Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe

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A B S T R A C T

Liquid biofuels provide one of the few options for fossil fuel substitution in the short to medium-term and they are strongly being promoted by the European Union as transport fuel (such as ethanol) since they have the potential to offer both greenhouse gas (GHG) savings and energy security. A “well to wheel” analysis has been conducted for poplar based ethanol by means of the Life Cycle Assessment (LCA) approach. The aim of the analysis is to assess the environmental performance of three ethanol applications (E10, E85 and E100) in comparison with conventional gasoline. To compare the environmental profiles, the study addressed the impact potentials per kilometre driven by a middle size passenger car, taking into account the performance difference between ethanol blends and gasoline. According to the results of this study, fuel ethanol derived from poplar biomass may help to reduce the contributions to global warming, abiotic resources depletion and ozone layer depletion up to 62%, 72% and 36% respectively. Reductions of fossil fuel extraction of up to 80% could be achieved when pure ethanol is used. On the contrary, contributions to other impact categories would be increased, specifically to acidification and eutrophication. In both categories, ethanol based blends are less environmentally friendly than conventional gasoline due to the higher impact from the upstream activities. Research focused on the reduction of the environmental impacts should be pointed forward poplar cultivation as well as ethanol conversion plant (enzyme manufacturing, energy production and distillation). In this study poplar cultivation was really intensive in order to obtain a high yield. Strategic planning according to the location of the crops and its requirements should help to reduce these impacts from its cultivation.

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1. Introduction

The progressive depletion of non-renewable fossil fuels and mankind’s growing concern regarding climate change and atmospheric pollution, has led to an interest in the use of renewable fuels. Nowadays, 40% of the total energy consumption worldwide is in the form of liquid fuels such as gasoline and diesel [1]. In fact, transport is almost fully dependent on these kinds of liquid fuels. Special attention has been paid to the potential use of biomass for production of alternative and renewable fuels to be used in vehicles. Liquid biofuels, especially ethanol, provide one of the few options for fossil fuels substitution in the short- to medium-term and are strongly promoted by the European Union [2]: they have the potential to offer both greenhouse gas (GHG) savings and a secure supply of energy [3].

Ethanol derived from biomass has the potential of being an environmentally friendly transportation fuel as well as an alternative to gasoline [4]. In fact, it is used in the light duty vehicle fleet in a large number of countries [5]. Traditionally, ethanol has been produced from starch and sugar crops such as cassava, rice, wheat, barley, corn grain or sugarcane [6]. However, a variety of biomass feedstocks can be used for ethanol production (second-generation ethanol), e.g. mill wastes, municipal solid wastes and/or lignocellulosic biomass [7]. Corn based ethanol processes have been commercialized, but an economical and energy efficient process for the conversion of cellulosic material to ethanol has not been achieved yet [8,9]. However, the land use requirement can cause the competition with food and nature, which is becoming the main driving force of the development of advanced process technologies to produce ethanol from lignocellulosic materials (low value
agricultural co-products or wastes like corn stover, wheat straw, sugarcane bagasse, wood or grass).

Several studies were conducted on the environmental impact of ethanol, focusing mainly on two main aims related to the use of biofuels: reduction of primary fossil fuel extraction and reduction of GHG [10–15]. According to these studies, the production and use of cellulosic ethanol have the potential to result in significant abatement of GHG emissions since the carbon released as CO2 from combustion of the fuel would be incorporated into the regrowth of the plant. In addition, reduction of up to 50% of fossil fuel consumption could be achieved in comparison with the use of gasoline [16].

This study is focused on one woody potential feedstock to produce ethanol. Poplar (Populus sp.) is an example of the implementation of energy crops in Europe for biomass or biofuel in energy forestry systems. It is a fast growing and short rotation energy crop, which is widely used for the manufacture of paper pulp, pallets and cheap plywood [17]. The advantages of the agricultural production of poplar include the fact that it is a crop with a known tradition in Europe specifically in Spain where 135,720 ha were cultivated in 2008 [18], high yields, high ecological interest and low biomass production costs [19,20]. Fig. 1 shows the distribution of poplar dedicated areas in Spain based on statistics data from the Spanish Ministry of the Environment and Rural and Marine Affairs [15], which were mapped using the ArcView GIS 3.2 program [21]. Another social and economic benefits of using poplar as feedstock to ethanol production are that this crop does not compete with food and feed crops such as cereals [8,11]. However, the poplar cultivation presents also disadvantages such as high water requirements which limit the natural distribution of poplar [19,20]. Therefore, establishment of poplars as an energy crop could compete with other crops in areas having sufficient water and land availability [22]. Strategic planning should be a key factor in the environmental and energetic performance of this crop taking into account the location and local climatic conditions.

Poplar is an ideal candidate for cellulosic ethanol production [23–25] and an alternative to other energy crops since its biomass presents a chemical composition richer in cellulose and hemicellulose [26] which are the main raw materials for sugar conversion. In addition, poplar could also be interesting in comparison with the use of forest waste with this aim because of forest wastes are commonly used as raw materials in power plants (heat and electricity production) [27].

This study focuses on poplar biomass as a second-generation biofuel, involving the use of cellulosic technology. The objective is to perform an assessment of energy and environmental performance of ethanol using life cycle assessment (LCA) approach. In particular, the analysis compares the environmental performance of i) ethanol in a 10% blend with gasoline (E10), ii) ethanol in an 85% blend with gasoline (E85) and iii) pure ethanol (E100) with conventional gasoline (CG). The full life cycles of ethanol and gasoline are analysed, including the production and transport of the raw materials and fuels, the production of electricity and the use of fuels in a middle size passenger car. So far, although previous

**Nomenclature**

- AD: abiotic depletion
- AC: acidification
- CG: conventional gasoline
- EP: eutrophication
- E10: ethanol based fuel: 10% ethanol + 90% gasoline by volume
- E85: ethanol based fuel: 85% ethanol + 15% gasoline by volume
- FFV: flexi fuel vehicle
- FF: fossil fuels extraction
- FE: fresh water aquatic ecotoxicity
- GW: global warming
- GHG: greenhouse gas
- HT: human toxicity
- LCA: life cycle assessment
- LCI: life cycle inventory
- ME: marine aquatic ecotoxicity
- OD: ozone layer depletion
- PO: photochemical-oxidants formation
- E100: pure ethanol
- TE: terrestrial ecotoxicity

![Fig. 1. Poplar distribution in Spain per autonomous regions expressed in ha.](image)
LCA studies have been conducted to assess the environmental impacts of cellulosic ethanol from cellulosic feedstocks, no studies were found on ethanol produced from poplar biomass.

2. Methodology

Life Cycle Assessment approach (LCA) is defined as a methodology for the comprehensive assessment of the impact that a product has on the environment throughout its life cycle (from extraction of raw materials through manufacturing, logistics and use to scrapping and recycling, if any), which is known as a "from cradle to grave" analysis [28]. LCA is an objective process to evaluate the environmental burdens associated with a product by identifying natural resources consumption and emissions to environmental compartments, and to identify and implement opportunities to attain environmental improvements. The present study concerns the general comparison of technologies for the car driving function, without specific local circumstances playing a role.

2.1. Functional unit and alternatives

Ethanol is currently used as vehicle fuel mainly in two ways. The first one is blended with gasoline in 5–20% by volume for its use in vehicles without engine modifications. The second one is to use ethanol almost in its pure form (85–100%) in vehicles with modified engines.

In this study, ethanol is assumed to be used in two blends: E10 (10% ethanol and 90% gasoline by volume) and E85 (85% ethanol and 15% gasoline by volume) in a middle size flexi fuel vehicle (FFV). As a reference alternative, a hypothetical case of 100% ethanol is also taken into account (E100). LCA methodology was used to compare the environmental performance of these fuels in a "well to wheel" analysis with the use of conventional gasoline (CG).

The function of the study is to drive an FFV. The functional unit chosen to compare the life cycle flows is 1 km driven by a middle size FFV. Under these conditions, the amount of fuel required for travelling 1 km is calculated to be 66 g for CG, 69 g for E10, 92 g for E85 and 99 g for E100. The average fuel economy considered in the FFV under study running with CG, E10, E85 and E100 was 10.91 km/L, 10.51 km/L, 8.29 km/L and 7.78 km/L respectively [29,30].

2.2. System boundaries

All relevant processes are included within the boundary of the fuel systems, as shown in Fig. 2. Furthermore, those for capital goods and wastes management are included as well. The production and disposal of the car are outside of the system boundaries.

2.2.1. Poplar cropping subsystem (S1)

A standard hectare of experimental plot cultivated in Soria (Spain) was considered in this study since poplar is a traditional crop in this region [19,20]. The climate conditions in the region assessed are continental–Mediterranean. The mean annual temperature is 10.5 °C and annual rainfall is about 500 mm. The texture of the soil was sandy loam: sand 70–85%, silt less than 10% and clay less than 15%. Oxidizing organic matter was about 1% and pH around 6. The soil is light with good drainage [29]. The poplar plantation was established at a density of 10,000 plants/ha during three consecutive cycles (cuts) of 5 years each [19] during the whole life cycle [31].

The poplar cultivation is irrigated with water (28,000 m³/ha) in order to obtain a high productivity of biomass 216 oven dry tones per ha during 15 years.

The production of the different consumable inputs such as fertilizers NPK (9/18/27/) and simples fertilizer (ammonium nitrate 33%) and pesticides, use of machinery and diesel consumption and associated emissions were considered within the system boundaries as well as their transport from wholesale to farm gate. Diffuse emissions from fertilizer application and emissions from agricultural machinery (fertilizing, planting, harvesting and transport) have also been taken into account. A short description of diffuse emissions related to chemicals application is shown in Table 1.

The binding of CO₂ from the atmosphere was taken into account and estimated by the C-content in the dry matter multiplied by the stoichiometric factor 44/12, based on the assumption that the carbon in the biomass is completely taken from the air (~1.84 kg CO₂/kg dried biomass). The farmers transport to cultivate and supervise the crop was also included. Regarding harvested biomass, it was assumed to be converted into chips which make the transport easier.

2.2.2. Ethanol plant subsystem (S2)

In the ethanol plant, poplar biomass chips are converted to ethanol by biological conversion [32]. The ethanol production material and energy balances as well as ethanol yield are based on the ethanol conversion technology reported by the U.S. National Renewable Energy Laboratory [33] from corn stover, assuming that ethanol production efficiency is equal for other crops. However, feedstock composition was adapted to poplar biomass composition [25] (Table 2). The conversion of the dry biomass involves enzyme catalyzed hydrolysis followed by fermentation and distillation. The model considered in this study assumed that all sugars, obtained from cellulose and hemicellulose, were transformed into ethanol. Wastewater treatment from distillation and evaporation condensates produces biogas. The lignin fraction present in the biomass as well as other solids and the biogas are used as fuel to produce the energy requirements in the plant (electricity and steam). The production of the enzymes consumed in the conversion process was considered within the subsystem boundaries. Transportation of all the consumable materials up to the plant gate and the landfill of gypsum and ashes generated in the ethanol production process were included in this subsystem and they will be described below.

2.2.3. Ethanol blends production subsystem (S3)

The distribution of ethanol from an ethanol plant to a petrol station was assumed to be done by 32 tonne diesel lorries. The average distance was assumed to be 20 km [34]. The production of the gasoline as well as its transportation up to the petrol station, the mixture of gasoline and ethanol to produce E10 and E85 and, their regional storage were also included within the subsystem boundaries. When pure ethanol (E100) is used as fuel in an FFV, its delivery to a regional storage was also considered in this subsystem.

2.2.4. Ethanol blends use subsystem (S4)

Combustion of fuels described before in a representative FFV was evaluated and emissions were calculated according to the economy fuels and the functional unit selected. Manufacture, maintenance and disposal of the FFV were excluded from the subsystem boundaries.

2.3. Inventory analysis

The most effort consuming step of the execution of LCA studies is the collection of inventory data in order to build the life cycle inventory (LCI). Moreover, high quality data is essential to make a reliable evaluation. Data used in this study was collected from

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different sources and in many different ways. A large amount of data such as fertilizers production, diffuse emissions from fertilizers application, transport systems, ethanol production were handled. The procedure for LCI of the system under study is summarised in Table 3. As seen, data for the study was collected from different sources, which ensures the robustness of the study: field data, interviews, research reports and literature. Description of the hypotheses considered regarding transport activities in the ethanol life cycle is shown in Table 4. Background information from poplar cultivation (S1) was obtained from field data during the establishment of an experimental plot cultivated in Soria (Spain) [19]. Table 5 shows a short description of the inventory data for the poplar cultivation subsystem. Regarding the ethanol production subsystem (S2), the conversion process was modelled in this study for a biomass capacity treatment of 2000 tonnes/day and the ethanol production mass and energy balances necessary to carry out the LCA were based on the conversion technology developed by the U.S. National Renewable Energy Laboratory [33] and were adapted to the composition of poplar biomass. This technology is based on an enzymatic hydrolysis process followed by fermentation and it was selected because of its precision on presentation of the inventory data. The most relevant data for this subsystem are shown in Table 6.

2.4. Allocation procedure

Allocation is one of the most critical issues in LCA methodology. It is required for multi-output processes and the selection of an allocation approach for processes that produce more than one co-product can have a strong effect on the results. In this study, allocation procedure was not needed because poplar crops yield only lignocellulosic biomass. Concerning the ethanol plant, allocation was also avoided because of all electricity produced from wastes is consumed in the ethanol conversion and enzyme production processes. Thus, there is no surplus of electricity. Solid residues generated in the plant such as gypsum from distillation and ashes...
from boilers are sent to landfill and were considered as wastes. As a result, all the environmental burdens of the S2 were allocated to the cellulosic ethanol.

3. Life cycle energy and environmental performance

Life Cycle Impact Assessment was conducted using characterization factors from CML methodology [50]. The following potential impact categories have been considered in the analysis: abiotic resources depletion (AD), global warming (GW), ozone layer depletion (OD), human toxicity (HT), fresh water aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME), terrestrial ecotoxicity (TE), photochemical-oxidants formation (PO), acidification (AC) and eutrophication (EP). In addition, the analysis was completed with the energy use assessment, that is, the benefits of ethanol based fuels were assessed based on their life cycle fossil fuels extraction (FF) in terms of coal, crude oil and natural gas consumption.

Table 7 summarizes the LCA characterization results for each fuel under study. Change represents impacts of substituting any of the three alternatives for CG. Negative change implies a reduction in the environmental load compared to CG and positive value implies an increase in the environmental load.

The results show that the levels of emissions which contribute to AD, GW and OD are considerably reduced when shifting from CG to ethanol blends. According to these results, the higher the ethanol ratio in the blend, the higher the change in all these categories. These results are mostly due to the replacement of gasoline by ethanol and the higher contribution from activities related to feedstock production. Reductions up to 72% and 36% are achieved when E100 is used as transport fuel in terms of AD and OD respectively. Both results are connected because non-renewable fuels use presents the highest role in both categories and lower methane emissions from crude oil production onshore take place.

3.1. Global warming potential

Regarding GW, using ethanol based fuels is more advantageous than CG. The production and use of ethanol (E100) can avoid 0.16 kg CO₂ eq per km, which corresponds to a 62% GHG reduction. This result is mainly influenced by the carbon sequestered during crop growth which contributes to offset the GHG emissions although nitrous oxide emissions increase significantly when ethanol is involved in the blend mainly as a result of the diffuse emissions from the application of nitrogen based fertilizers during the poplar cultivation. For a better understanding of the results obtained, further breakdown of contributions to GW is performed. Fig. 3 shows the contribution of the main processes involved in the CG and ethanol based fuels life cycle. In CG and E10, the main contributor to GW is the blend use (~85% of total contributions) followed by gasoline production. This result is due to the high proportion of gasoline in the blend (90% in volume). Feedstock related activities present a negligible contribution (~3% of total). When E85 and E100 are used as transport fuel, the results entirely change and the ethanol conversion step becomes the main hot spot followed by the fuel use. According to Fig. 3, electricity production and distillation are the main responsible stages of the impact derived from the ethanol plant (~50% of total). If GHG emissions are analysed in detail, they are due mostly to three global warming

### Table 1
Main diffuse emissions from fertilizers application per ha of poplar plantation.

<table>
<thead>
<tr>
<th>Emissions to air</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃</td>
<td>9.95 kg</td>
</tr>
<tr>
<td>N₂O</td>
<td>2.98 kg</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.30 kg</td>
</tr>
</tbody>
</table>

### Table 2
Assumed composition (dry basis) of feedstock delivered to the refinery gate (adapted from Esteghlalian et al. [26]).

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>0.432</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>0.266</td>
</tr>
<tr>
<td>Xylan</td>
<td>0.216</td>
</tr>
<tr>
<td>Arabanan</td>
<td>0.033</td>
</tr>
<tr>
<td>Other sugar polymers</td>
<td>0.017</td>
</tr>
<tr>
<td>Lignin</td>
<td>0.213</td>
</tr>
<tr>
<td>Acetate</td>
<td>0.013</td>
</tr>
<tr>
<td>Ash</td>
<td>0.015</td>
</tr>
<tr>
<td>Others</td>
<td>0.061</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Table 3
Data sources for the life cycle inventory of poplar based ethanol production.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Data required</th>
<th>Data sources</th>
<th>Collecting method</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 Fuel use</td>
<td>Fertilizers use</td>
<td>Research reports and literature: [19,20,35–43]</td>
<td>Questionnaires</td>
</tr>
<tr>
<td></td>
<td>Labour use</td>
<td>Assumptions (see Table 4)</td>
<td>Literature review</td>
</tr>
<tr>
<td></td>
<td>Consumable materials &amp; biomass transport (mode, capacity and distance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diffuse emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2 Production capacity</td>
<td>Chemicals use</td>
<td>Research reports: [33,43–47]</td>
<td>Literature review</td>
</tr>
<tr>
<td></td>
<td>Nutrients use</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enzyme production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Landfill operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industrial equipment use</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater treatment plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consumable materials transport (mode, capacity and distance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3 Gasoline production and transport</td>
<td>Gasoline production</td>
<td>Research reports: [12,43,45]</td>
<td>Literature review</td>
</tr>
<tr>
<td></td>
<td>(mode, capacity and distance)</td>
<td>Assumptions (see Table 4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ethanol transport (mode, capacity and distance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ethanol, Gasoline and Blends storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4 Fuel use</td>
<td>Emission data of car driving</td>
<td>Research reports: [48,49]</td>
<td>Literature review</td>
</tr>
</tbody>
</table>

### Table 4
Hypotheses about transport activities related to ethanol life cycle.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Transport mode</th>
<th>Capacity ( tonnes)</th>
<th>Average distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizers, pesticides, fungicides and insecticides from wholesalers to farm</td>
<td>Diesel lorry</td>
<td>28</td>
<td>500</td>
</tr>
<tr>
<td>Poplar chips from farm to ethanol plant</td>
<td>Diesel lorry</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>Chemicals from wholesalers to ethanol plant</td>
<td>Diesel lorry</td>
<td>16</td>
<td>50</td>
</tr>
<tr>
<td>Solid wastes from ethanol plant to landfill</td>
<td>Diesel lorry</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Ethanol from ethanol plant to blending refinery</td>
<td>Diesel lorry</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>Ethanol blends to regional storage</td>
<td>Diesel lorry</td>
<td>32</td>
<td>34</td>
</tr>
</tbody>
</table>
gases: CO₂, N₂O and CH₄ (Fig. 4). N₂O emissions increase when changing from CG to ethanol blends since they come from the cultivation step, especially due to nitrogen based fertilizers production and use. CH₄ emissions are slightly reduced but large differences are identified concerning CO₂ emissions: the lower level of gasoline in the fuel means that less CO₂ is emitted from the gasoline production process, but more CO₂ is emitted from the ethanol production process (mainly energy production and distillation step). However, the carbon sequestered during the crop growth offsets the majority of these emissions, resulting in a reduction of the net emissions. Approximately 85% of total GHG emissions throughout the life cycle are cancelled by CO₂ uptake in agriculture (Fig. 3).

3.2. Ecotoxicity potential

With regard to HT, FE and ME, the contributions increase when ethanol blends with a high content of ethanol are used as transport fuel. Slight reductions can be achieved when E10 is taken into account (up to 5% in terms of ME). In all these impact categories, higher impacts from the upstream activities of ethanol blends govern the impacts of the fuel life cycle respect to CG. However, when E10 is considered, it is possible to reduce the contributing emissions because of the lower ratio of ethanol in the blend (10% in volume) and the higher fuel economy compared to E85 and E100.

With regard to TE and PO, changing from CG to ethanol blends creates an increase of the contributing emissions and again, due to the higher contribution from upstream activities in particular from ethanol production plant and agricultural activities (Fig. 5). Specifically, there is an increase of CO and NMVOC emissions from the use of diesel in agricultural machinery and biomass transport from the farm to the plant. There are also diffuse emissions of acetic acid and ethanol from the ethanol conversion related steps (enzyme and energy production, distillation and feedstock handling) which contribute to PO. Moreover, although the combustion of ethanol based fuels produces lower emissions of CO₂, there are higher emissions of acetaldehyde which also contribute to PO. As a result, contributions to PO from the blend increase with the ratio of ethanol in the blend as shown in Fig. 5.

3.3. Acidification and eutrophying potentials

In other environmental impact potentials, such as AC and EP, the similar results are obtained. Increasing the ratio of ethanol in the blend produces more acidifying and eutrophying emissions. Fig. 6 shows the main processes which contribute to AC. Once again, upstream activities are the main contributors, especially agricultural activities (~80% of total in E85 and E100), due to the production of fertilizers and the use of agricultural machinery (combustion emissions from diesel). Therefore, more SO₂ and NOₓ are emitted to the atmosphere. The diffuse emissions derived from the application of fertilizers are another important hot spot in terms of AC mainly due to NH₃ emissions. Fig. 7 shows that activities related to poplar cultivation are the main source of eutrophying emissions. This high contribution is due to NH₃ and NOₓ emissions from nitrogen based fertilizer production and application and diesel use in agricultural machinery and tractors.

3.4. Fossil fuels extraction

Table 8 shows the results in terms of fossil fuel extraction (in kg coal eq). According to our results, shifting from CG to ethanol blends results in a reduction of non-renewable fuel requirements. Although shifting from CG to ethanol blends increases the consumption of liquid fuel by agricultural machinery (usually diesel), less gasoline is necessary to propel the car and hence, a reduction of up to 78% of total fossil fuels consumption when E100 is used. It can easily be seen that crude oil contributes largely to the FF, followed by natural gas and coal, respectively. The high reduction of crude oil in blends with high ratio of ethanol is related to the lowest ratio of gasoline in them. However, coal requirements can be increased more than 50% due to the fact that more diesel is required for the feedstock cultivation.

4. Discussion

Although the amount of biofuels produced in the European Union is growing, the quantities remain small compared to the total volume of fossil transport fuels sold (approximately 0.3% of all EU petrol and diesel fuel in 2003) [51]. There are a few obstacles and constraints that need to be overcome if second-generation ethanol is to be regarded as a sustainable and cost-effective source of energy. Nowadays, biofuels are commercially uncompetitive with fossil fuels (petrol and diesel) in Europe because the technology is still in a process of development. Although lignocellulosic biomass is abundant and inexpensive, not all cellulose biomass is suitable and can be used as feedstock due to the constraints of present technology to hydrolyze the biomass efficiently in terms of cost and energy consumption [1]. However, in other countries such as Brazil and the USA, ethanol is
already produced on a large scale and it can be easily blended with gasoline to operate in spark ignition engines or in its pure form (100% ethanol) in some passenger cars [52]. Numerous LCA studies have tried to analyse the environmental benefits and weaknesses of using ethanol–gasoline blends from lignocellulosic feedstocks [5,53] as well as from sugar crops [13,54–59].

The environmental advantages of biomass based ethanol, regarding gasoline substitution and GHG emissions mitigation, have been observed in all of them. However, disadvantages have been highlighted in other environmental categories. The end-results of an LCA are dependent on several factors e.g. the systems boundaries and allocation procedure. However, the definition of the functional unit (the unit to which the results of an LCA are related and used for the communication of the LCA-results) is crucial. The results can entirely change in terms of e.g. GW. Regarding this subject, Kim and Dale [29] evaluated the using of E10 and E85 (derived from corn grain) in comparison to CG. According to these authors, using ethanol fuels is better than CG in order to reduce GHG emissions. However, E10 application offers more credits for GW than E85 when ethanol production oriented functional unit is assumed and E85 is the best option when a functional unit based on travelled distance is taken into account.

In this study, the functional unit was based on 1 km of distance driven by a FFV. According to our results, the use of ethanol blends reduces the contributions to AD, GW and OD as well as the extraction of fossil fuels (FF). Our results are similar to those obtained by other authors who also analysed ethanol production and use from biomass, in terms of fossil energy and GHG emissions [16,53–58]. Nguyen et al. [10] reported that the use of cassava based ethanol can provide reduction in GW compared to CG which corresponds to 62% of GHG emissions per litre of ethanol. In our study, we have obtained reductions of 73% of GHG emissions per litre of ethanol (using a fuel economy 7.78 km/L for E100 and 10.91 km/L for CG). Spatari et al. [32] studied the production and use of ethanol from corn stover and switchgrass. According to this study, ethanol from corn stover is slightly more attractive than from switchgrass since life cycle emissions were 33% lowest. However, in both case studies the GHG emissions are considerably lower than emissions reported in our study, up to 34% and 56% with regard to switchgrass and corn stover, respectively. Lin et al. [16] studied ethanol from sugarcane and reported values close to our results, not only in GW, but also in AD and OD. Differences based on the nature of feedstock and its content of cellulose and hemicellulose can have a big influence on the results. In this context, Ryan et al. [51] reported a range of estimates of the equivalent CO2 emissions savings as a result of using ethanol instead of gasoline. Several kinds of feedstocks were analysed: sugar, starch crops, lignocellulosic crops and residues. The wide range of values obtained seems

### Table 7

LCA characterization results (per functional unit) for the potential impact categories under study. Acronyms: CG – conventional gasoline; E10 – ethanol in a 10% blend with gasoline; E85 – ethanol in an 85% blend with gasoline; E100 – 100% ethanol.

<table>
<thead>
<tr>
<th>Category</th>
<th>CG</th>
<th>E10</th>
<th>Value</th>
<th>% Change</th>
<th>CG</th>
<th>E10</th>
<th>Value</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD (kg Sb eq)</td>
<td>1.62 × 10^{-3}</td>
<td>1.58 × 10^{-3}</td>
<td>-2.5</td>
<td></td>
<td>7.21 × 10^{-4}</td>
<td>-55.5</td>
<td>4.55 × 10^{-4}</td>
<td>-71.9</td>
</tr>
<tr>
<td>GW (kg CO2 eq)</td>
<td>0.255</td>
<td>0.246</td>
<td>-3.5</td>
<td></td>
<td>0.125</td>
<td>-51.0</td>
<td>0.096</td>
<td>-62.4</td>
</tr>
<tr>
<td>OD (kg CFC-11 eq)</td>
<td>3.14 × 10^{-8}</td>
<td>3.07 × 10^{-8}</td>
<td>-2.2</td>
<td></td>
<td>2.22 × 10^{-8}</td>
<td>-29.3</td>
<td>2.00 × 10^{-8}</td>
<td>-36.3</td>
</tr>
<tr>
<td>HT (kg 1,4-DB eq)</td>
<td>0.014</td>
<td>0.014</td>
<td>-2.1</td>
<td></td>
<td>0.019</td>
<td>-29.9</td>
<td>0.021</td>
<td>-42.4</td>
</tr>
<tr>
<td>FE (kg 1,4-DB eq)</td>
<td>2.47 × 10^{-3}</td>
<td>2.43 × 10^{-3}</td>
<td>-1.6</td>
<td></td>
<td>3.27 × 10^{-3}</td>
<td>-32.4</td>
<td>3.55 × 10^{-3}</td>
<td>-43.7</td>
</tr>
<tr>
<td>ME (kg 1,4-DB eq)</td>
<td>12.5</td>
<td>12.0</td>
<td>-4.0</td>
<td></td>
<td>13.0</td>
<td>+4.0</td>
<td>13.5</td>
<td>+8.0</td>
</tr>
<tr>
<td>TE (g 1,4-DB eq)</td>
<td>0.281</td>
<td>0.288</td>
<td>+2.5</td>
<td></td>
<td>0.460</td>
<td>+63.7</td>
<td>0.516</td>
<td>+83.6</td>
</tr>
<tr>
<td>PO (g CH4 eq)</td>
<td>0.160</td>
<td>0.166</td>
<td>+3.8</td>
<td></td>
<td>0.252</td>
<td>+57.5</td>
<td>0.273</td>
<td>+70.6</td>
</tr>
<tr>
<td>AC (g SO2 eq)</td>
<td>0.744</td>
<td>1.13</td>
<td>+51.9</td>
<td></td>
<td>5.30</td>
<td>+612</td>
<td>6.58</td>
<td>+784</td>
</tr>
<tr>
<td>EP (g PO2 eq)</td>
<td>0.075</td>
<td>0.163</td>
<td>+117</td>
<td></td>
<td>1.09</td>
<td>+1351</td>
<td>1.38</td>
<td>+1740</td>
</tr>
</tbody>
</table>

**Fig. 3.** Contributions of main processes involved in GW (kg CO2 eq/km) for all fuel options. Acronyms: CG – conventional gasoline; E10 – ethanol in a 10% blend with gasoline; E85 – ethanol in an 85% blend with gasoline; E100 – 100% ethanol.

**Fig. 4.** Breakdown of net GHG emissions (kg CO2 eq/km) of all fuel options. Acronyms: CG – conventional gasoline; E10 – ethanol in a 10% blend with gasoline; E85 – ethanol in an 85% blend with gasoline; E100 – 100% ethanol.
to be a result of differences in production yields, cultivation methods and the use of by-products in the production chain.

There is a great difference between our study and other consulted studies: the allocation approach. Commonly, agricultural crops yield more than one product and to estimate the energy use and emissions associated with the feedstock used to ethanol conversion, an allocation between the feedstock and the remaining by-products is necessary (e.g. corn stover and corn grain, cane molasses and sugar). The choice of the allocation procedure (mass or economic) is essential for the outcomes [16,54]. On the contrary, in poplar cultivation only poplar biomass is obtained. Therefore, not only all the impacts from agriculture are assigned to this feedstock, but also the carbon sequestered during the biomass growth.

With regard to FF, fossil fuel extraction decreases when ethanol based fuels are used as transport fuel. This conclusion was also reported by other studies with different kinds of feedstocks [16,29,53–57]. Sheehan et al. [12] reported a comparison of non-renewable energy consumption for E85 from different feedstocks (corn grain, grasses, trees and corn stover). According to that study, fossil fuel savings for corn stover and trees based ethanol are considerably high (~80%) and significantly better than the savings associated with corn grain based ethanol (~33%). In addition, E100 (from corn stover) reduces crude oil consumption by 95% for each kilometer driven. Our results fit in with this study, achieving a reduction of 65% and 82% in E85 and E100 applications, respectively.

Regarding HT and ecotoxicity based categories, our results are slightly below to the results obtained by Lin et al. [16]. Although the lignocellulosic feedstock taken into account is different in both studies (poplar biomass and sugarcane), in both case studies, mostly agricultural process contributes to these impact categories mainly due to the production of agrochemicals and agricultural machinery. Therefore, the cultivation methods and biomass yield could influence the results.

For impacts on PO, AC and EP, our results entirely fit in with Fu et al. [5], where ethanol production and use from balsam fir were evaluated. The contributions to all these impact categories are higher when shifting from CG to ethanol blends. This is due to the fact that feedstock cultivation and ethanol production contribute significantly to all these impact categories, between 48 and 95% of the impacts in E100 application. Other studies reported higher values on PO and AC [16,54,55] and lower contributions to EP [16]. However, in all of them feedstock cultivation (including fertilizer and pesticide production) is a notable contributor. It is interesting to notice that the allocation procedure (if necessary), the intensity of the agricultural activities and the sources of energy in the ethanol conversion process are critical for determining whether CG is more environmentally friendly than ethanol based fuels in terms of these impact categories.

5. Conclusions

The present study shows the results of an LCA performed upon poplar biomass based fuel ethanol and its use in FFV whether blended or not with gasoline. The poplar biomass composition, rich in cellulose and hemicellulose, makes it an interesting alternative to making ethanol to compete with conventional gasoline. Poplar cultivation, biomass processing and transport to refinery gate,
ethanol conversion and transport to blending refinery, blending of ethanol with gasoline in two ethanol fuel applications (E10 and E85) and, E10, E85 and E100 burning in FFV were evaluated and compared with CG.

Despite the detail that has been maintained throughout the study, there are limitations which include the uncertainty in the life cycle inventory data associated to the ethanol conversion technology since it is under development and the uncertainty poplar biomass is not being used nowadays as commercial ethanol production feedstock.

According to the results of this study, cellulosic fuel ethanol as a blend with gasoline (or pure) may help to reduce greenhouse gas emissions as well as to avoid abiotic resources depletion and ozone layer depletion up to 62%, 72% and 36% respectively.

Reductions of fossil fuel extraction of up to 80% could be achieved when pure ethanol is applied, contributing to a more secure energy supply. However, using ethanol from lignocellulosic feedstocks (in this case, poplar biomass) would increase the contributions to other impact categories, such as eutrophication, acidification and, photochemical-oxidants formation (more than 100% in terms of EP and AC). Agricultural activities related to feedstock production are notable contributors to the environmental performance as well as activities related to the ethanol conversion process, such as energy production and distillation process. Thus, technological development in both agriculture and ethanol production can help lower the environmental impacts. In addition, environmental performance could be improved if improvement alternatives are proposed in terms of doses of fertilizers applied.

6. Recommendations

The production and use of ethanol as transport fuel allow an improvement of the environmental impacts in terms of greenhouse gas emissions and fossil fuel extraction in comparison to gasoline. However, impacts are still considerable in terms of other impact categories such as acidification and nutrient enrichment, where improvements should be made to reduce the contributions (specifically focused on agricultural practices). Further research could be focused on developing a strategic planning to identify the potential regions for the cultivation of this kind of crop in order to increase the biomass yield and to reduce agricultural practices and fertilizers doses.

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