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Environmental sustainability of bioethanol production from wheat straw in the UK☆

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ABSTRACT

A UK-based environmental sustainability study on bioethanol production from wheat straw was conducted using a Life Cycle Assessment (LCA) approach. Five pathways with leading pretreatment technologies (dilute acid, steam explosion with and without catalyst, liquid hot water, and wet oxidation) were modelled using process simulation software AspenPlus™, and their advantages and disadvantages were evaluated from an environmental perspective. In a contribution analysis of the environmental profiles for the near-term prospective scenarios, results indicated that the enzyme is a main contributor in all pathways. In addition to enzyme production, acid catalyst and base for its subsequent neutralisation also cause significant environmental burdens for dilute acid and steam explosion with catalyst pathways. By comparing the five wheat straw production pathways with petrol, it was suggested that those using pretreatment with steam explosion, liquid hot water and wet oxidation can be environmentally favourable over petrol. However, a sensitivity analysis conducted by expanding the ethanol system boundary to include the consequential effects of removing wheat straw from the field, suggested an increase in the overall environmental burdens of ethanol life cycles but certain wheat straw ethanol pathway (i.e. with steam explosion pretreatment) still remain environmentally favourable over petrol.

Contents

Abbreviations: AD, anaerobic digestion; GHG, greenhouse gas; ADP, abiotic resources depletion potential; HTP, human toxicity potential; AP, acidification potential; LCA, life cycle assessment; CHP, combine heat and power; LCIA, life cycle impact assessment; CFC^{-11}, trichlorofluoromethane; LHW, liquid hot water; COD, chemical oxygen demand; ODP, Ozone layer depletion potential; DA, dilute acid; POCP, photochemical-oxidants creation potential; DB, dichlorobenzene; SE, steam explosion; EP, eutrophication potential; SEAC, steam explosion with acid catalyst; FAETP, freshwater aquatic ecotoxicity potential; TEP, terrestrial ecotoxicity potential; FFV, flexible-fuel vehicle; WO, wet oxidation; FPU, filter paper unit; WWT, wastewater treatment; gwp_{100}, global warming potential (100 year horizon); VOC, volatile organic compounds

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1. Introduction

Biofuels have been recognised to be an alternative transport fuel to gasoline for decades and can be produced from a variety of sources including sugars, plant oils and lignocellulosic biomass. Agricultural wastes such as corn stover, wheat straw and sugarcane bagasse are becoming attractive feedstocks for bioethanol production since their utilisation is not competitive with food.

As one of the major crops in the UK, wheat is cultivated in many parts of the country [1]. The UK annual wheat straw yield has been estimated to be between 8 and 10 million tonnes [2]. In recent years, the market price of wheat straw has varied from approximately £25 per tonne in 2000 to £52 per tonne in 2010 [3]. However, due to rising gasoline prices and particularly the availability and relatively low cost of wheat straw compared with other lignocellulosic biomass, it serves as a potentially attractive feedstock for producing bioethanol.

Currently, several biorefineries in Europe utilising wheat straw as a feedstock to produce bioethanol have progressed to demonstration scale. Inbicon in Denmark produces 4300 t of bioethanol and also 11.1 thousand tonnes of molasses (65% dry matter) from 30,000 t wheat straw per year. Abengoa in Spain is processing wheat straw at the rate of 70 t per day, and produces over 5 million litres of ethanol per year. Süd-Chemie AG in Germany has started construction for a plant which will produce up to 1000 t of ethanol per year from wheat straw. Outside the EU, Iogen in Canada is also operating an ethanol biorefinery with wheat straw as its primary feedstock [4]. These established biorefineries suggest that bioethanol production from wheat straw is viewed as a potentially economically attractive pathway.

From an environmental point of view, the greenhouse gas (GHG) emission reduction target for the EU is 20% by 2020 (from 1990 levels), and for the UK it is 34% [5]. Therefore, timely environmental assessments in combination with economic analyses, on the potential of second generation (2G) bioethanol from lignocellulosic resources are required to assist policy making. There have been numerous studies on LCA of bioethanol from different biomass sources, such as corn stover [6,7], willow [8], switchgrass [9,10], miscanthus [10] and sugarcane [7,11]. Most of these focus on GHG emissions rather than a broad range of impact categories in their life cycle assessment and report example GHG emissions ranging from 7 g CO_2 eq./MJ for switchgrass derived ethanol [10] to 21 g CO_2 eq./MJ for sugarcane ethanol in Wang et al. study whilst 21 g CO_2 eq./MJ in Seabra et al.'s study [11]. The variations are mainly due to aspects of the methodologies applied and to differences in the technologies and data for the agricultural sector, bioethanol conversion technologies. By comparing bioethanol derived from such lignocellulosic biomass sources with the conventional fuel in some of these studies, GHG emissions savings against gasoline are found between 44% and 95% [7,12].

Review of the literature as summarised above indicates that there is currently relatively little research focused on assessing the 'well-to-wheel' environmental profile with full impact categories of wheat straw-derived bioethanol. Two comprehensive reviews have been published recently by Cherubini et al. [13] and Singh et al. [14] including the updated developments and challenges on the environmental sustainability assessment of bioenergy/bioethanol. It has been suggested that LCA is an appropriate approach to evaluate the potential use of lignocellulosic feedstocks in bioethanol production, screen new technologies, and to identify the main drivers of the environmental profile of bioethanol, thereby indicating priority areas for potential improvements [15–18]. However, there is an ongoing debate regarding the potential effects caused by the removal of agricultural residues.

Except for a few literature reports [19,20], the effects caused by wheat straw removal for bioethanol production purposes are neglected in most bioethanol LCA studies. Removal of wheat straw rather than ploughing back to the field may raise several concerns: (1) decreasing the soil quality which leads to additional synthetic fertiliser applied to balance the nutrients removed with the straw, (2) increasing field emissions due to applying additional fertiliser, and (3) decreasing soil organic carbon stock which leads to a loss of carbon as CO_2 to atmosphere. These effects caused by wheat straw removal on ethanol life cycles and comparison results with petrol are discussed thoroughly in this study.

In our previous study, the economic feasibility for several cases of bioethanol production at industrial scale from wheat straw using different 'state-of-the-art' pretreatment technologies (i.e. steam explosion with and without acid catalyst, liquid hot water, dilute acid and wet oxidation) have been conducted [21]. It was found that bioethanol production with steam explosion or liquid hot water, with a production cost at £0.28/L, can be economically competitive with petrol in a prospective scenario with a reduced enzyme loading [21]. It also indicated that policy support in the form of tax exemptions and the access to the wheat straw prices of £35/tonne or lower could significantly enhance competitiveness of bioethanol with petrol. In this study, the environmental profiles of these cases defined above are assessed using an LCA approach with many impact categories considered, and are then compared with the conventional transportation fuel petrol.

2. Methodology

LCA is a method assessing the environmental impacts of a product through its life cycle from the raw material acquisition and production, transportation to end-use and disposal. The LCA study was conducted with regard to ISO 140440 and its related standards [22]. With regards to the Life cycle impact assessment (LCIA), the characterisation model CML baseline 2000 v2.05 incorporated in software Simapro v7.3 was applied [23].