15th European Roundtable on Sustainable Consumption and Production
(15th ERSCP)
2012, May 2 – 4, Bregenz, Austria

An Environmental Life Cycle Assessment Analysis of Lignocellulosic Bioethanol as an Alternative Transportation Fuel

Daylan, B [1,2], Ciliz, N [1,2], Mammodov, A[1,2], Tükenmez, A.S [1,2]
[1] *Bogazici University Institute of Environmental Sciences, 34342 Bebek, Istanbul – Turkey*
Tel: +90 212 359 6947, Fax: +90 212 257 5033
[2] *Bogazici University, Sustainable Development and Cleaner Production Center 34342 Bebek, Istanbul – Turkey*

**basak.buyukbay@boun.edu.tr*

Abstract

Considering the threat of oil depletion and increasing level of greenhouse gas (GHG) emissions, a shift from fossil resources to renewable biofuels is ongoing to secure long-term low carbon energy supplies. Bioethanol from lignocellulosic feedstocks seems to be a viable alternative for renewable transportation fuels produced from food crops and conventional gasoline (CG) due to the limited competition with food production and 45-65% GHG emission reduction. Within this scope, the objective of this paper is to conduct a Life Cycle Assessment study (LCA) by using the GaBi4 LCA software and the EDIP 2003 methodology for lignocellulosic bioethanol blends - E10 and E85 (10% and 85% in volume of bioethanol with gasoline, respectively) - and CG to compare these fuels in terms of environmental aspects.

The audit focus point for potential environmental impacts of fuel life cycles are global warming, acidification, aquatic and terrestrial eutrophication, photochemical oxidant formation and ozone layer depletion potentials. 1 km traveling distance with a flex-fuel vehicle (FFV) is taken into account as functional unit for the life cycle analysis of each fuel blends from production to combustion. According the LCA results, one kilometer driven by E10 and E85 fueled vehicle could reduce the GHG emissions by 4.3% and 47% and ozone layer depletion emission by 3% and 66% with respect to CG, respectively. However, shifting from gasoline to lignocellulosic bioethanol increases the emissions which contribute to eutrophication and photochemical ozone depletion. In terms of acidification potential, E85 shows better result than E10 and CG.

Keywords: lignocellulosic bioethanol, life cycle assessment, environmental performance, E10, E85

Introduction

Transportation sector is a significant contributor to GHG emission, accounting for about 20% of global CO_2 emissions. Furthermore, it is 98% dependent on fossil fuel. Biofuels have a large potential of reducing CO_2 emissions throughout the fuel cycle, since the vehicle combustion of biofuels does not contribute to net emissions of CO_2 which is absorbed by the biomass feedstock through photosynthesis. (Magnusson, 2007).

Traditionally, bioethanol has been produced from starch and sugar crops such as rice, wheat, barley, corn grain or sugarcane. However, because of the restrictions in the use of food crops for bioethanol production and the expensive feedstock cost (55% of production costs stem from feedstock cost), low value agricultural products or wastes, like corn stover, wheat straw, bagasse from sugar cane, wood, and grass have been started to use for bioethanol production (second generation bioethanol) (Luo et al., 2009[a] ; Garcia et. al., 2009). According data of the Exploitation of Agricultural Residues in Turkey Report, while annual production capacity of wheat straw is 3.5 million tons, 4.1 million tons of corn stover is produced as lignocellulosic residue in Turkey (LIFE Programme, 2005).

Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs and interpreting the results of the inventory analysis (Hauschild and Wenzel, 2000). The objective of this study is to conduct a comparative LCA study of bioethanol fuel blends (E10-10% and E85-85% in volume of bioethanol with gasoline) and conventional gasoline (CG) considering an overall evaluation of the impacts of these fuel systems from production to combustion on the environment throughout their life cycle. Within this scope, lignocellulosic residues such as wheat straw and corn stover have been selected as feedstock for the production of bioethanol to evaluate the environmental impacts of the production and use of E10 and E85 in a flexi fuel vehicle (FFV) versus CG throughout their whole life cycle.

Methodology

LCA is a decision making tool for evaluating the potential environmental impacts of a product on the environment over the entire period of its life cycle. The results of an LCA can quantify the overall damages on human and ecological health and material welfare of a product service and address opportunities for improvement in the defined categories (Beer et al., 2007; Jensen and Thyo, 2007; Luo et.al, 2009[b]). At this study, LCA analysis has been carried out to compare the environmental

performance of FFV automobiles fuelled with blends of bioethanol (E10 and E85) and CG. The environmental burdens associated to bioethanol production and consumption has been evaluated by identifying consumption of natural resources (raw materials, energy and chemicals) and emissions to air, water and soil compartments together with the identification of opportunities to attain environmental improvements.

Goal and Scope Definition

The aim of this study is to apply a comparative LCA analysis for E10, E85 and CG to evaluate and compare the environmental impacts of both lignocellulosic bioethanol produced from wheat straw and corn stover and CG production and combustion throughout their life cycle. At this study, wheat straw and corn stover was selected as feedstocks for bioethanol production as they have the highest annual production capacity in Turkey. The scope of the study includes the life cycle of bioethanol fuel use from a cradle to grave perspective, including "feed stock acquisition (baling and transport)" (S1), "bioethanol production" (washing/milling/pretreatment/enzymatic hydrolysis, simultaneous saccharification and co-fermentation, SSCF)"(S2) and "combustion of bioethanol blends" (S3).

Functional Unit

In the LCA studies, all relevant inputs and outputs in the Life Cycle Inventory (LCI) phase and the final impact scores in Life Cycle Impact Assessment (LCIA) phase are expressed with a reference flow, which is called functional unit (FU). In case of motor fuels, as long as mobility is concerned, this term must be related to mechanical energy, in other words, to the distance travelled (Gnansounou et.al., 2009). In this study, 1 km traveling distance FU perspective driven by a flex-fuel vehicle (FFV) is taken into account as the FU for the life cycle analysis of each fuel blends -E10, E85 and CG- from production to combustion.

System Boundaries

The system boundaries of the bioethanol production and consumption is divided three sub-system; "feed stock acquisition" (S1), "bioethanol production" (S2) and "combustion of bioethanol blends (blend use)" (S3).

Feedstock acquisition subsystem (S1) consist of baling of wheat straw and corn stover in the field, transportation of bales to the temporary storage area and transportation of bales to the bioethanol plant**.** At this part of the study, agricultural subsystem for cereal harvesting is not included in the system boundary since wheat straw and corn stover are accepted as by-products of wheat and corn production.

The ethanol production materials and energy balances as well as ethanol yield are based on the ethanol conversion technology reported by the National Renewable Energy Laboratory from corn stover, assuming that ethanol production efficiency is equivalent for other lignocellulosic feedstocks. Bioethanol production subsystem (S2) is divided in eight processes: (i) feedstock handling and storage; (ii) pretreatment and conditioning; (iii) saccharification and co-fermentation; (iv) distillation and dehydration; (v) storage of ethanol; (vi) wastewater treatment plant (WWTP); (vii) energy production through a boiler using solids form distillation, syrup and biogas, and (viii) enzyme production. Gypsum generated from the solid–liquid separation and ashes from the energy production are sent to landfill.

The distribution of bioethanol from the production plant to a petrol station and its use is considered within combustion stage of bioethanol blends (S3) subsystem. Moreover, gasoline production and its transportation to the petrol station are also included within this subsystem boundary.

Life Cycle Inventory (LCI)

During the inventory analysis (LCI), quantification of natural resource consumption and waste and emission generation within the scope of bioethanol product life cycle has been yielded.

In feedstock acquisition (S1), diesel consumption is resulted from transportation and loading/uploading of straw/stover bales. In the process of "loading bales", bales of 160 kg are loaded onto a 2-tyre-trailer with maximum 8 tons capacity to transport the bales to the temporary storage. The distance between the farm and the interim storage is assumed to be 50 km. Transportation from the temporary storage area to the bioethanol production plant is done by 16 ton total and 10.3 payload capacity trucks. The sheeting of the stack is made of low density polypropylene, with an approximate sheet thickness of 1 mm and a density of 920 kg/m^3 and the assumption of 100 km average distance between storage and the production plant is considered.

In milling process (S2), energy produced form lignin combustion supplies the required electrical energy. Lime, sulfuric acid and vinyl acetate for pretreatment are transported by a 16 ton lorry and the distance between their production facilities and the bioethanol plant is assumed to be 15 km. The final disposal of the gypsum is considered to be a landfill with a distance of 25 km away from the bioethanol plant. The major chemicals consumed in SSCF process are cellulase, corn step liquor (CSL) and diammonium phosphate (DAP). The electrical energy consumed for the machinery in SSCF and cellulase production processes are supplied by a boiler through lignin combustion. CSL and DAP are transported by a lorry of 16 tons capacity for a distance of 15 km. In cellulase production, ammonia, and urea are consumed as nutrients. A 30 km distance is considered for ammonia and urea transportation to the bioethanol

plant. 1000 kg purified ethanol up to 99.5% is obtained and sent to ethanol storage area. In the boiler, electrical energy and steam is produced by lignin combustion, and ash is the process residue which is transported for 25 km to be disposed of a landfill.

The combustion of fuels described before in an average passenger car is evaluated and emissions are calculated according to the amount of bioethanol and gasoline necessary to drive the equivalent distance according to the functional unit. Inventory data for the gasoline production and distribution to the blending refinery is taken from GaBi 4 software of Ecoinvent database (GaBi 4 Manual, 2003).

Results and Discussion

3.1 Life Cycle Impact Assessment

The data summarized in the inventory phase are interpreted through classification, characterization, and normalization stages using GaBi4 software. Life Cycle Impact Assessment (LCIA) has been conducted using characterization and normalization factors from EDIP 2003 methodology. The following environmental impact categories have been considered in the analysis: acidification (in m^2 UES -area of unprotected ecosystem-), aquatic eutrophication (in kg NO_3^- eqv.), terrestrial eutrophication (in m^2 UES), photochemical oxidants formation (to human health in person * ppm * h), global warming (in kg CO_2 eqv.) and stratospheric ozone depletion (in kg R11 eqv).

3.1.1. Classification

In this step, the impact categories have been defined and the exchanges in the inventory have been assigned to impact categories. The emission types resulted from various stages of the life cycles of bioethanol and their environmental impact categories are given in Table 3.1.

Table 3.1. Classifications of emissions to impact categories (Garcia et. al., 2009)

Impact Category	**Emissions**	**Unit**
Acidification (AP)	SO_2, NO_x, HCI, HF, NH_3, HS	in m^2 UES
Aquatic eutrophication (AEP)	NO_x, NH_3, NH_4^+, NO_3^-, PO_4^{-2}	in kg NO_3- eqv
Terrestrial eutrophication (TEP)	NH_3, NO_x	in m^2 UES

Global warming (GWP)	CO_2, CH_4, CO, NMVOC, N_2O	in kg CO_2 eqv
Photochemical oxidant formation (POP)	CO, CH_4, NMVOC, NO_x	person * ppm * h
Stratospheric ozone depletion (SOP)	Halocarbons (CFCs, HCFCs)	in kg R11 eqv

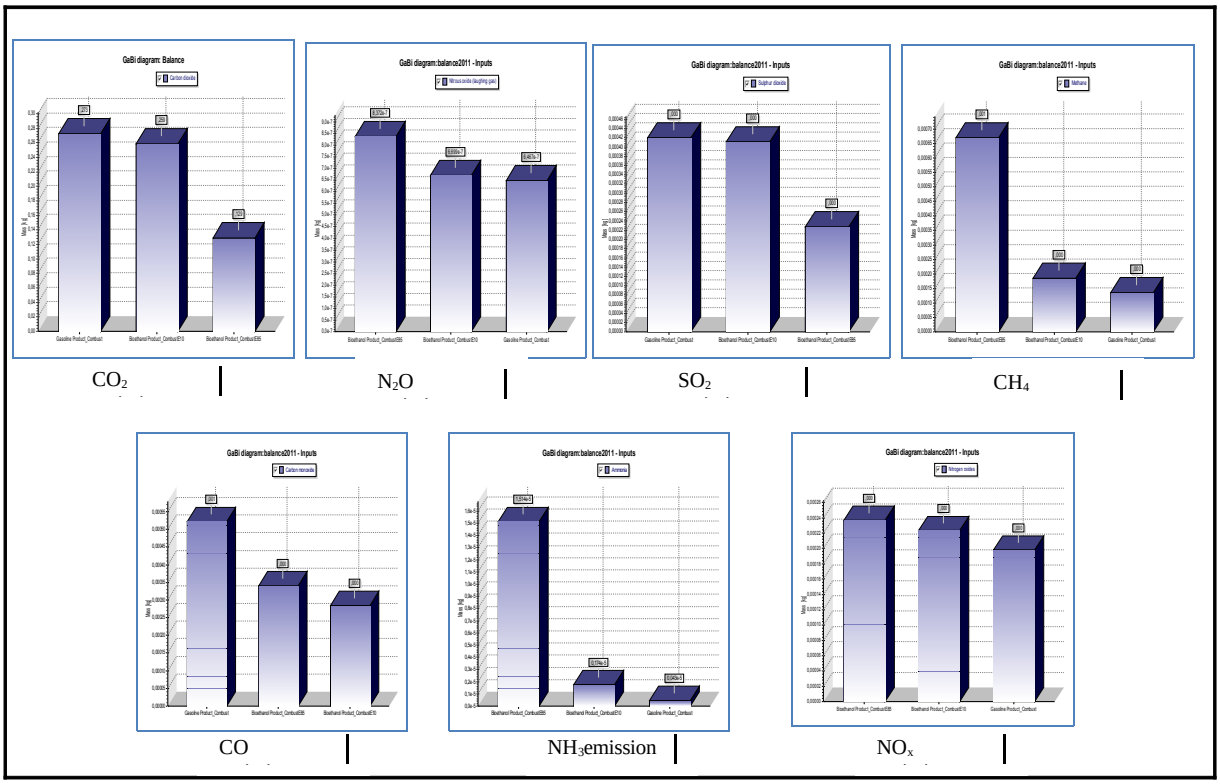

Figure 3.1. Quantities of emissions released from whole life cycle of bioethanol blends (E10 and E85) and conventional gasoline (CG)

CO_2 emissions are lower by 52% and 5% than CG for E85, respectively. Regarding CG fuel life cycle, the main CO_2 emission releases are stem from fuel combustion and gasoline production phases causing 84% and 15.5 % of CO_2 emissions, respectively. While 48% and 44% of CO_2 emissions are resulted from bioethanol refinery and fuel combustion phase of E85, 84% and 15% of CO_2 emission are stem from fuel combustion and petrol production stages of E10, respectively. CO emissions of CG are also higher than E85 and E10 by 46% and 38%, respectively. N_2O emissions are decreased by 21% and 23% for E10 and CG with respect to E85. The reason for high emissions rate of N_2O for E85 is the nitrogen based chemical consumption in SSCF process and high exhaust gas emission of bioethanol fuel combustion. While NH_3 emissions of E85 are higher than E10 and CG by 88% and 97%, NO_x emissions of CG lower than E10 and E85 by 9% and 17%. The fuel extraction and combustion stages are the main processes accounting for organic emission for CG. SSCF stage, together with above mentioned processes, is also responsible for organic emission release for E10 and E85. CH_4 emissions are lower by almost 74% for CG and E10 compared to E85. SO_2 emissions are lower by about 81% for

E85 than E10 and CG. In respect to E10 fuel life cycle, 85% and 10% of SO_2 emission are resulted from fossil fuel extraction and fuel combustion stages, respectively.

3.1.2. Characterization

The potential contributions from the emissions of the life cycle of bioethanol blends (E10–E85) and CG are calculated for all of the selected impact categories in the characterization stage. The contribution of emissions for each impact category and characterization of the emissions into relevant categories are run by GaBi 4.

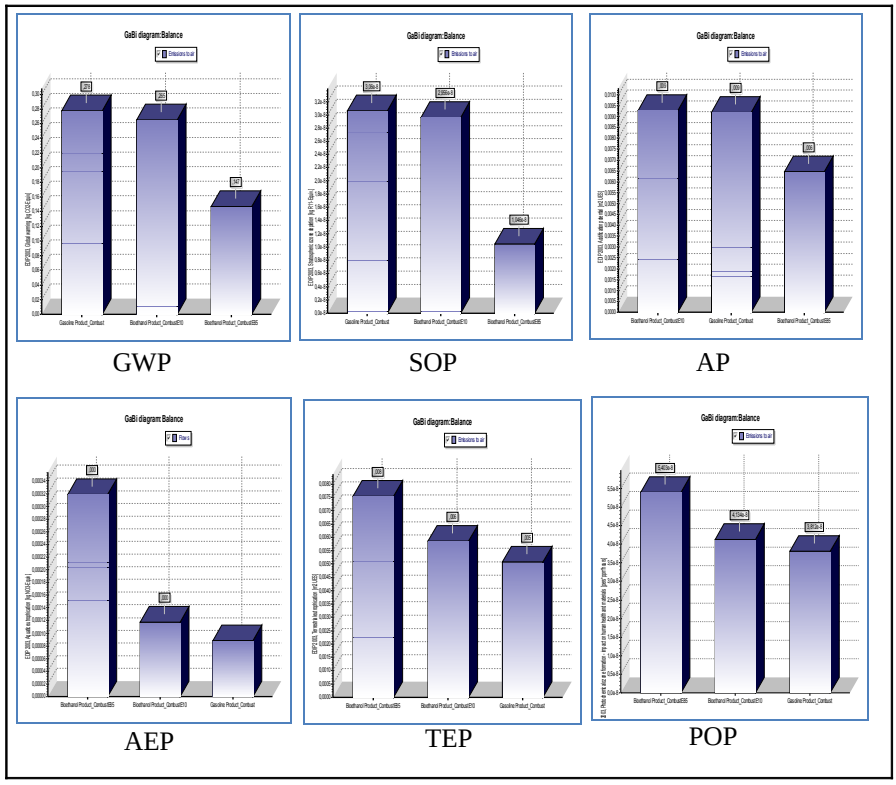

Figure 3.2 The comparison of total environmental impact potentials of E10, E85 and CG

Figure 3.2 summarizes the LCA characterization results of E10, E85 and CG for 1 km distance**.** The results show that the levels of emissions which contribute to global warming are considerably reduced when shifting from CG to bioethanol blends for both E10 and E85. While, total GHG emissions resulting from CG fuel life cycle based on 1 km traveling driven distance is 0.277 kg CO_2-eqv, total GHG emissions of E10 and E85 life cycle are 0.265 kg CO_2-eqv and 0.147 kg CO_2-eqv and resulting 4.3% and 47% GHG emission reduction with respect to CG fuel life cycle, respectively.

For the assessment of E10 and CG, it can be deduced that the main contributor to global warming is the fuel combustion (~85% of total contributions) followed by fossil fuel extraction. When E85 are used as transport fuel, the results entirely change and the bioethanol production stage (~48% of total) becomes the main hot spot followed by the blend use step (~45% of total) in terms of GHG emissions.
The results of LCIA showed that the levels of emissions which contribute to SOP are considerably reduced when shifting from CG to bioethanol blends. SOP of E10 and E85 fuel life cycle based on 1 km traveling driven distance resulted nearly 3% and 66% reduction with respect to CG fuel life cycle, respectively.

Considering the overall life cycle of E10, E85 and CG, the acidifying impact is typically characterized by the release of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). The level of AP for E10 is almost same with CG and AP of E85 lower than CG and E10 by 29%. Since the selected feedstocks (by-products of cereal production) are not a part of agricultural production system, emissions from fertilizer consumption and agricultural machinery are not taken into consideration in characterization studies. According to characterization results, using CG offers better environmental performance for photochemical ozone depletion than using E10 and E85 providing 7.4% and 28% reduction, respectively.

Using CG offers better environmental performance for TEP than using bioethanol blends of E10 and E85 providing 13% and 33% TEP reduction respectively, because of the higher NH_3 emissions from the N-based chemical consumption for SSCF process and the N-based exhaust emissions (e.g. NO_x) of fuel combustion subsystem. AEP of CG is also lower than E10 and E85 by 25% and 72%, respectively for the same reason mention in TEP.

3.1.3. Normalization

Mainly, there are two general goals in normalization. Firstly, it supports the software user in having an impression of the relative scaling of the calculated impact potentials. Secondly, it leads to the individual impacts to be combined into a dimensionless final score to compare all environmental impacts using the same scale (Garcia et. al, 2010). Within the frame of LCA, normalization provides the information on which contributions are, in relation to each other, small or large. The normalized potentials are fractions of the impact from an average person's contribution to the total and expressed as person-equivalent. GaBi4 calculates the normalized impact potentials according to EDIP 2003 factors. The normalized impact potential (NEP) of global warming is larger for CG life cycle than E10 and E85. However, E10 and CG life cycle has the highest acidification potential with 4.22e-6 and 4.18e-6 values, respectively

between the selected fuel types. As seen in Figure 3.3, NEP for global warming has the highest impact potential among the others with 3.05e-5, 1.69e-5 and 3.19e-5 for E10, E85 and CG fuel life cycles.

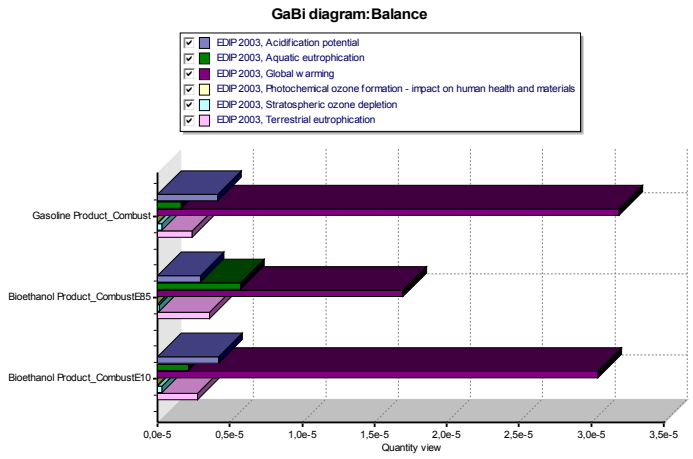

Figure 3.3. Normalized impact potentials of E10 and E8 life cycle vs. CG life cycle

1. Conclusion

This study focused on identifying the environmental impacts associated to the production and use of ethanol-based fuels (E10 and E85) and CG taking into account the functional unit based on the 1 km driven distance. Relevant impact categories; acidification, eutrophication, photochemical ozone formation, global warming and ozone layer depletion have been evaluated.

According to the LCIA results, E10 and E85 fueled vehicle can reduce the GHG and ozone layer depletion emissions as well as a reduction in the dependence on fossil fuels. One kilometer driven by E10 and E85 fueled vehicle reduce GHG emissions by 12.8 g and 130.5 g CO_2 equivalent with respect to CG, resulting 4.3% and 47% GHG emission reduction, respectively. In the traveling distance-oriented functional unit perspective, E85 fuel application offers better environmental performance than the E10 fuel application in terms of GW, AP and SOP by 45%, 21% and 55%, respectively as the environmental burdens are normalized to travelling distance. However, E10 fueled application offers better environmental performance in AEP, TEP and POP than the E85 fueled application by 63%, 25% and 24%, respectively. However, shifting from gasoline to ethanol increases the emissions which contribute to AEP (AEP of CG is lower than E10 and E85 by 25% and 72%, respectively), TEP (TEP of CG is lower than E10 and E85 by 13% and 33%, respectively) and POP (POP of CG lower than E10 and E85 by 7.4% and 28%, respectively) since ethanol fuelled vehicles release more NO_x, NH_3 and N_2O in all their life cycle including bioethanol production and fuel combustion stages.

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