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Research paper

Energy self-sufficient production of bioethanol from a mixture of hemp straw and triticale seeds: Life-cycle analysis

Michael Buck*, Thomas Senn

Institute of Food Science and Biotechnology, Subinstitution Yeast Genetics and Fermentation Technology, Universität Hohenheim, Garbenstraße 23, 70599 Stuttgart, Germany

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ABSTRACT

Industrial hemp shows exceptional potential for cellulosic ethanol production, especially regarding yields per hectare, costs and environmental impact. Additionally, co-products, such as high-value food-grade oil, increase the value of this plant. In this work, hemp straw was steam-exploded for 45 min at 155 °C and hydrolysed with a cellulase/xylanase mixture. Up to 0.79 g g^{-1} of cellulose was degraded and subsequent simultaneous-saccharification-and-fermentation with added triticale grist resulted in >0.90 g g^{-1} fermentation of cellulose. Hemp straw is very suitable, as it contains 0.63 g g^{-1} of cellulose and only 0.142 g g^{-1} of hemicellulose.

A 2000 m^3 a^{-1} ethanol biorefinery requires a land use of 3 km^2 each for hemp and for triticale. A total of 2630 kg ethanol and 150 kg hemp oil can be gained from 1 ha. Slurry and triticale straw serve as raw material for the biogas fermenter or as animal feed. Biogas supplies thermal and electric energy in combined heat and power. Ethanol will remain at 0.66 € dm^{-3} based on market prices. In addition, data have been calculated for market prices plus and minus 30% market prices (0.51–0.81 € dm^{-3}). Carbon dioxide (CO_2) abatement for ethanol achieves 121 g MJ^{-1} CO_{2eq} for a combined ethanol/biogas plant. The CO_2 abatement costs vary from 38 € to 262 € t^{-1} CO_{2eq}.

1. Introduction

Feedstock costs dominate total costs in ethanol production [1]. Many investigations are based on low-cost substrates, such as wheat straw, so-called waste materials or co-products. After the building up of a plant that uses these materials, market prices for the substrates increased hugely [2]. Hence, the profitability of such a plant decreases. A more modest approach consists of the use of an agricultural crop with a high glucan content and high yield per hectare, e.g. fibre hemp *Cannabis sativa* L. Industrial hemp is characterised by glucan contents of more than 60% in dry matter (DM) [3] and a yield ranging from 5.6 t ha^{-1} DM in the United Kingdom to 25 t ha^{-1} DM in Italy [4]. Application of genetically modified yeasts that ferment xylose and arabinose increases ethanol yield. The data of Pakarinen et al. [5] predict 33% higher ethanol yields.

Hemp production improves the soil structure with its enormous root growth [6], especially in landscapes that are suitable for grain production. A low demand for fertilizers of 70–90 g m^{-2} marks hemp as an environmentally friendly crop [7]. Fast plant growth causes fast soil coverage that inhibits the sprouting of pest plants and secondary growth. Its high durability against plant diseases decreases the application of pesticides to a minimum [8].

Hemp dominated the fibre market worldwide in earlier times and was used especially for sailcloth and cordage [9]. Nowadays, hemp cultivation has been revived in many countries throughout the world. Hemp fibres are still under investigation and requested as tissue [10], composite [3,11] and paper [12]. Hemp hurds, also called shives, serve as an energy source in power plants, animal and pet bedding, garden mulch, and are used in light-weight concrete or for ethanol production [13]. Oil extracts from hemp seeds are widely demanded for the cosmetics [14] and pharmaceutical industry [15,16] and as a high-value food oil [17]. Casas and Rieradevall i Pons [18] analysed the use of hemp oil diesel. The whole hemp plant can be used for ethanol and methane production [19,20] and combustion [21,22].

A continuous ethanol plant requires the biomass to be storable after harvest. Hemp straw achieves DM contents >0.9 g g^{-1} after field retting and does not need any further treatment in storage.

* Corresponding author.
E-mail addresses: Michael.Buck@uni-hohenheim.de (M. Buck), Thomas.Senn@uni-hohenheim.de (T. Senn).

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Frost-retting has been shown to avoid mould growth, especially compared to unretted hemp straw [23]. Ensiling of fresh substrate presents another storage possibility, however, it greatly increases the transport weight. Furthermore, storage requires anaerobic conditions. Bacteria will usually build up in an acidic environment by the fermentation of free sugars into organic acids. Due to the lack of free sugars, cut hemp needs to be pre-hydrolysed by enzymes or treated with acids for preservation [24].

Hemp substrate needs to be cut or chopped prior to cellulose digestion. Zhang et al. [25] have related particle size to the cellulose conversion grade of steam-exploded substrates. However, the pretreatment conditions considered were more extreme than in this work. Considering other publications, steam-explosion treatments with or without acid or alkaline addition have been carried out between 170 and 250 °C [26–30].

Furthermore, Zhang et al. [31] predicate synergies between cellulases and pectinases in steam-exploded and ensiled hemp. Both the very common dew retting in the fields and water retting cause pectin degradation by bacterial pectinases [32]. Pakarinen et al. [20] confirmed enhanced enzymatic accessibility to the biomass after enzymatic or chemical pectin removal. Similarly, cellulases interact synergistically with xylanases. Hu et al. [33] reported enhanced hydrolysis yields if xylan is degraded. A huge challenge arises from enzyme binding to the surface of lignin molecules, as it makes them unavailable for cellulose degradation [34]. Digestion of lignin to phenols solves that problem; however, those hydrolysates lead to toxic fermentation brews and complicate yeast fermentation. Furthermore, several cellulases are very susceptible to phenols [35].

Different strategies for the production of fossil fuels have to be compared to lignocellulosic ethanol production. Life cycle analyses (LCAs) take account of material, energy and pollution flows. Although calculations of flows for the use of the same energy crop under the same conditions and application should not differ very much between different studies, assessment methodologies for the impact of biofuels do differ [36–39]. Differences in feedstock, country, scope of approach, system boundaries, land use change, by- and co-products and costs are the key issues [39]. The kind of conversion technology applied especially influences the yield, costs and environmental impacts [40]. Lee [41] described the same challenges in conversion technology in 1997 as today. Furthermore, available arable land limits the profitability of ethanol plants by increasing transport distances [42].

The potential of one kind of renewable energy can be determined regarding the yield per hectare, environmental impact or monetary efforts. The CO_2 abatement costs estimate monetary input per saved ton of CO_2 emissions using bioenergy. An advanced calculation also has to take external costs into account. These costs are not part of the market price of a product, but have to be paid as social costs [43]. The German Federal Ministry of the Environment proposes a calculation of costs of 20, 70 and 280 € t^{-1} CO_2 equivalent. Indeed, costs and especially savings of renewable energies receive only a little attention in publications [44].

2. Material and methods

2.1. Goal and scope

This LCA presents an ethanol biorefinery combined with biogas combined heat and power (CHP) plant. An essential part of the ethanol production is the co-fermentation of the non-food cereal triticale and cellulose from hemp. The biogas fermenter is powered by slurry enriched with triticale straw. Furthermore, cultivation of the energy crops is included. The residues from the biogas fermenter return to the fields and decrease the consumption of fertilizers.

The analysis includes the flows for ethanol, electricity and hemp oil production from well-to-tank and well-to-wheels. Inputs are regarded for energy crop cultivation and processing in biorefinery. Output is limited to ethanol, electricity and hemp oil. The costs for the building of the biorefinery, running costs and deprecation are discussed in the financial analysis, which is based on an output of 2000 m^3 ethanol per year. The crops have been considered with their market prices. However, the production costs are regarded.

The study focuses on the creation of small regional biorefineries and conversion of existing starch-based distilleries. The concept is supposed to assure independence from oil-producing countries and companies.

The work is prepared to meet the criteria for cross-compliance and sustainability. A land-use change is not considered.

2.2. Biomass

Untreated hemp straw (*Cannabis sativa* L.) of the variety USO 31 was provided by a hemp briquette and food dealer (CHIRON, Mietingen, Germany). The hemp was cultivated in the district of Oberschwaben, Germany, cut into 60 cm pieces, dried in the field and harvested with a modified combine harvester at a DM of >0.85 g g^{-1}. The stalks were stored in a barn during the winter and shipped in March. The stalks arrived at a DM of 0.916 g g^{-1} and were pretreated immediately. Compositional materials were investigated using the laboratory analytical procedure “Determination of Structural Carbohydrates and Lignin in Biomass” from the National Renewable Energy Laboratory (NREL, Washington, USA). The hemp straw used contained glucan 0.63 g g^{-1}, xylan 0.142 g g^{-1}, lignin 0.146 g g^{-1}, ash and others substances 0.082 g g^{-1} in DM.

The triticale seeds used were a blend of different varieties. The grain was milled to grist with a hammer mill (Retsch SR2, Haan, Germany) combined with a 0.5 mm sieve. The DM was 0.894 g g^{-1} and had a glucan content of 0.661 g g^{-1} in DM.

2.3. Pretreatment

The hemp stalks were cut with a cutting mill (Retsch SM 100 comfort, Haan, Germany) equipped with a 10 × 10 mm sieve and pretreated with steam (ibW, Althengstett, Germany) for 45 min at 155 °C with water only. Treatment conditions have been adapted from Fleischer [45]. The DM attained 0.105 g g^{-1} after steam explosion. The biomass was portioned into wide mouth Polyethene bottles, frozen immediately and stored at −20 °C until needed. The substrate was defrosted in hot water prior to use.

2.4. Enzymes

Hemicellulose was degraded with β-glucosidases, exocellulases, endocellulases and xylanases, supplied by Erbslöh (Geisenheim, Germany). Enzymes for the hydrolysis experiments of hemp were applied in concentrations of 13.6 or 27.2 mg g^{-1} DM, respectively. The enzyme application was 27.2 mg per g DM for the fermentation experiments. The enzyme activity of that mixture had been determined previously with a modified Somogyi-Nelson test and resulted in 350 Units mg^{-1} xylanase activity, 86 U mg^{-1} endocellulase activity, 11 U mg^{-1} exocellulase activity and 19 U mg^{-1} β-glucosidase activity.

The Stargen mix (Danisco, Copenhagen, Denmark) was applied for triticale mashes and required 1 g kg^{-1} enzyme solution of the acid α-amylase GC 626, hemicellulase Optimash BG, peptidase Fermgen, and gluco- and α-amylase Stargen 002.