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Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar)

Sara González-García [a,b,*], M. Teresa Moreira [b], Gumersindo Feijoo [b], Richard J. Murphy [a]

[a] Department of Life Sciences, Sir Alexander Fleming Building, Imperial College London, and Porter Alliance, London SW7 2AZ, UK

[b] Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain

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ABSTRACT

A life cycle assessment (LCA) study was carried out to evaluate the environmental implications of the production and use of ethanol from three fast-growing wood crops: eucalyptus, black locust and poplar in flexi-fuel vehicles. The production of a blend rich in ethanol: E85 (85% ethanol and 15% gasoline by volume) was assessed and the results compared with those of conventional gasoline (CG) in an equivalent car. The following environmental categories were evaluated: fossil fuels use (FF), global warming potential over 100 years (GWP_{100}), photochemical oxidant creation potential (POCP), acidification potential (AP) and eutrophication potential (EP).

The use of ethanol derived from black locust was found to be the option with the lowest impact in most categories with reductions of 97%, 42%, 41% and 76% for GWP_{100}, AP, EP and FF respectively in comparison with CG.

Concerning the production stage of ethanol (excluding the stages of blending and use), black locust has the lowest environmental impacts due to the low levels of agricultural inputs during its cultivation. The poplar scenario has higher impacts in AP and EP due to the emission of diffuse substances from fertilizer application and the eucalyptus scenario in GWP_{100}, POCP and FF due to the use and requirements of heavy machinery during harvesting.

The use of the LCA methodology has helped to identify the key areas in the life cycle of ethanol. Special attention should be paid to ethanol production related activities and forest activities oriented to the feedstock production.

1. Introduction

The world is progressively depleting its fossil energy resources. The current dependence on oil for the production of energy and chemicals results in substantial emissions of greenhouse gases (GHG) as well as the progressive depletion of non-renewable resources [1,2]. This has motivated more support for the development of renewable energies to develop long-term reliable sources of energy supply [3].

The transport sector is almost entirely dependent on fossil fuels and nearly 94% of the energy used was obtained from oil in 2007 [4]. This sector is also responsible for around 21% of GHG emissions, especially due to road transport [5]. In this context, new strategies promote the use of the biomass in the future supply of energy, chemicals and materials [6,7].

Intensive research on biofuels is focused on the identification of potential feedstocks as well as the development of advanced conversion processes. Nowadays, ethanol used in

* Corresponding author. Department of Life Sciences, Sir Alexander Fleming Building, Imperial College London, and Porter Alliance, London SW7 2AZ, UK. Tel.: +44 2075945389; fax: +44 2075842056.

E-mail addresses: s.gonzalez-garcia@imperial.ac.uk, sara.gonzalez@usc.es, sara.gez.garcia@gmail.com (S. González-García).

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Europe is primarily derived from corn and other food based crops, commonly known as first-generation (1G) ethanol [5]. However, the use of land in this kind of feedstocks for energy purposes is considered to compete with food and feed production. Among the biomass based fuel options, lignocellulosic ethanol (second generation, 2G) has received special interest because of the wide diversity of potential sources of lignocellulose worldwide, the production opportunities from perennial crops with low agricultural inputs and beneficial GHG balances in comparison with gasoline [8,9]. Lignocellulosic biomass rich in fermentable sugars (cellulose and hemicellulose) can be converted into ethanol by either biochemical or thermochemical processes. This potential source of ethanol is abundant, economically viable [10] and do not compete directly with food or feed [11]. Examples of 2G feedstocks include residues from agriculture, forestry and wood processing, organic wastes and energy crops for instance winter cover crops, perennial grasses or fast-growing plantations such as short rotation coppices (SRC) and short rotation forestry (SRF).

Concerning the technology for ethanol production, significant efforts are being made towards the improvement of production technologies and many countries have implemented or are implementing programs for the addition of ethanol to gasoline [3,5,12–14]. Lignocellulosic ethanol development up till now has been constrained by its production costs which have limited large scale deployment. However, progress in enzymatic stages, pre-treatment and fermentation processes are making the 2G production process progressively more viable [15,16].

Life Cycle Assessment (LCA) methodology has proved to be a valuable tool for analysing the environmental considerations of products or processes. A number of publications are already available on LCA studies carried out to identify the environmental performance of the ethanol produced from different lignocellulosic feedstocks such as corn stover [11,12,17], flax shives [18], Ethiopian mustard [19], switchgrass [11,20], cane molasses [21], alfalfa stems [22] and poplar [23]. Differences found among existing studies are partially due to the lack of a commercial process of lignocellulosic ethanol [5]. A general conclusion from all these studies is that lignocellulosic 2G ethanol would provide environmental advantages over gasoline by reducing non-renewable energy consumption and greenhouse gas (GHG) emissions. The studies also recognise that ethanol production could have adverse effects on impact categories such as acidification and eutrophication, due to emissions related to agricultural activities, particularly from the use of fertilizers.

Fast-growing wood crops such as willows, poplars, black locust, eucalyptus or chestnut have been traditionally considered to produce local fuelwood, wood material, fibres for cellulose industries and, more recently, energy [24,25]. These crops are promising feedstocks because of high yields, low costs, opportunities for use on lower-quality lands and biodiversity support at the landscape level.

This paper aims to assess the environmental performance of lignocellulosic ethanol production of three kinds of fast-growing biomass: eucalyptus (*Eucalyptus globulus*), poplar (*Populus spp*) and black locust (*Robinia pseudoacacia*) in order to identify the best option from an environmental point of view. In addition, the use of this ethanol in a flexi-fuel vehicle (FFV) is assessed using a cradle-to-grave, attributional LCA approach. The LCA is based on a comparison of the environmental performance of the ethanol in 85% blends with gasoline (E85) with a conventional gasoline (CG) reference across five environmental impact categories: fossil fuel use, global warming potential (GWP_{100}), acidification potential (AP), eutrophication potential (EP) and photochemical oxidant creation potential (POCP). The selection of these five categories was based on that they are commonly considered on bioenergy related studies [11,17–23] as well as in order to justify the challenges for the European Union in terms of transport fuels: the decrease of GHG emissions and the security of energy supply [19].

2. Life cycle assessment

2.1. Methodology

LCA evaluates the environmental burdens by identifying resource and energy consumptions and emissions to various environmental compartments resulting from the particular life cycle and includes opportunities to identify priority areas where improvement actions will have the greatest effects on reducing environmental impacts [26].

2.2. Functional unit

The choice of the functional unit (FU) is dependent on the aim of the study. This paper was sub-divided for convenience into two main parts: i) the first part related to the ethanol production system so the FU was based on 1 kg of ethanol, ii) the second part related to the FFV driving function so the FU was based on 1 km distance driven by a mid-size FFV. The average fuel use rates for the FFV considered on CG and E85 were 91.7 mL km^{-1} and 120.6 mL km^{-1} respectively [27,28], giving the amount of fuel required to travel 1 km as 66 g for CG and 92 g for E85.

2.3. Feedstock species

The wood species considered in this study: eucalyptus, black locust and poplar are abundant renewable lignocellulosic materials. They present a sugar rich composition (Table 1) and can be potentially converted into ethanol.

2.4. System boundaries

In order to get comparable and consistent data, it is crucial to have a clear definition of the system boundaries. An overview of the assumed ethanol process, which was the same for all the three feedstocks studied, is shown in Fig. 1.

The model used in the study is an updated and somewhat modified version of the model described by Aden et al. [12]. The proposed ethanol plant has a processing capacity of 100 t h^{-1} of raw material and it is operated for 8160 h y^{-1}. All the relevant processes, included within the boundaries of the fuel systems, are shown in Fig. 1. The systems were divided into four main subsystems: Feedstock cultivation (S1), ethanol