ENVIRONMENTAL BALANCE OF BIOETHANOL FROM CORN GRAIN: EVALUATION OF DIFFERENT PROCEDURES OF CO-PRODUCTS ALLOCATION

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ABSTRACT: A Life Cycle Assessment for bioethanol production from corn grain was performed, in order to assess the environmental impacts of the process and to compare it to the production of gasoline. The analysis considered the entire system, which was required to produce 1 MJ of fuel energy content (as lower heating value). It included corn cultivation, starch extraction, using the modified wet milling process that allows to separate germ and fiber before sending gluten and starch mixture to the bioethanol plant. Environmental analysis was carried out using a detailed LCA software (Simapro 7.0), adopting EcoIndicator 99 for the evaluation of the global burden and IPCC (100-years) methodology for the calculation of greenhouse gas balance of the chain. In particular it was performed a sensitivity analysis regarding the allocation model using four procedures based on output weight, energy content, market value and replacement value of co-products. Results obtained demonstrate that the LCA of bioethanol from corn grain is highly sensitive to the allocation method used and that, without coproduct credits, the global environmental balance is higher than gasoline. Among the impact categories, the major burdens regard respiratory inorganics, land use, due to the corn cultivation, and fossil fuels consumption.
Keywords: life cycle assessment (LCA), bio-ethanol, CO_2 balance

1 INTRODUCTION

Bioethanol derived from biomass is often considered a significant contributor for a sustainable transportation fuel. There are two primary technologies to make bioethanol fuel on industrial scale. The first option, in wide use today, is to convert the starchy part of foods such as corn into bioethanol through seven steps: starch extraction, liquefaction, saccharification, fermentation, distillation, dehydration and denaturing. When sugarcane is used, only four or five steps are required: milling, pressing, fermentation and distillation, dehydration (only in case of alcohol blends). Although bioethanol has the advantage of being derived from renewable sources, its use for fuel was often criticized as being environmentally not sustainable, especially regarding greenhouse gas emissions (GHG). Therefore the Italian Biomass Research Centre has conducted a life cycle analysis of this chain, evaluating not only the GHG index, but also all environmental impacts.

In this analysis, one of the most critical issues is represented by the allocation procedure of coproducts, which allows to divide the environmental burdens, associated with a multi-output process, to the main product and its coproducts.

According to ISO standards [1, 2], the allocation should be avoided by dividing the unit process into two or more subprocesses or expanding the product system to include the additional functions related to coproducts.

Furthermore, ISO standards [1, 2] also state: where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships or other relationships between them.

In this study a sensitivity analysis was conducted to illustrate the consequences of the alternative approaches both on global environmental balance and greenhouse gas emissions.

2 LIFE CYCLE ASSESSMENT

Life Cycle Assessment was carried out with the assistance of a commercial LCA software package, SimaPro 7.0. It is an open structure program that can be used for different types of life cycle assessments. The production stage, the use stage and the end of life scenario can be specified in as much detail as necessary by selecting processes from the database and by building processes trees, which can be drawn by the program.

LCA studies are composed of several interrelated components: goal definition and scoping, inventory analysis, impact assessment and improvement assessment. In the following, each step is described with regard to this work.

2.1 Goal and scope definition

In this paper it was analyzed the environmental impact of bioethanol obtained from corn maize and used as a fuel (E95 - ethanol blended with five percent unleaded gasoline) for buses. The functional unit of the life cycle analysis was 1 MJ of mechanical energy from fuel combustion.

Fig. 1 shows the general system boundaries for the scenario considered in this study, in which machineries and infrastructures were not taken into account; then the corn bioethanol chain was compared to fossil diesel chain used in the same buses.

Currently most anhydrous ethanol is distilled from corn starch, which can be produced by the dry milling or wet milling process. In the wet milling process [3] the corn kernel is steeped or soaked, to allow it to be separated into germ, fiber and gluten; they are recovered and processed as coproducts of the process, obtaining corn oil, corn gluten meal and corn gluten feed. In dry milling [4] the corn is ground into flour (meal) and processed without the separation of the component parts. In this paper it was considered a variation of the wet milling process, which eliminates much of the capital investment required for complete corn fractionation. In modified wet milling [5], a shorter steeping cycle is used, which allows only for fiber recovery, used as animal feed (containing a minimum of 21% crude protein), and germ separation. There is no separate gluten section as in standard wet milling. The separated germ slurry, which contains most of the oil found in corn, is dewatered and dried for coproduct sales. Modified wet milling does not produce a clean starch stream, as the gluten component is carried along with starch into the saccharification section. A final coproduct, with high nutrient density and containing a minimum of 60% total protein, is produced.

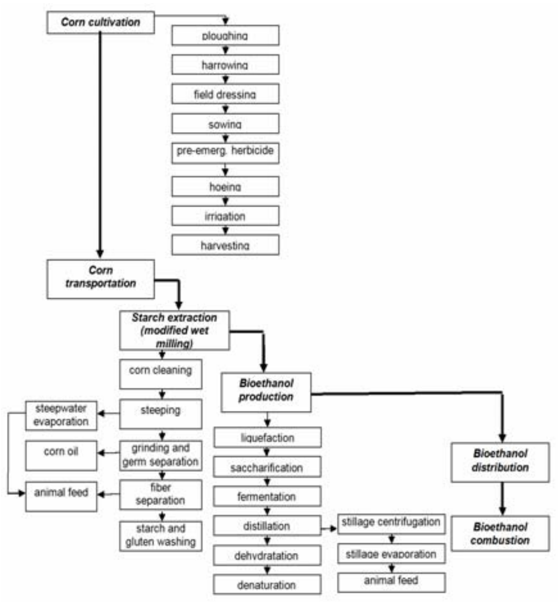

Figure 1: Production of bioethanol from corn maize through Modified Wet Milling process.

2.2 Inventory analysis

Each product or service has to be represented as a system in the inventory analysis methodology. It is a quantitative description of all the flows of materials and energy across the system boundary, either into or out of the system itself.

2.2.1 Corn cultivation

It was considered a corn cultivation system characterized by an investment of 70.000 seeds per hectare and annual harvesting with a yield of 10 ton grain/ha [6].

For each process the following quantities were considered, assuming data from lterature: the amount of machinery needed for a specific operation (operating machines and driving machines), fuel consumption for agricultural machines, amount of fertilizer and pesticide used, atmospheric emissions produced by diesel engines, heavy-metal emissions from tyre abrasion [7], ammonia, dinitrogen monoxide and NO_x air emissions from the application of fertilizers, phosphates water emissions from the application of fertilizers [8], VOC air emissions from the application of pesticides and soil pollution deriving from the remained of pesticides in the soil [9]. Data about diesel and materials consumption are listed in Table I.

It was considered the impact of land occupation too, assuming an occupation (1 year) of land for corn cultivation (0,0565 m^2yr/MJ) and a transformation of land from unknown utilization to corn cultivation (0,0565 m^2/MJ).

At last the carbon dioxide absorption by corn plant was taken into account, equal to 1,37 kg CO_2/kg grain [7].

Table I: Data summary for the agricultural operations.

Agricultural operations	Diesel (kg/ha)	Materials
ploughing	26,10	-
harrowing	4,44	-
field dressing	5,29	urea: 326 kg/ha; K_2O: 65 kg/ha; TSP: 208 kg/ha
sowing	3,82	seeds: 21 kg/ha
pre-emergency herbicide	1,76	atrazine: 4,65 kg/ha
hoeing	3,28	-
irrigation	3,78 (for the irrigation plant installation)	water: 1100 m^3/ha; electricity: 807 kWh/yr
harvesting	33,30	-

2.2.2 Corn transportation

For the transportation of corn grain to the ethanol plant, it was assumed a mean distance of 50 km, with a 28 tons lorry and characterized by a load factor equal to 47%. The atmospheric, soil and water emissions (due to tyre abrasion) and fuel consumption (0,29 kg diesel/km) were calculated referring to [10]

2.2.3 Starch extraction

Data (Tab. II) about energy and mass flows were taken from [3]. In the corn oil extraction, diesel is used in a boiler to produce steam, employed in a rotary steam dryer. This phase is necessary to reduce the germ moisture from 50-60% to 2-4%.

Table II: Data summary for the starch extraction operations.

Operations	Materials (unit/kg corn grain)
corn cleaning	electricity: 0,0046 kWh
steeping	water: 0,0016 m^3; electricity: 0,00232 kWh; 0,00075 kg; sulphur dioxide: 0,00075 kg
steepwater evaporation	water: 0,00026 m^3; electricity: 0,0057 kWh; sulphur dioxide emission: 0,000234 kg
grinding and germ separation	electricity: 0,0112 kWh
corn oil extraction	water: 0,000046 m^3; electricity: 0,00506 kWh; diesel: 0,0031 kg
fiber separation	electricity: 0,0255 kWh
fiber drying	electricity: 0,0041 kWh
starch and gluten washing	electricity: 0,0052 kWh

2.2.4 Bioethanol production

The mash (gluten and starch) obtained from starch extraction process is sent to the ethanol plant, which is divided in seven steps [11]:

- Liquefaction: the mash is mixed with water and an enzyme (alpha amylase) and passes through cookers where the starch is liquefied. A pH of 5,5-6,2 is maintained by adding sodium hydroxide and sulphuric acid, while enzyme is stabilized with calcium blending. Heat is applied to enable

liquefaction. Cookers with a high temperature stage (110 º C) and a lower temperature holding period (60 ºC) are used.
- Saccharification: the mash from the cookers is cooled and the enzyme gluco-amylase is added, to convert starch molecules into fermentable sugars (dextrose).
- Fermentation: yeast is added to the mash to ferment the sugars to ethanol and carbon dioxide. Using a continuous process, the fermenting mash flows through several fermenters, until the mash is fully fermented and leaves the tank.
- Distillation: the fermented mash contains about 10% alcohol, as well as all the non-fermentable solids from the corn and the yeast cells. The mash is then pumped to the continuous flow, a multi-column distillation system where the alcohol is removed from the solids and water. The alcohol leaves the top of the final column at about 96% strength and the residue mash, called stillage, is transferred from the base of the column to the co-product processing area, where is centrifuged and evaporated to obtain animal feed and condensate, that is recycled in the steeping phase.
- Dehydration: the alcohol passes through a dehydration system, with zeolitic molecular sieves, where the remaining water is removed. The alcohol at this stage is called anhydrous (pure, without water) ethanol and is about 99,3% strength.
- Denaturing: ethanol used for fuel is finally denatured with a small amount (5%) of gasoline to make it unfit for human consumption.

Data about this step were taken from [5], in which it is analyzed a plant that produces 7300 litres/hour of bioethanol from 160 ton/hour of corn grain; therefore bioethanol yield is equal to 0,46 litres/kg of corn grain. The following resources were considered as input data:
- water: 0,0207 l/kg of corn grain;
- zeolite: 0,000086 kg/kg of corn grain;
- sulphuric acid: 0,000887 kg/kg of corn grain;
- calcium: 0,000146 kg/kg of corn grain;
- urea: 0,0000883 kg/kg of corn grain;
- electricity: 0,088 kWh/kg of corn grain;
- liquid ammonia: 0,000858 kg/kg of corn grain;
- thermal energy (from burning natural gas to produce steam): 2515,7 kJ/kg of corn grain.

Energetic consumptions for enzymes and yeasts production were not taken into account.

Emissions from the bioethanol plant were the ones from natural gas combustion and the following [5]:
- carbon dioxide (from fermentation process): 0,427 kg/kg of corn grain;
- volatile organic compounds (from fermentation, distillation and dehydration processes): 0,0000149 kg/kg of corn grain;
- particulate (from operation and cleaning cyclones): 0,000818 kg/kg of corn grain;
- wastewater (from stillage evaporation, distillation and dehydration processes): 0,0000108 l/kg of corn grain. The wastewater is characterized by high BOD contents and acid pH, therefore it was taken into account a treatment divided into three stages (mechanical, biological and chemical), including sludge digestion.

2.2.5 Bioethanol distribution

For the transportation of bioethanol to the distribution, it was assumed a mean distance of 50 km, with a 40 tons tanker and characterized by a load factor equal to 46%. The emissions and fuel consumption (0,348 kg diesel/km) were determined as described in 2.2.2.

2.2.6 Bioethanol combustion

It was considered that bioethanol was used as a petrol blend (E95) in buses. The petrol needs to be included for safety (flame visibility) and starting purposes. Blend is characterized by a lower heating value equal to 27,78 MJ/kg and the petrol fraction is 0,0018 kg/MJ. Table III reports emissions from E95 combustion [12].

Table III: Emissions from E95 combustion in buses undergoing an urban drive cycle.

Substances	g/l
CO	24,90
CO_2	2607,90
THC	8,50
OMHCE (Organic Material Hydrocarbon Equivalent)	9,19
NO_X	13,77
PM	0,38
Ethilic alcohol	5,57
Formaldehyde	0,24
Acetaldehyde	1,28

2.3 Impact assessment

Impact assessment was carried out considering eleven impact categories (carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, fossil fuels) classified into three damage categories: Human Health (HH), Ecosystem Quality (EQ) and Resources (R). Finally, the application of weighting factors to determine the relative importance, or seriousness, of a category results may be represented as a single score in eco-indicator points (Pt).

In this study the impact assessment was performed by the EcoIndicator 99 LCIA method [13]. This method was preferred to others because it provides the most relevant impact assessment categories relative to this study. The index chosen for the impact assessment is the hierarchist's version, which represents the most balanced view amongst all the perspectives on nature.

Finally the balance of greenhouse gas emissions was analyzed adopting the IPCC methodology, with a time horizon of 100 years [14].

2.4 Coproducts allocation

Coproducts (defined as products with similar revenues to the main product) allocation is one of the most controversial issues in the development of the methodology for life cycle assessments, as it may significantly influence or even determine the result of the assessments. All industrial processes have multiple input streams and many generate multiple output streams. Usually, only one of the outputs is of interest for the life cycle assessment study, therefore the analyst needs to determine how much of the energy and material requirements and of the environmental releases associated to the process should be attributed, or allocated, to the production of each coproduct [15].

When coproducts are present, it must determine how much of the burdens associated to operating and supplying the multi-output process should be allocated to each co-product.

The guidance provided by the International Standards Organization (ISO) [2] recognizes the variety of approaches that can be used to treat the allocation issue and, therefore, requires a step-wise approach The standard calls to avoid allocation if possible, using substitution approach, and secondly to model approaches which reflect the physical or other relationships between the process outputs and its inputs. In the substitution approach, the main conventional process for producing a coproduct is used to generate comparative effective credits, which are then subtracted from the life cycle inventory of the process chain under investigation.

As regards allocation approaches, there are basically three ways to split environmental burdens between the main product and its coproducts, based on energy content, market value and output weight basis.

In this paper the four above-mentioned models were used to determine the global environmental burden (expressed in Points) and the greenhouse gas emissions for corn bioethanol. In this biofuel chain there are two coproducts represented by corn oil (0,04 kg/kg of corn grain) and animal feed (0,23 kg/kg of corn grain); in particular it was assumed that 80% (0,184 kg) of animal feed has the same nutrient properties of corn gluten feed and the remaining (0,046 kg) has the same characteristics of corn gluten meal [16].

In substitution approach it was assumed that corn gluten meal could replace both corn grain (with a displacement ratio of 1,529:1, in terms of kg of displaced product on kg of coproduct) and nitrogen in urea (0,023:1) used as animal feeds, corn gluten feed could replace always corn grain (1:1) and nitrogen in urea (0,015:1) and corn oil could substitute soybean oil in the market with the same quantity (1:1) [17]. Environmental credits of coproducts were calculated assuming the relative processes described in the Simapro libraries. Therefore, in substitution approach the allocation ratio (AR) was different according to what environmental impacts were analyzed. The allocation ratios for bioethanol and coproducts were obtained according to equations (1, 2):

$$AR_{bioethanol} = EB_{bioethanol}/(EB_{bioethanol} + EB_{coproducts}) \quad (1)$$

$$AR_{coproducts} = EB_{coproducts}/(EB_{bioethanol} + EB_{coproducts}) \quad (2)$$

where

$EB_{bioethanol}$ = environmental burden (in terms of mPt or gCO_2eq) of bioethanol;

$EB_{coproducts}$ = environmental burden (in terms of mPt or gCO_2eq) of coproducts.

Allocation on energy content basis was performed in terms of gross energy, that is the total amount of energy, in any form, contained in the feedstuff or biofuel. It would represent the energy (or heat) given off if the feed or biofuel were somehow totally combusted. For bioethanol it was assumed a value of gross energy equal to 23,4 MJ/liter [18] (obtaining 10,76 MJ/kg of corn grain) while for coproducts the following values were assumed:

- corn oil: 38,94 MJ/kg (1,56 MJ/kg of corn grain) [19];
- animal feed (as corn gluten meal): 21,08 MJ/kg (0,97 MJ/kg of corn grain) [20];
- animal feed (as corn gluten feed): 18,07 MJ/kg (3,33 MJ/kg of corn grain) [20].

From these assumptions, it was obtained an allocation ratio of 64,8% for bioethanol and 35,2% for coproducts.

An economic analysis of corn bioethanol chain was conducted considering the market scenario of United States. For bioethanol it was considered an effective price of 0,39 $/liter [21] (corresponding to 0,18 $/kg of corn grain) (average value in the period from August 2006 to January 2008) while for coproducts the following average wholesale prices were assumed [22]:

- corn oil: 0,69 $/kg (0,028 $/kg of corn grain);
- animal feed (as corn gluten meal): 0,34 $/kg (0,016 $/kg of corn grain);
- animal feed (as corn gluten feed): 0,05 $/kg (0,009 $/kg of corn grain).

In this case the allocation ratio was 77,5% for bioethanol and 22,5% for coproducts.

As regards allocation on output weight basis, it was considered only the weight of bioethanol (0,37 kg/kg of corn grain, assuming a density of 0,795 kg/liter) and its coproducts (0,27 kg/kg of corn grain), regardless of the operation's purpose or the coproducts economic values. Therefore the allocation ratio was 57,5% for bioethanol and 42,5% for coproducts.

3 RESULTS AND DISCUSSION

In Table IV the results (expressed in mPt) of environmental impact of corn bioethanol chain, splitted between the damage categories of EcoIndicator 99 model, are presented, applying the substitution approach. The agricultural land use was separated in order to identify its relative environmental impact. In EcoIndicator 99 the land use impact category describes the environmental impacts of utilizing and reshaping land for human purposes.

Table IV: Simapro results for the damage categories (in mPt) with coproducts.

Damage category	Total	Human health	Ecosystem quality	Resources
Total	5,81	1,02	3,63	1,16
Corn cultivation	3,71	1,13	0,897	1,68
Corn transp.	0,106	0,0273	0,0066	0,0726
Starch extraction	-7,69	-2,25	-2,64	-2,79
Bioethanol production	2,24	0,528	0,015	1,7
Bioethanol distribution	0,0225	0,0054	0,0014	0,0158
Bioethanol combustion	2,35	1,58	0,284	0,482
Land use	5,07	0	5,07	0

Table V: Simapro results for the impact categories (in mPt) with coproducts.

Impact category	Corn cultivation	Corn transp.	Starch extraction	Bioethanol production	Bioethanol distribution	Bioethanol combustion	Land use
Carcinogens	3,71E-03	1,06E-04	-7,69E-03	2,24E-03	2,25E-05	2,35E-03	5,07E-03
Resp. organics	2,89E-04	8,37E-08	-7,82E-04	4,40E-06	1,79E-08	9,54E-07	0
Resp. inorganics	4,46E-07	4,53E-08	-6,24E-07	1,93E-07	8,69E-09	2,15E-05	0
Climate change	1,34E-03	2,27E-05	-1,42E-03	2,45E-04	4,39E-06	1,14E-03	0
Radiation	-5,04E-04	4,40E-06	-4,50E-05	2,76E-04	9,56E-07	4,16E-04	0
Ozone layer	3,79E-06	5,64E-09	-3,90E-06	2,21E-06	1,23E-09	4,59E-08	0
Ecotoxicity	6,03E-08	4,25E-09	-9,43E-08	5,11E-08	9,24E-10	2,66E-08	0
Acidif/ Eutroph.	9,12E-05	2,40E-06	-3,14E-04	3,71E-06	5,22E-07	9,81E-07	0
Land use	6,33E-04	4,17E-06	-6,36E-04	6,30E-06	8,49E-07	2,83E-04	0
Minerals	1,73E-04	2,57E-08	-1,69E-03	5,03E-06	5,60E-09	2,58E-07	5,07E-03
Fossil fuels	3,22E-05	1,30E-08	-4,22E-05	2,10E-06	2,83E-09	1,96E-07	0

In Table V results splitted between impact categories are reported; the following considerations about the main impact categories could be done:

- carcinogens: it is due to water emissions from herbicides application and air emissions (mostly cadmium) from diesel combustion in tractors. The negative contribution derives from coproducts (in particular from soil emissions avoided that would be caused if the substitutive products were cultivated);
- respiratory inorganics: the main contributions are the air emissions of nitrogen oxides (77%) caused by bioethanol combustion, particulate (16%) from bioethanol production (6,5%) and ammonia, from urea application; the negative input is due to the nitrogen fertilization avoided for the coproducts (soybean and corn) cultivation step;
- climate change: the main contribution is due to the carbon dioxide emission from fermentation process, while the negative input derives from carbon dioxide absorption by corn plant;
- acidification/eutrophication: corn cultivation and bioethanol combustion are the principal processes that concur to this impact category, because of nitrogen oxide air emissions from bioethanol combustion, urea application and ammonia air emissions from urea spreading. The impact is mitigated by ammonia emissions avoided from coproducts cultivation;
- land use: the impact of land use for corn cultivation is about equal to 45% of the global score. This put some doubts about the weight assigned to this environmental impact by EcoIndicator 99 model.
- fossil fuels: two fossil resources are mostly consumed in the biofuel chain: natural gas (84%) and crude oil (15,7%). These fossil resources are used above all in corn cultivation phase, in which natural gas is employed for urea production. Also in this case the impact is mitigated by avoiding fossil resources consumption in the coproducts cultivation step.

The score of starch extraction process was negative because coproducts environmental credits were put into this phase.

The same analysis was conducted excluding processes relative to the production of the substitutive products, in order to quantify the allocation ratio for the substitution approach. It was obtained that the global environmental burden was equal to 13,7 mPt and therefore the allocation ratio was 42,4% for bioethanol and 57,6% for coproducts.

As regards greenhouse gas emissions balance (expressed in g of CO_2 equivalent (CO_2eq)), the 100-years IPCC methodology [14] was applied and results obtained are reported in Table VI (in this analysis no emissions of greenhouse gas were associated to land use category).

Adopting the same methodology, it was calculated the greenhouse gas emissions balance without coproduct credits, obtaining the result of 47,6 gCO_2eq and a value of allocation ratio equal to 78,4% for bioethanol and 21,6% for coproducts.

Table VI: Greenhouse gas emissions of corn bioethanol chain with coproducts

Process	gCO_2eq/MJ
Corn cultivation	-124
Corn transportation	1,07
Starch extraction	-8,82
Bioethanol production	67,2
Bioethanol distribution	0,23
Bioethanol combustion	102
Total	37,3

Results, in terms of global environmental impact and greenhouse gas emissions, for the different counting models of coproducts are summarized in tables VII and VIII.

Table VII: Global environmental burden adopting different allocation methods for coproducts.

Allocation pathway	Allocation ratio (%)		Global burden (mPt/MJ)
	Bioethanol	*Coproducts*	
Substitution	42,4	57,6	5,8
Energy content	64,8	35,2	8,9
Market value	77,5	22,5	10,6
Output weight basis	57,5	42,5	7,9
Global burden (mPt/MJ) without coproducts			*13,7*

Table VIII: Greenhouse gas emissions adopting different allocation methods for coproducts.

Allocation pathway	Allocation ratio (%)		GHG (gCO_2eq/MJ)
	Bioethanol	*Coproducts*	
Substitution	78,4	21,6	37,3
Energy content	64,8	35,2	30,8
Market value	77,5	22,5	36,9
Output weight basis	57,5	42,5	27,4
GHG ($gCO_2eq./MJ.$) without coproducts			*47,6*

3.1 Comparison with diesel chain

Corn bioethanol chain was compared to fossil diesel chain used in the same buses. Processes relative to fossil chain were drawn from EcoInvent library [23] (except for combustion phase) and data were normalized to the functional unit of 1 MJ of mechanical energy from fuel combustion.

Processes considered for fossil chain were:

- crude oil extraction;
- crude oil transport from extraction site to refinery;
- crude oil refining;
- diesel transport to storage centre;
- diesel combustion in buses.

Data of diesel combustion in buses were taken from [12] and are reported in Table IX.

Table IX: Emissions from diesel combustion in buses undergoing an urban drive cycle.

Substance	g/MJ
CO_2	69
CH_4	0,001
N_2O	0,002
CO	0,092
NO_x	0,736
NMVOC	0,055
Particulate	0,023

As regards global environmental burden, results (Tab. X) show that bioethanol chain has a lower environmental impact (about 21,5%) than fossil chain only when it was used substitution approach (-29,2%) and allocation on output weight basis (-3,5%).

Table X: Simapro results for diesel chain.

Damage category	Diesel
Total	8,19
Human health	1,81
Ecosystem. quality	0,362
Resources	6,02

Besides if land use impact is considered negligible (in this case global burden would be equal to 8,63 mPt without coproducts), since soil used is anyhow destined to food or energy crops cultivation, the impact of bioethanol chain will be lower than fossil chain in any cases.

A comparison between biofuel and fossil chains was also conducted on the basis of greenhouse gas emissions. For diesel chain it was obtained a value of 83,9 gCO_2eq/MJ, which is higher than the scores determined for bioetahnol chain in each case.

4 CONCLUSIONS

The LCA analysis of producing bioethanol from corn grain was carried out considering the overall process, characterized by corn cultivation, starch extraction with Modified Wet Milling, starch conversion into bioethanol, bioethanol distribution and combustion processes. Data for each phase were obtained from the Literature and by calculation.

The environmental analysis was conducted in terms of ecological impact, applying the EcoIndicator 99 method, and of GHG balance, adopting the IPCC (100-years) methodology.

The ecological analysis, without coproducts credits, showed that main impacting phases were due to the corn cultivation (64,3%), bioethanol production (16,4%) and bioethanol combustion (17,2%). The agricultural process was characterized by a high score, mostly attributing to the land use impact category.

Furthermore, it was analyzed the influence of allocation procedure used to count the environmental credit of coproducts. Sensitivity analysis showed that the choice of the allocation method is one of the substantial issues in bioethanol LCA and influences the final results more significantly than any other parameter of life cycle inventory. Even if it is not possible to consider an allocation method better than another, substitution approach is desirable because it accounts for the complete life cycle of the biofuel and the coproducts. This approach can be used if the substitute products are clearly identified and if sufficient information is available to determine the environmental burden intensity of their production processes.

Furthermore, for the corn bioethanol chain, the use of the other allocation approaches is characterized by some disadvantages.

In the energetic procedure, the energy content of the coproducts is a measurement of their food nutritional values and it is not a good proxy for energy in a fuel context.

The disadvantage of market value approach is that prices of bioethanol and coproducts are determined by a large number of market factors, unrelated to environmental burden.

The output weight basis approach has limited justification because of the weak causality between life cycle energy inputs and emissions and the mass of coproducts; in particular, the weight of a product is not always a good measurement of its energy value.

Results showed that the influence of the allocation procedure choice is more remarkable in the global environmental burden evaluation. Only with the application of substitution approach, it was obtained a substantial reduction of environmental score compared to fossil chain. The analysis of coproducts environmental burden takes into account that the impact categories characterized by the main credits are fossil fuel (2,86 mPt), land use (1,69 mPt) and respiratory inorganics (1,46 mPt, principally due to the ammonia emissions, caused by fertilizers application during the substitutive products cultivation).

In terms of greenhouse gas emissions, substitution approach attributes the major impact to the bioethanol; in this case the greenhouse gas saving was equal to 55,5% while adopting the other allocation methods the following values were obtained: 63,3% (energy content), 56% (market value) and 67,3% (output weight basis).

However this result will need to be revised considering the direct and indirect land use change effects, which could sensibly modify the greenhouse gas balance. Direct land use change occurs when feedstock for biofuels purposes (e.g. corn for bioethanol) displace a prior land use (e.g. forest), thereby generating possible changes in the carbon stock of that land. Indirect land use change occurs when pressure on agriculture due to the displacement of previous activity or use of the biomass induces land use changes on other lands. Moreover, biofuels production will also increase the supply of coproducts; even though the land use change is generated by the coproduct, it can be considered as an indirect effect of the biofuel pathway [24].

As regards direct land use change, default values of greenhouse gas emission factors are available, while actually, for evaluation of indirect land use change, does not exist any scientifically recognized methodology.

In the EU's recent proposed Directive on the promotion of the use of energy from renewable sources [25], a simplified rule was proposed to account annualised emissions from carbon stock changes caused by direct land use change, dividing total emissions equally over 20 years:

$$e_l = (CS_R - CS_A) \text{ x } 3.664 \text{ x } 1/20 \text{ x } 1/P \qquad (3)$$

where

e_l = annualised greenhouse gas emissions from carbon stock change due to land use change (measured as mass of CO_2eq per unit of biofuel energy);

CS_R = the carbon stock per unit area associated with the reference land use (measured as mass of carbon per unit area, including both soil and vegetation). The reference land use shall be the land use in January 2008 or 20 years before the raw material was obtained, whichever was the later;

CS_A = the carbon stock per unit area associated with the actual land use (measured as mass of carbon per unit area, including both soil and vegetation);

P = the productivity of the crop (measured as biofuel or other bioliquid energy per unit area per year).

In the bioethanol chain, if the land where the corn was produced was permanent grassland in January 2008, the parameters in (1) assume the following values:

CS_R = 181 ton carbon/ha [25];

CS_A = 82 ton carbon/ha [25];

P = 97.060 MJ/ha (assuming that lower heating value for bioethanol is equal to 21,1 MJ/litre [18]).

Therefore greenhouse gas emissions from direct land use change would be equal to 186,9 gCO_2eq/MJ, corresponding to 146,5 gCO_2eq/MJ for bioethanol, with substitution approach (allocation ratio: 78,4%).

This result shows that corn bioethanol chain not always allows to reach a greenhouse gas saving compared with fossil chain if the effects of land use change are considered. Hence it would be recommended to define exact methodologies for the evaluation of direct and indirect land use changes, in order to insert these impacts in the environmental balance of biofuel chains.

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