Renewable and Sustainable Energy Reviews 46 (2015) 100–119

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of bio-conversion pathways of lignocellulose-to-ethanol: Sustainability assessment based on land footprint projections

Hsien H. Khoo

Institute of Chemical Engineering Sciences, 1 Pesek Road, Jurong Island, Singapore 627833, Singapore

ARTICLE INFO

Article history:
Received 27 May 2014
Received in revised form
11 December 2014
Accepted 7 February 2015
Available online 9 March 2015

Keywords:
Lignocellulose–ethanol
Farm-to-fuel
Bio-conversion methods
Land footprint

ABSTRACT

A review of 55 pretreatment and bio-conversion methods for the production of lignocellulose–ethanol was carried out. Bio-conversion studies include enzymatic fermentation, simultaneous saccharification and fermentation, process modelling, supply chain simulations, Life Cycle Assessment and other experimental studies. A new sustainability indicator labeled Land Footprint, from farm-to-fuel, was introduced. The Land Footprint (LF) results are projected for bio-ethanol derived from stover and switchgrass from U.S., sugarcane bagasse from Brazil and India, and rice husk and straw from China and India. In order to produce 1 million L bio-ethanol, bagasse and rice straw are observed to have the highest potential to be sustainable resources that demand the least amount of agricultural land. The Land Footprints for both countries are 85 ha-yr for bagasse–ethanol and 80 ha-yr for China rice straw–ethanol. The Land Footprints per 1 million bio-ethanol from switchgrass and stover in the U.S. are 140 ha-yr and 366 ha-yr, respectively. Utilizing stover as a feedstock, an estimated LF of 14.7 million ha-yr is required to satisfy up to 50% of U.S.'s year 2022 bio-ethanol mandate. The more efficient switchgrass–ethanol would require 4.4–6.6 million ha-yr agricultural land to meet 40–60% of bio-ethanol demands for year 2022. As the most productive crop per hectare of land, sugarcane bagasse require about 2.4 million ha-yr land to supply sufficient amount of bagasse to meet up to 60% of bio-ethanol national demands.

Contents

E-mail address: khoo_hsien_hui@ices.a-star.edu.sg

http://dx.doi.org/10.1016/j.rser.2015.02.027
1364-0321/

1. Introduction

In view of continuously rising petroleum costs and dependence upon non-renewable fossil-based materials, a lot of attention has been given to alternative energy resources. The decades-long dominance of petroleum companies as major sources of energy, raw materials and chemicals, is seeing a gradual switch to bio-based industries that are producing the same products from biomass. However, the transition from a petroleum-based economy to one that exploits the potential of biomass is not without new technological, ecological and sustainability challenges [1,2].

The conversion of biomass resources to biofuels such as bio-ethanol is globally gaining significant prominence for the last 20 years. In order to be sustainable, new value chains of biomass-to-bioenergy products requires the successful deployment of innovative biotechnologies [3], as well as efficient utilization of land. The increasing use of bio-based fuels or materials from biomass is causing countries worldwide to use a growing amount of land, which may lead to the expansion of cropland and intensive biomass cultivation at the expense of natural ecosystems [4]. Therefore, concerns for land use for biomass feedstock production are being considered as one of the key factors in determining bio-product sustainability [2].

1.1. Land utilization

The growing demand for biofuels also led to the increased pressure for available land to grow crops used for fuel and consequently increased land competition to produce crops for food [1,4]. Several other authors have explored the topic of Land Use (LU) and Land Use Change (LUC) in terms of greenhouse gas emissions, biodiversity loss and soil erosion [5–7]. For example, Wicke et al. [8] reported that although biofuels have proven to bring economical advantages for many developing countries, they have caused significant ecosystem damages via deforestation to clear land for biomass cultivation.

If biofuel production were to be introduced at large-scale or national levels, social concerns such as safeguarding global food supply and security have to be accounted for [9]. Lignocellulosic biomass is considered in this article as a potential sustainable resource for the production of bio-ethanol, with the consideration that food supply will not become a threat to society [10]. Lignocellulosic biomass resources are found in many crop residues, such as stover from corn, bagasse from sugarcane and husk or straw from rice. In this study, effective land utilization is taken as a significant sustainability indicator for biomass-to-bioenergy or bio-product pathways.

This work offers a fresh perspective of sustainable land use and its availability, and attempts to provide some insights into the limits of producing biofuels. Due to the abundant sources of biomass resources along with the spectrum of information on emerging and present biotechnologies found in literature (e.g., [11–15]), the scope of this work is made more feasible by focusing on five selections of non-food biomass resources: (i) corn stover; (ii) switchgrass; (iii) sugarcane bagasse; (iv) rice straw; and (v) rice husk.

The main objective of this work is two-fold: first to perform a review of existing biomass-to-biofuels methods; and next, estimate a new sustainability indicator, Land Footprint (area required) for the production of bio-based energy or chemical products. A farm-to-fuel or bio-product perspective is adopted to trace the activities involved throughout the production chain. Apart from bio-chemical and other conversion methods, sugar contents and conversion/yield amounts are taken into consideration to estimate the Land Footprint. The results are expected to provide some insights and guidelines for gauging land use requirements where the demand for bio-based fuels, materials and chemicals continue growing.

1.2. Selected (non-food) biomass resources

The countries that are the foremost producers of corn, switchgrass, sugarcane and rice are selected for investigation. This section provides brief descriptions on corn and switchgrass from U.S., sugarcane bagasse from Brazil and India, and finally, rice straw and husk from China and India. The details of various crop yields, ranks, and ratios of residues-to-crops, are compiled in Table 1. These data are sourced from various reports [16–29].

1.2.1. Corn stover

Corn (*Zea mays L.*) is grown in 41 states across the United States, taking up about 34 million hectares (ha) of agricultural land area in 2010 [30]. Corn stover has a great potential as a cellulosic biomass resource for bio-ethanol production in the country due to its large supply. As a non-food biomass resource, stover consists of the stalk, leaf, cob, and husk fractions. The mid ranges of stover-to-whole corn are reported to be about 0.585 [23]. Sheehan et al. [30], on the other hand, cited 0.59 as common ratio of stover-to-whole corn. Here, a ratio of $r=0.58$ is assumed for stover-to-whole corn on a dry weight basis. Emerging bio-technologies focusing on the hydrolysis of cellulose to fermentable sugars for bio-ethanol has grown [11–13] and along with them is the increased demand for corn stover supply. Such novel bio-technologies are carried out in lab- and pilot-scale to convert stover to bio-ethanol efficiently [21–22].

1.2.2. Switchgrass

Switchgrass (*Panicum virgatum* L.) is a perennial C4 grass native to North America and is considered as one of the most valuable sources of biomass [31]. As a natural component of the tall-grass prairie in the U.S. ecosystem, studies have shown that the perennial grasses are a promising and sustainable source of biomass feedstock due to high yield potential and low input demands [32–33]. Switchgrass is being evaluated in the U.S. as cellulosic bio-energy crop. According to Schmer et al. [24], an estimated 3.1 to 21.3 million hectares (ha) of existing agricultural land in the U.S. can be converted to perennial grasses for bioenergy. Research efforts focusing on breeding and seedling have seen improvements in the productivity of switchgrass that (about 13.4–22.3 t/ha) exceed the yield range of corn (6.3–8.7 t/ha), making the biomass resource compete favourably both as a sustainable agricultural crop and as biofuel for industry [23,26]. The high cellulosic content of switchgrass also makes it an ideal candidate for bio-ethanol production.

1.2.3. Sugarcane bagasse

Sugarcane (*Saccharum officinarum*) has for decades been providing food and energy for society. The top three major producers were Brazil (40%), India (19%), China (6%) [28]. With a sugarcane output of