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Bioethanol production from various waste papers: Economic feasibility and sensitivity analysis

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HIGHLIGHTS

- Bioethanol produced from waste papers can be economically competitive with petrol.
- Biomass feedstock cost is the main contributor to bioethanol cost.
- Pre-treatments reduce the cost of bioethanol made from newspaper and office paper.
- Increasing solids loading and enhancing fermentation can reduce bioethanol cost.
- Plant capacity affects the bioethanol cost significantly.

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ABSTRACT

As a significant fraction of municipal solid waste, waste paper is a potential source for producing bioethanol. In the present paper, bioethanol production from various waste papers (newspaper, office paper, cardboard and magazine) using an enzyme complex (Cellic Ctec 1) was evaluated from an economic standpoint. Four bases cases without pre-treatment and two state-of-the-art cases (including dilute acid pre-treatment for office paper and oxidative lime pre-treatment for newspaper) were constructed using laboratory experimental data, literature values, expert consultations and simulation using AspenPlus™. Several scenarios were also carried out to assess the sensitivity of various technology parameters (i.e. solids loading in saccharification, anaerobic digestion and fermentation efficiency, and sugar yields in pre-treatment). The sensitivity analysis suggested that the economic performance of bioethanol produced from waste paper could be improved significantly with an up to 25% reduction in minimum ethanol selling price (MESP) by increasing solids loading in saccharification and with a 6% reduction in MESP by enhancing fermentation efficiency. The comparison of the bioethanol selling price at pump (reference year 2009) and the petrol price showed bioethanol produced from newspaper, office paper and cardboard were economically competitive with petrol.

1. Introduction

Concerns over climate change effects and energy security have become prominent in public life in recent years. World energy consumption is predicted to increase by 50% to 2030 according to a prediction from the United States Energy Information Agency [1] and US retail gasoline prices have soared from 0.83 $/gallon in 2000 to 3.49 $/gallon in 2011 [2]. Such factors have stimulated the search for viable, alternative transport fuels. The UK is the third largest consumer of energy amongst the EU 27 countries, albeit with a relatively low dependency (25%) on energy imports in 2010 due to its large domestic energy production (mainly oil and gas) [3,4]. However, the share of renewable energy in the total energy consumption for the UK is relatively low as 3.3% in 2010 though progresses has been made toward the EU's Renewable Energy Directive (RED) target of 15% by 2020 [5].

Compared with the first generation (1G) biofuel produced from food crops, second generation (2G) biofuels from lignocellulosic biomass or agricultural wastes have many advantages. For instance, most second generation biofuels are considered to be able to deliver substantial GHG emissions reductions when compared with petrol [6,7]. However, the development of 2G biofuels is also

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challenging, for example securing a low-cost and stable feedstocks, minimising land use changes caused by demand for biomass feedstocks and optimising bioethanol production technologies. Considering these challenges, waste papers as part of the degradable fraction in municipal solid waste (MSW) have potential to be a promising feedstock for bioethanol production. The reasons for this include: (1) waste papers are relatively abundant in the UK, reaching 8.8 million tons in 2008 due to reasonably efficient MSW collection and sorting systems, (2) they are economically competitive with other biomass feestocks because of the relatively low costs (average £40/ton), (3) they contain relatively high levels of carbohydrates that are potential convertible to bioethanol, (4) they are likely to be easily digestible without aggressive physical or chemical pre-treatments, (5) utilisation of waste papers for bioethanol production may offer a useful and valuable alternative route to managing these papers in addition to/as a complement to recycling. There is also a potentially available resource of waste papers in the UK because only 45% of recovered papers were recycled domestically while the remaining were exported overseas (in 2008) and in parallel the UK imported approximately 4.9 million tonnes of pulp and paper products. This reflects the fact that not all recovered paper is demanded by UK paper mills because paper quality specifications mean there are limits to increasing the recycled content in paper products [8] and, furthermore, (6) paper recycling technology itself has limitations, for example, effective deinking technology is needed to produce high quality paper products, paper fibres can only be recycled through a limited number of cycles and recycling to paper is very difficult for waste paper that has been mixed with other 'organic' waste (kitchen/garden waste etc.). Economic analysis has been used as a promising tool to assist the biofuels research community in identifying key cost drivers, evaluating novel technologies and assessing new process configurations. The National Renewable Energy Laboratory (NREL) in the US has developed a detailed techno-economic model for corn stover-based bioethanol production process design, to evaluate new developments and technologies [9–11]. The NREL model has been adapted in several studies, including the present research [12–18].

In a previous study, we reported composition and high-solids loading saccharification results for various waste papers [18]. These laboratory-derived primary data have been used here to adapt the NREL corn stover-based model to a suitable process design for bioethanol production from waste papers [18]. The effects of varied feedstock, process and technology parameters on the economic analysis of ethanol from waste papers as reflected in the calculated minimum ethanol selling price (MESP) are investigated in the present study. This work aims to provide a detailed economic assessment for waste papers-derived bioethanol production with sensitivity analysis and discussion on the robustness of this approach to biofuel production.

2. Materials and methods

2.1. Composition of waste papers

Waste papers were collected locally in London, UK. They are (1) newspaper *The London Paper* previously distributed in the central London area, (2) printed office paper and packaging cardboard locally from Imperial College London, and (3) glossy magazine (supermarket catalogue). Their compositions were analysed in our previous study [19] in accordance with Sluiter et al. [20] and are listed in Table 1.

2.2. Saccharification of waste papers

The enzyme complex used in this study, Cellic Ctec 1 (cellulolytic enzyme cocktail) was donated by Novozymes A/S, Demark. Its activity was measured to be 120 FPU/ml of liquid product as supplied [21]. Waste papers were blended with water at 15% (w/w) for 10 min in a bench-top blender. Sulphuric acid was used to adjust the pH of slurry to 5.2 due to its alkalinity. High-solids loading (15% w/w) saccharifications for the four types of paper were performed at laboratory scale at 50 °C for 72 h using an overhead stirred reactor. Monomer sugars concentrations were detected by HPLC with a Biorad Aminex HPX-87P column operating at 80 °C, water mobile phase and a flow rate of 0.6 ml/min. Sugar yields in terms of the percentage of monomer sugar released from carbohydrates were calculated.

Table 1
Composition of waste papers (All results are presented as percentages of as-received waste paper) [19].

	Newspaper	Office paper	Magazine	Cardboard
Moisture	7.25	4.90	4.40	5.90
Glucan	43.78	55.69	34.35	49.56
Xylan	6.59	13.91	4.51	7.75
Galactan	1.76	0.00	1.89	1.78
Mannan	6.78	0.00	5.42	4.78
Arabinan	1.73	0.00	1.74	1.46
Lignin	16.82	5.78	14.19	14.86
Extractives	3.65	1.87	3.30	2.40
$CaCO_3$	1.98	7.71	2.52	3.96
Ash	9.49	7.57	28.83	9.32

2.3. Processes configuration

Process configurations for four base cases (waste paper-to-bioethanol processes) and two state-of-the-art cases (office paper-to-bioethanol with dilute acid pre-treatment and newspaper-to-bioethanol with oxidative lime pre-treatment) are given in Sections 2.3.1 and 2.3.2. The process parameters and the values applied in sensitivity analysis are presented in Section 2.3.3.

2.3.1. Base cases

Fig. 1 shows the process design for the waste papers-to-bioethanol base cases [18].

Waste papers are unloaded, unwrapped and go through a metal removal process in the feedstock handling area (A100). In the blending area (A200), waste papers are pulped at 15% w/w solids loading in pulpers with a cycle time of 15 min (10 min blending, 5 min feeding time). The maximum capacity for this high solid content blending is 10.43 dry tonne per batch at an energy consumption of 30 kW/dry tonne [22,23]. The pulped paper slurry is then saccaharified enzymatically at 50 °C for 72 h in reactors arranged as a continuous train (A300). The sugar yield data obtained experimentally was applied in developing the output from the saccharification reactor design. A recombinant bacterium *Zymomonas mobilis* which both ferments pentose and hexose is used in the fermentation (A400). The hydrolysate from saccharification and nutrients of corn steep liquor and diammonium phosphate (DAP) are then sent to seed incubation and fermentation tanks operated at 40 °C for 36 h [9]. The conditions and nutrients loadings in seed incubation and fermentation tanks are adopted from the NREL process [9]. The bioethanol yield from glucose in the fermentation is 95% [9]. Total sugar lost due to contamination in the fermentation process was assumed to be 7% according to NREL [9]. Bioethanol from fermentation is then purified to 99.5% (w/w) using distillation, rectification and molecular sieve adsorption processes (A500). The solid cake with a moisture content below 50% obtained from the distillation bottoms *via* a series of press filter separations is sent to the combustion area (A800) and the liquid fraction is sent to the waste water treatment (WWT) area (A600) where biogas is produced in anaerobic digestion and water is further cleaned in