0,00080 (SimaPro Database 2003)		

Table 2 Unit Process 2: Sugar cane plantation

Inputs		**Outputs**	
Non renewable resources	**Quantity (kg/10000 km)**	**Emissions to air**	**Quantity (kg/10000 km)**
Diesel	2,70	CO_2 (from diesel)	1,18 (SimaPro Database 2003)
Crude oil IDEMAT (from diesel)	0,22 (SimaPro Database 2003)	NOx (from diesel)	0,015 (SimaPro Database 2003)
Crude oil ETH (from diesel)	0,11 (SimaPro Database 2003)		
Pesticides	0,05	**Emissions to water**	
		Oil (from diesel)	0,000019 (SimaPro Database 2003)
Renewable resources			
Sugar cane (biomass)	560,00		
Water (from diesel)	0,044 (SimaPro Database 2003)		
Energy consumption	**Quantity (MJ/10000 km)**		
Unspecified energy (from diesel)	0,45 (SimaPro Database 2003)		

acidification, nutrient enrichment, ecotoxicity (ET), and human toxicity. The land use will be addressed according to the area used annually for 1 t of ethanol.

The functional unit of this study is 10,000 km of urban driving in a standard car using ethanol as the only fuel. Considering a mean consumption of 8 km/l, the reference flow is 1,000 kg of ethanol. The results are calculated assuming the average sugarcane and ethanol productivity from 2001 to 2008, which are 72 t sugarcane/ha and 85 l ethanol/t sugarcane, according to the primary data. For the reference flow, the sugarcane plantation area is 0.20 ha, which is the needed land use for this 1-year crop cultivation.

Allocation used in process unit 6: steam and electrical energy cogeneration, because it studied a sugarcane cultivation and industrial process only for the production of ethanol, named autonomous distillery. The steam, made by water and the bagasse heat in unit 6, is used in the ethanol industrial process to generate electrical energy cogeneration. The steam allocation to the fuel ethanol is performed according to the mass of steam used only in the fuel ethanol process, not considering the amount used to generate electricity, which is used in another process outside the ethanol lifecycle. The sugarcane related CO_2, CO and hydrocarbons, except for methane emissions (from sugarcane burning, bagasse energy cogeneration and fuel

Table 3 Unit Process 3: Chemicals application

Inputs		**Outputs**	
Non renewable resources	**Quantity (kg/10000 km)**	**Emissions to air**	**Quantity (kg/10000 km)**
Calcium Carbonate	48,00	CO_2 (from diesel, P_2O_5 and $CaCO_3$)	2,59 (SimaPro Database 2003; Kulay 2000)
Nitrogen –N_{total}	11,76 (Macedo et al. 2004)		
Phosphorus - P_2O_5	5,64 (Macedo et al. 2004)	**Emissions to water**	
Potassium - K_2O	14,80 (Macedo et al. 2004)	Desliming emissions (from P_2O_5)	56,85 (Kulay 2000)
Diesel	1,90	Demagnetization emissions (from P_2O_5)	46,50 (Kulay 2000)
Pesticides	0,68	Flotation emissions (from P_2O_5)	6,50 (Kulay 2000)
		N (from diesel and nutrient application)	2,35 (SimaPro Database 2003)
Renewable resources			
Water (from diesel, P_2O_5 and $CaCO_3$)	4755,33 (SimaPro Database 2003; Kulay 2000)		
Energy consumption	**Quantity (MJ/10000 km)**		
Electrical energy (from P_2O_5)	2,22 (Kulay 2000)		
Unspecified energy (from diesel)	0,66 (SimaPro Database 2003)		

Table 4 Unit Process 4: Harvesting

Input		**Outputs**	
Non renewable resources	**Quantity (kg/10000 km)**	**Emissions to air**	**Quantity (kg/10000 km)**
Diesel	31,34	CO_2 (from diesel)	113,24 (SimaPro Database 2003)
Crude oil ETH (from diesel)	25,82 (SimaPro Database 2003)	Particulate matter (from sugar cane burning and diesel)	37,50 (SimaPro Database 2003; Alves 1991)
Crude oil IDEMAT (from diesel)	6,34 (SimaPro Database 2003)	NOx (from sugar cane burning and diesel)	9,31 (SimaPro Database 2003; EMBRAPA 1997)
		CH_4 (from sugar cane burning and diesel)	4,26 (SimaPro Database 2003; EMBRAPA 1997)
Renewable Resources		CO (from diesel)	0,63 (SimaPro Database 2003)
Water (from diesel)	1,29 (SimaPro Database 2003)	NO_2 (from diesel)	0,29 (SimaPro Database 2003)
		Hydrocarbons – not CH_4 (from diesel)	0,19 (SimaPro Database 2003)
Energy consumption	**Quantity (MJ/10000 km)**		
Unspecified energy (from diesel)	100,75 (SimaPro Database 2003)		

ethanol combustion) are not considered in the fuel ethanol lifecycle, since they come from a renewable source. Another important consideration is that the soil partly comprises the technosphere; therefore, emissions of nutrient applications, pesticides, and soil correctors were not ascribed to this environmental component. For each unit process, the following specific considerations and allocations are indicated for the annual procedure:

1. *Soil preparation*. As sugarcane is allowed to regrow with the same stalk five times after cut, it is necessary to renew 20% of the crop each year by planting new sugarcane. For the reference flow, this area is 0.04 ha. According to primary data, the old sugarcane is removed using machines at 35.8% of this area (0.01 ha) and chemicals at 64.2% of this area (0.03 ha).
2. *Sugarcane plantation*. As an extension of activity 1, activity 2 is also performed on 0.04 ha. The equipment used for the manual plantation are trucks to transport partial sugarcane, tractors to open trenches on the field and to spread some pesticides on the field, and buses for the transportation of workers.
3. *Chemical applications*. Tractors are used for of pesticide and fertilizer applications in the total sugarcane area (0.20 ha). For the pesticide application emissions the PestLCI software was used, in agreement with the international consensus model for comparative assessment of chemicals—USEtox (Hauschild et al. 2007), in which only emissions that come out of the production system ground level and that interfere with the air or water quality were assessed. The same consideration that the soil is part of the technosphere was used for the fertilizer, assuming for the nitrogen (Ntotal) the following considerations: loss by volatilization of NH_3, 15%; loss by volatilisation N_2O, 2%; surface runoff and percolation, 20% (Ocean Studies Board and Water Science and Technology Board 2000). For the phosphorus (P), it assumed that there is a surface runoff of 10%, following the Brazilian characteristics (Shigaki 2006).

Table 5 Unit process 5: Fuel hydrated ethanol industrial process

Inputs		**Outputs**	
Non renewable resources	**Quantity (kg/10000 km)**	**Emissions to water**	**Quantity (kg/ 10000 km)**
Sulfuric Acid (H_2SO_4)	11,31	H_2SO_4	11,31
Renewable resources			
Water	118613,00		
Steam	2750,00		
Energy consumption	**Quantity (MJ/ 10000 km)**		
Electrical energy	1238,40		

Table 6 Unit process 6: electrical energy cogeneration

Inputs		Outputs	
Renewable Resources	**Quantity (kg/10000 km)**	**Emissions to air**	**Quantity (kg/10000 km)**
Water	14625,27	Particulate matter	1,76 (Factor et al. 1998)
		NOx	1,48 (Factor et al. 1998)
Non Renewable Resources	**Quantity (kg/10000 km)**		
Lubricant	0,01	**Energy production**	**Quantity (MJ/10000 km)**
		Electrical energy	2439,90

4. *Harvesting*. Harvesting is carried out every year in the total area from May to August. Sugarcane harvesting in the State of São Paulo is carried out on average 63.8% manually and 36.2% with machines. Burning prior to harvesting, to facilitate cutting, is used on 75% of the total area. After cut, the sugarcane is transported by trucks to the industrial process.
5. *Fuel ethanol industrial process*. The traditional process to produce fuel hydrated ethanol in Brazil is considered. The industrial transformation into hydrated ethanol begins with the washing of sugarcane. The washed sugarcane is transported by conveyor belts to the millings, where the sugarcane juice is extracted. The products of the sugarcane milling are the juice, the filter cake, and the bagasse. The juice is used to produce alcohol, the filter cake is used as field fertilizer, and the bagasse is burned to generate steam and electricity in cogeneration plants. The extracted juice enters decanters, where solid materials are separated from the juice. Then, the juice is inoculated by yeast (Saccharomyces), which converts sacharose ($C_{12}H_{22}O_{11}$) into ethanol (C_2H_5OH) and carbon dioxide (CO_2) by fermentation cubs. The fermentation product is transported to two distillation columns to elevate the alcohol concentration. The products of the distillation are hydrated alcohol 97°GL and vinasse,[1] the latter of which is used as fertilizer in the sugarcane fields. This process results in the production of 15 l of vinasse/l of ethanol produced and 4,085 kg of bagasse[2]/kg of ethanol.
6. *Electrical energy cogeneration*. Steam is produced using water in boilers by the heat from the bagasse, and the electrical energy is by steam-driven generators. For steam generation, there is a water consumption of 2 kg/kg of bagasse. For each kilogram of bagasse, there is a production of 2 kg of steam. So, for the reference flow, 4,085 t of bagasse produce 8.17 t of steam. From the total steam mass produced, 67.32% is used in the ethanol industrial process. The allocation considers this amount to the fuel ethanol lifecycle.
7. *Irrigation*. The irrigation is done by aspersion using mainly vinasse, the coproduct of ethanol distillation, with some decomposed solid residues, which are transported to the sugarcane crop field by trucks.
8. *Ethanol distribution*. The distribution of the fuel ethanol is by trucks. The truck loads 30,000 l, and the average distance from the ethanol industry to the gas station is 150 km. Thus, for the reference flow of 1,000 kg of ethanol (1,250 l), the transportation operation is equivalent to driving a fully loaded truck a distance of 6.25 km.
9. *Use of fuel ethanol in cars*. It is assumed that hydrated fuel ethanol (96°GL) uses 100% fuel in a 1,600 cm^3 car engine in an urban area, with an average consumption of 8 km/l. Only the fuel used in cars during the use phase is calculated, not the other impacts of the car's lifecycle.

3 Results and discussion

3.1 Lifecycle inventory analysis

The main results of the LCI for the whole lifecycle of fuel ethanol are presented per 10,000 km of alcohol-propelled driving in Figs. 1, 2, 3, 4, 5. The data sources are indicated in front of the name of each substance in the Tables 1 to 9, according to the corresponding references. The substances without the references are primary data, which were collected directly from the lifecycle activities of fuel ethanol.

The energy consumption and production of the ethanol lifecycle is presented in Fig. 2. It consumes less energy than its own production, mainly on account of the electricity cogeneration system (unit process 6). But this process is highly dependent on water, which can be verified according to the renewable resources consumption in Fig. 3. Including the energy of ethanol produced, considering a calorific value less than 21.10 MJ/kg, there is a net production of electricity and energy in the alcohol of 22198.77 MJ/t

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[1] Vinasse is the byproduct of the alcohol distillation that is recycled to the field.

[2] Bagasse is the solid byproduct of the juice extraction that is used to produce energy.

Table 7 Unit process 7: irrigation

Inputs		Outputs	
Non Renewable Resources	**Quantity (kg/10000 km)**	**Emissions to air**	**Quantity (kg/10.000 km)**
Diesel	4,68	CO_2 (from diesel)	0,91 (SimaPro Database 2003)
		NOx (from diesel)	0.012 (SimaPro Database 2003)
Renewable Resources		**Emissions to water**	
Water	125,76	CxHy (from diesel)	0,000013 (SimaPro Database 2003)
		H_2 (from diesel)	0,000020 (SimaPro Database 2003)
Energy consumption	**Quantity (MJ/10000 km)**		
Unspecified energy (from diesel)	0,31 (SimaPro Database 2003)		

alcohol, disregarding the consumption of direct electric power of the product system analyzed.

The main quantities of nonrenewable resource inputs per functional unit are presented for all ethanol lifecycles (Fig. 4). Calcium carbonate ($CaCO_3$), diesel, lubricants, nutrients, and sulfuric acid are the most consumed.

Even not considering the CO_2, CO, and hydrocarbons (excepted methane) emitted from sugarcane-related processes, the substances which are emitted to the atmosphere in the largest quantities are CO_2, oxides of nitrogen, methane, and CO (Fig. 5). The largest quantities of substances emitted to water are due to the diesel production and wastes from the production of phosphate fertilizers (Fig. 6).

The main environmental aspects of the fuel ethanol LCI are presented for each activity per 10,000 km of alcohol-propelled driving in Tables 1 to 9. All materials are calculated in mass (kilogram) because it is an adiabatic unit (not changing according to temperature or pressure) and the energy consumption in MJ, as the standard unit used on LCI studies. For water, it can relate, in general, 1 kg as 1 l.

The high consumption of liming as pH soil correction is noted at unit process 1 (Table 1). In the second unit process, sugarcane input generally comes from the previous harvesting. Diesel is the largest consumption for sugarcane plantation. For the outputs, CO_2 emission from the diesel product chain is the largest (Table 2). Unit process 3 is highly intensive on nonrenewable and renewable resources mainly because of the nutrient application and liming. The outputs are mainly due to the chemicals and diesel use and the phosphorus production wastes (Table 3). Unit process 4 is the largest emission activity of emissions to air (Table 4), mainly because of the burning prior to harvesting and the highly intensive use of machinery using diesel. The highlight of the analysis inventory results of unit process 5 (Table 5) is the high water consumption due to the sugarcane washing at the beginning of the industrial process. The washing is necessary especially due to the burning during harvesting, when the sugarcane exudes sugar juice which glues large quantities of dust onto the cane. The high water consumption happens due to the steam generation for electrical energy production (Table 6). The irrigation, in unit process 7, is mainly made with industrial waste which comes from sugarcane. So, it is not considered as external input, only the additional water that is used. The emissions are mainly due to the diesel consumption (Table 7). The ethanol distribution is by trucks using diesel and the highest quantity of air emission is CO_2 due to the diesel consumption (Table 8). The use of ethanol as 100% car fuel leads mainly to NOx emissions (Table 9).

3.2 Lifecycle impact assessment

The results of the lifecycle impact assessment are shown in the following paragraphs for each category of impact per

Table 8 Unit Process 8: Ethanol distribution

Inputs		Outputs	
Non Renewable Resources	**Quantity (kg/10000 km)**	**Emissions to air**	**Quantity (kg/10.000 km)**
Diesel	1,33	CO_2 (from diesel)	0,52 (SimaPro Database 2003)
		NOx (from diesel)	0,01 (SimaPro Database 2003)
Energy consumption	**Quantity (MJ/10000 km)**		
Unspecified energy (from diesel)	0,57 (SimaPro Database 2003)		

Table 9 Unit Process 9: Use of fuel ethanol

Outputs	
Emissions to air	**Quantity (kg/10.000 km)**
NOx	10,90 (COPERSUCAR 1989)

10,000 km of alcohol-propelled (Fig. 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17).

Global warming Harvesting is the unit process that most contributes to global warming, mainly because of burning and the diesel used on trucks for product transportation, tractors for harvesting, and buses for the transportation of workers (Fig. 7).

Photochemical ozone formation For photochemical ozone formation, harvesting is also the activity with the strongest contributions due to the burning in harvesting and emissions from diesel use (Fig. 8).

Acidification The acidification impact potential is mostly due to the NOx emitted by the ethanol combustion during the use phase because of the use of sulfuric acid in the industrial process and because of the NOx emitted by the burning in harvesting (Fig. 9).

Nutrient enrichment The major consequence of the intensive fertilizer use on the field is the high nutrient enrichment impact potential associated with this activity. Also, the use of ethanol contributes to this impact potential (Figs. 10, 11, 12).

Ecotoxicity No chemical emissions are recorded for unit processes 5–9 with ET impact potential. For the others, the main contributions to the ecotoxicity impact potential come from the chemical applications during crop growth, because of the high quantity of pesticides applied. The terrestrial toxicity potentials are low because of the assumption that the field is considered part of the technosphere and the emissions from the field to the surrounding environment are unknown (Figs. 13, 14). If the field were considered part of the ecosphere, this would be typically two orders of magnitude higher.

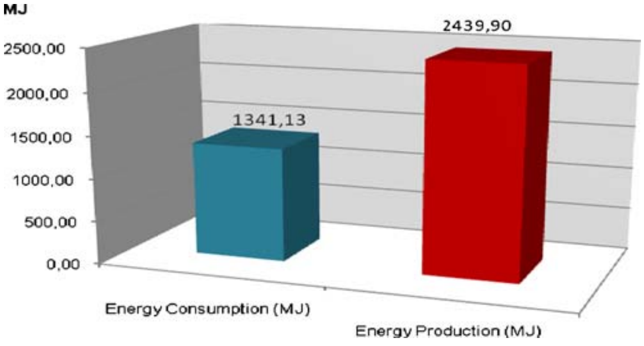

Fig. 2 Energy consumption and production of fuel ethanol lifecycle activities

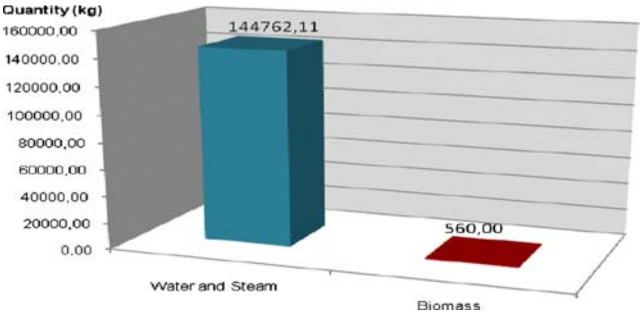

Fig. 3 Renewable resource inputs

Human toxicity For HT, there are emissions that contribute to all unit processes (Figs. 15, 16, 17). The activity that presents the highest impact potential for human toxicity via air and via soil is harvesting, mainly due to the emissions by the burning and the use of diesel. Via water, HT potential is high in activity 5 because of the use of lubricant on the machines (Fig. 16).

The aforementioned impact potentials have been normalized by the EDIP method, using world and European normalization references, which represent the annual average impact from an average citizen—a person equivalent, PE. The normalization references for the global impacts are based on an average global citizen and for the regional impacts are based on an average European citizen given that EDIP normalization references have not yet been

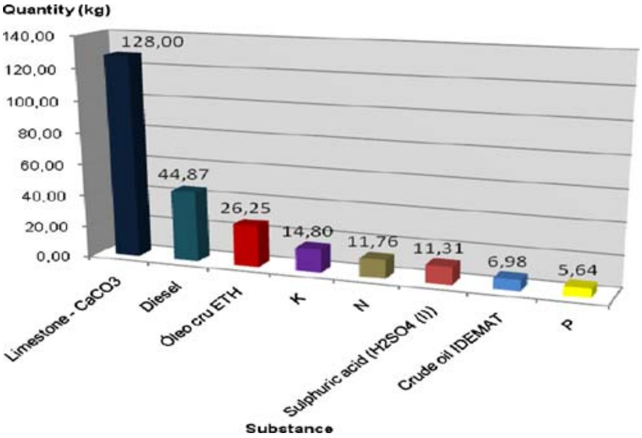

Fig. 4 Nonrenewable resource inputs

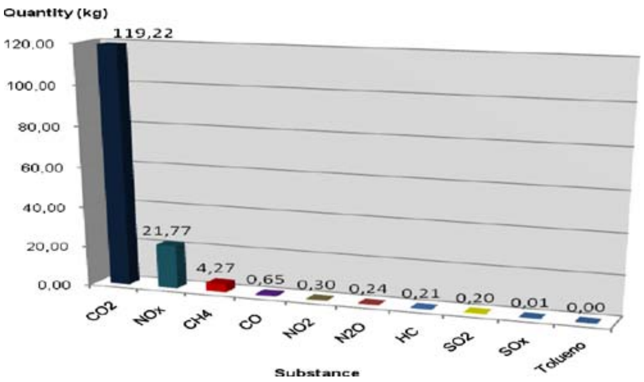

Fig. 5 Emissions to air

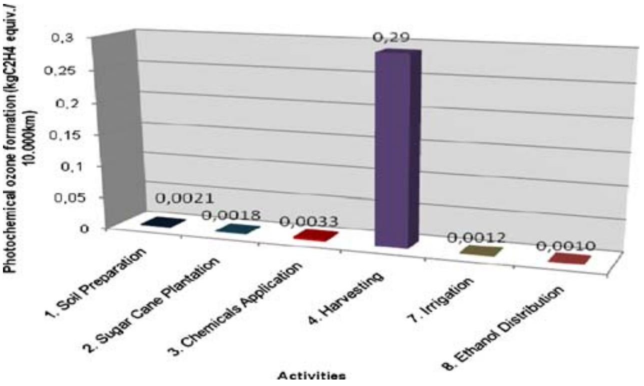

Fig. 8 Photochemical ozone formation impact potentials

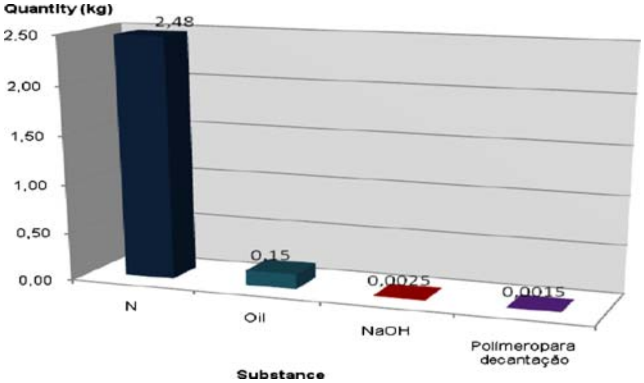

Fig. 6 Emissions to water

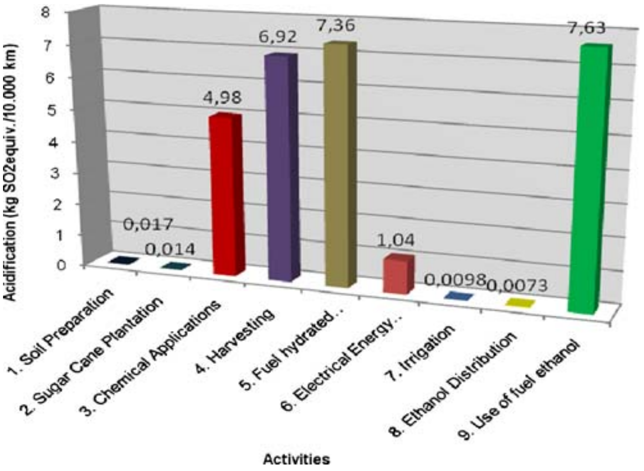

Fig. 9 Acidification impact potentials

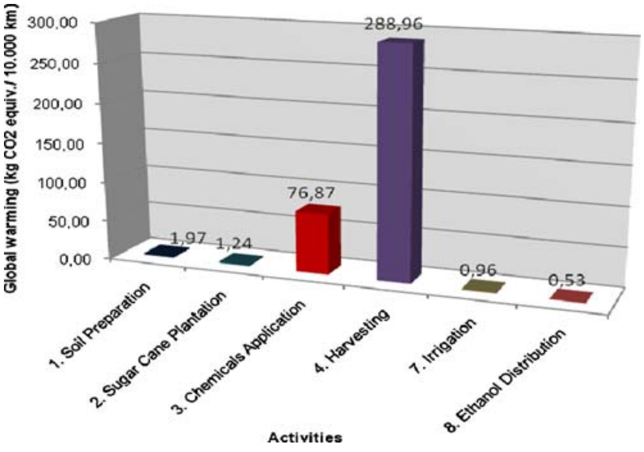

Fig. 7 Global warming impact potentials

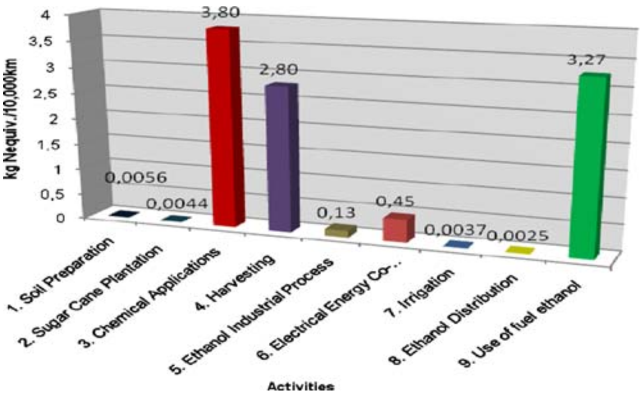

Fig. 10 Nutrient enrichment impact potentials (Neq)

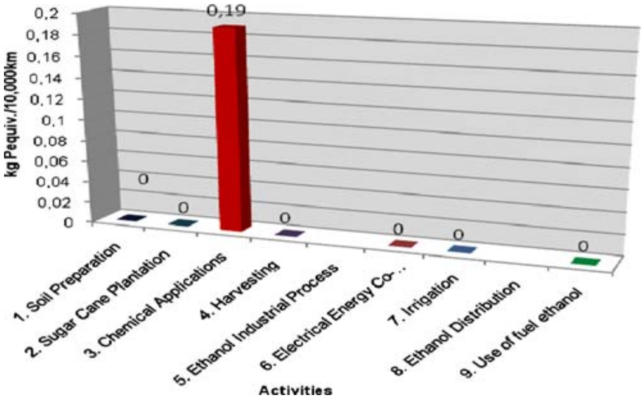

Fig. 11 Nutrient enrichment impact potentials (Peq)

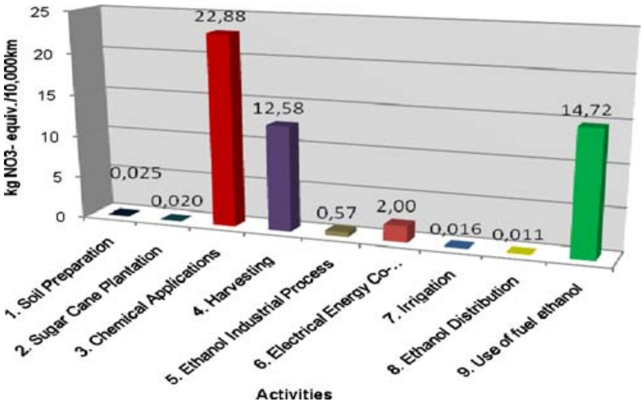

Fig. 12 Nutrient enrichment impact potentials (NO3eq)

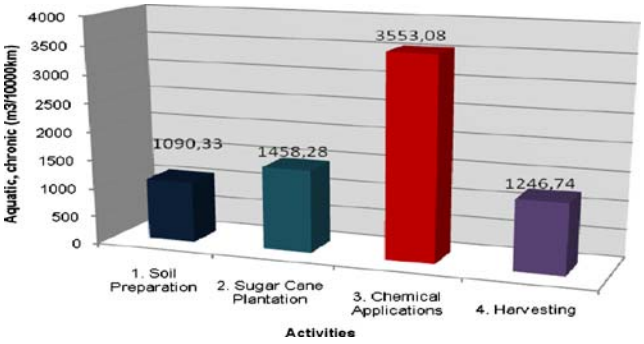

Fig. 13 Ecotoxicity impact potentials in water (chronic)

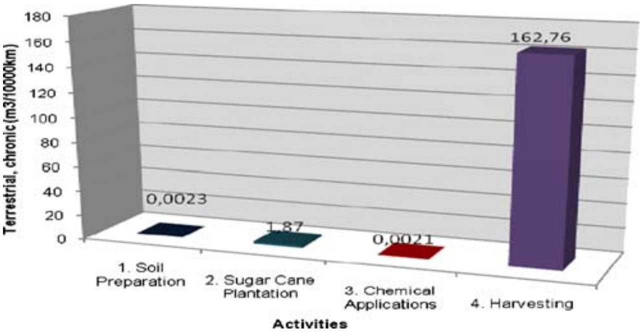

Fig. 14 Ecotoxicity impact potentials in soil

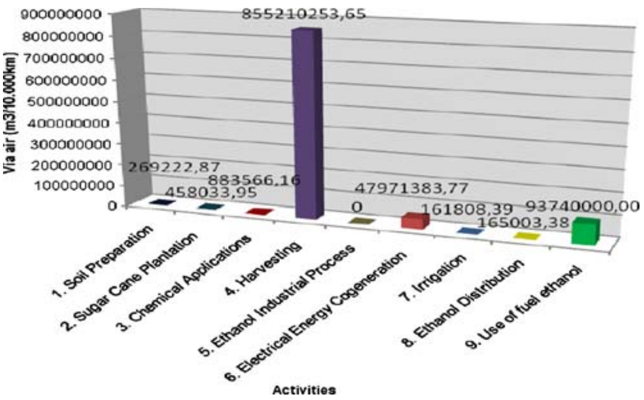

Fig. 15 Human toxicity impact potentials via air

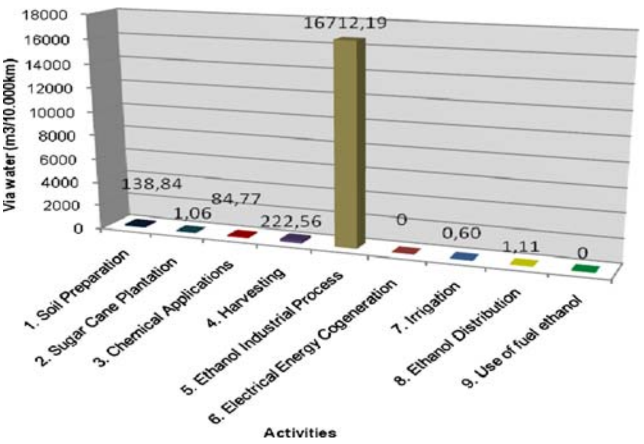

Fig. 16 Human toxicity impact potentials via water

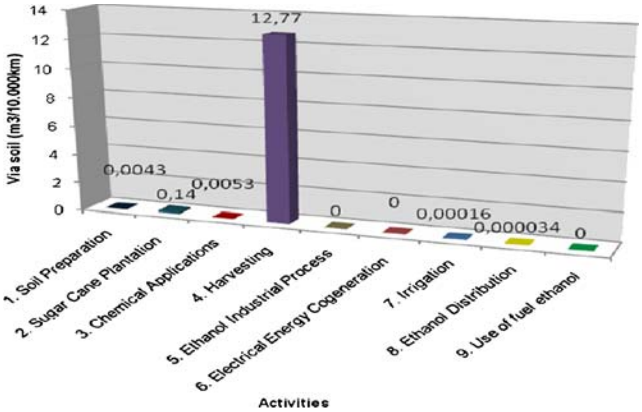

Fig. 17 Human toxicity impact potentials via soil

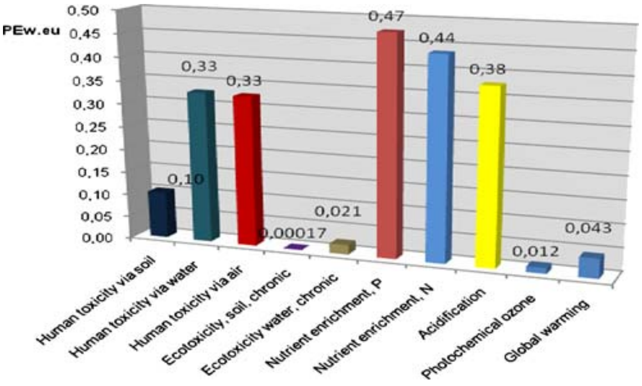

Fig. 18 Normalized impact potentials for fuel ethanol lifecycle

developed for Brazil. Calculation information for other regions show that the variation between countries or regions is modest, i.e., a factor 2–5 (Stranddorf et al. 2005). The normalization results indicate that nutrient enrichment, acidification, and human toxicity via air and via water are the biggest impact potential for the lifecycle of fuel ethanol (Fig. 18).

4 Conclusions

The conclusions reached for the LCI are that the fuel ethanol lifecycle consumes a high quantity and diversity of nonrenewable resources during its lifecycle. This consumption occurs because the product system, especially the rural activities of the sugarcane cultivation, is highly mechanized, with intensive use of pesticides, nutrients and diesel. The inputs of renewable resources are high mainly because of the water consumption in the industrial phases, due to the sugarcane washing. During the lifecycle of alcohol, there is a surplus of electricity due to the cogeneration activity. Another focus point is the quantity of air emissions and the diversity of the substances emitted, especially during the harvesting, because of the sugarcane burning and the high consumption of diesel.

The LCIA conclusions are that the fuel ethanol lifecycle contributes to all the impacts analyzed: global warming, ozone formation, acidification, nutrient enrichment, ecotoxicity, and human toxicity. The main causes for the biggest impact potential indicated by the normalization is the nutrient application, the burning in harvesting, and the use of diesel.

5 Recommendations and perspectives

The recommendations for the ethanol lifecycle are: to harvest the sugarcane without burning; to have more environmentally benign agricultural conservative techniques, for instance avoiding the use of nutrients and pesticides; to replace diesel for a renewable fuel (e.g., biodiesel from vegetable oils and fuel ethanol); not to wash sugarcane and implement water recycling systems during the industrial processing, and improvement on the system of gas emissions control during the use of ethanol in cars mainly for NOx. Further studies on the fuel ethanol from sugarcane may analyze in more detail the social aspects, biodiversity, and the land use impact.

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