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Importance of policy support and feedstock prices on economic feasibility of bioethanol production from wheat straw in the UK

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ABSTRACT

The economic feasibility of producing bioethanol from wheat straw in the UK using various state-of-the-art pretreatment technologies (steam explosion with and without acid catalyst, liquid hot water, dilute acid and wet oxidation) is assessed in this study. Under the current-technology base-case modeled using high enzyme loadings demonstrated at the laboratory-scale, wet oxidation pretreatment had the lowest minimum ethanol selling price (MESP) of £0.347/L ($2.032/gal). A contribution analysis showed feedstock price and enzyme cost were the two greatest contributors to the MESP, which led to a prospective case study and sensitivity analysis for assessing the effects of these two factors on the potential for economically competitive wheat straw-to-bioethanol UK supply chains. Prospective case studies modeled with a reduced enzyme loading and cost, demonstrated that although pretreatment scenarios with liquid hot water and steam explosion without acid catalyst were the closest to petrol pump prices, policy support in the form of tax exemptions could significantly enhance competitiveness of bioethanol with conventional fuel. A sensitivity analysis of feedstock prices also demonstrated that access to wheat straw prices of £35/t or lower would allow bioethanol production to be competitive with petrol under the best case scenario.

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Abbreviations: CHP, Combined heat and power; COD, Chemical oxygen demand; CSL, Corn steep liquor; DA, Dilute acid; DA, Diammonium phosphate; FPU, Filter paper unit; GHG, Greenhouse gas; HMF, 5-hydroxymethyl-furfural; ISBL, Inside-battery-limits; LHW, Liquid hot water; MESP, Minimum ethanol selling price; NREL, National renewable energy laboratory; SE, Steam explosion; SECA, Steam explosion with sulphuric acid catalyst; TCI, Total capital investment; WO, Wet oxidation; WWT, Wastewater treatment; VAT, Value-added tax

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1. Introduction

The transportation sector is under increasing pressure to improve vehicle efficiency as well as to diversify transport fuel sources as approaches to reduce reliance on fossil fuels. Alternative transport fuels such as natural gas, hydrogen and biofuels are seen potential routes to reduce energy insecurity and environmental pressure. However, the production of biofuels from lignocellulosic biomass is considered to be the most promising option in the short-term as their market maturity is above the other alternatives [1,2]. In 2010, transport accounted for 21% of the UK's domestic GHG emissions—this was further increased to 26% when shipping and aviation were included [3,4]. The UK government's commitment to reducing transport-derived carbon emissions is driven by targets such as the EU Renewable Energy Directive which requires that 10% of transport fuel come from renewable sources by 2020, as well as the Renewable Transport Fuels Obligation which mandates that fuel suppliers increase the proportion of biofuels to reach 5% (by volume) of total road transport fuel by 2013 [4–6]. As a result of these policy measures, statistics reveal that domestic emissions, which rose steadily from years 1990 to 2007, have fallen back to their initial 1990 levels due to improvements in vehicle fuel efficiency and increased uptake of biofuels [4].

Agricultural wastes, as one type of lignocellulosic resource, can comprise up to 50% of agricultural production, and are regarded as cheap, abundant and accessible feedstocks for bioethanol production [7]. The UK produces around 11.9 million tonnes of cereal straw annually, with a 4.9 million tonne surplus [8]. Wheat straw accounts for 54% by mass of the total straw produced in the UK (oil seed rape 20%, barley 20%, oats 4% and others 1%) [9]. Wheat production in the UK ranks third amongst the EU 27 countries, with a total area covering 1.8 million hectares [10,11]. Though the composition of wheat straw compared to wood has been shown to have less cellulose and lignin and more hemicellulose, it still contains between 60% to 80% of its biomass composition as polysaccharides and thereby represents a significant potential resource of sugars for bioethanol production [9].

Numerous studies have investigated the technological feasibility of biochemically converting wheat straw into bioethanol, notably the effect that various pretreatments have on enhancing sugar conversion efficiencies [12–17]. A recent study by Talebnia et al. [17] has reviewed these technological routes and has suggested the commercial potential that bioethanol from wheat straw may have based on evaluations of techno-economic studies for other lignocellulosic feedstocks. From these reviews, it is generally concluded that pretreatment is a necessary step in the biochemical conversion process to ensure production of fermentable sugars within an industrially acceptable set of conditions [18,19]. Through combinations of increasing accessible surface area, partially/fully removing lignin and/or hemicellulose and disrupting interactions between cell wall components, an effective pretreatment aims to improve enzyme accessibility to glucan, thereby increasing the amount of sugars available for fermentation [20,21]. Successful pretreatments on wheat straw, of which include dilute acid, steam explosion, liquid hot water and wet oxidation amongst others, have been shown to enhance sugar yields after enzymatic saccharification, achieving up to 74% to 99.6% of the theoretical maximum [13,14,16,17].

Existing techno-economic assessments of bioethanol production from various feedstocks including corn stover, poplar, eucalyptus and waste papers amongst others have been widely reported in the literature; however there is yet to be an in-depth analysis of the economic viability of wheat straw for this purpose [22–31]. These assessments are useful tools for providing insight into possibilities for process optimisation, cost reduction, and comparison of alternative technology scenarios. In this work we have adapted and modified the techno-economic model in Humbird et al. [22] to build five pretreatment process scenarios for bioethanol production from wheat straw in the UK. The effects of these scenarios are evaluated using the minimum ethanol selling price (MESP) as the principal indicator of their economic feasibility.

2. Materials and methods

The composition of wheat straw, the conditions of the pretreatments applied on wheat straw and the results from the subsequent enzymatic saccharification are derived from research literature. This information has been used as input for the process design and simulation carried out using AspenPlus^{TM} software. The generated mass and energy balances are used for further economic analysis to assess the economic feasibility of bioethanol produced from wheat straw for comparison with conventional transportation fuel petrol.

2.1. Composition of wheat straw

The compositional data of wheat straw derived from research literature has been normalised and averaged in this study [13,14]. Wheat straw, with a moisture content of 6.5% (w/w), contains 34.6% glucan, 21.1% xylan, 2.3% arabinan, 0.9% galactan, 18.0% lignin, 2.2% acetyl groups, 5.6% ash and 15.4% extractives (w/w on a dry basis).

2.2. Pretreatment and saccharification

A recent comprehensive review by Talebnia et al. [17] summarised the pretreatment methods on wheat straw which have been modelled in this study. The conditions of these pretreatments and results for the subsequent enzymatic saccharification are listed in Table 1. It should be noted that in order to complete the process design, some assumptions have been made in the present work for the information that was not reported in the literature. For example, it is assumed that there is no 5-hydroxymethyl-furfural (HMF) formed in liquid hot water and wet oxidation pretreatments, and no xylan is degraded into furfural in liquid hot water pretreatment. When not reported, the conversion yields of arabinan and galactan during pretreatment have also been assumed to be the same as xylan and glucan, respectively. Similarly, C5 and C6 sugar yields in enzymatic saccharification have also been assumed to be the same as xylose and glucose yields, respectively. Where only the glucose yield is reported, it is assumed that other polysaccharides have the same conversion efficiencies.