Engineering in Agriculture, Environment and Food xxx (2015) 1–8

Contents lists available at ScienceDirect

Engineering in Agriculture, Environment and Food

journal homepage: http://www.sciencedirect.com/eaef

Technical paper

Evaluation of the life cycle of bioethanol produced from soft carbohydrate-rich and common rice straw in Japan with land-use change

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ARTICLE INFO

Article history:
Received 29 April 2014
Received in revised form
11 September 2014
Accepted 12 January 2015
Available online xxx

Keywords:
Rice straw
Soft carbohydrate
Bioethanol
Land-use change
CO_2 emission
Cost

ABSTRACT

This study evaluates the life cycle of ethanol produced from soft carbohydrate (SC)-rich rice straw (cv. *Leafstar*) and common rice straw (cv. *Koshihikari*) while considering land-use change to estimate CO_2 emissions, energy balance (expressed as Net Energy Ratio, NER), and production costs. Three different pretreatment methods were considered: the DiSC (direct saccharification of culms), RT-CaCCO (room temperature-CaCCO) and CaCCO (calcium capturing by carbonation) processes. Although the reduction in CO_2 emission was found to be 59%, 42% and −3.5% for the DiSC, RT-CaCCO and CaCCO processes, respectively, the CO_2 emission reduction decreased significantly when land-use change was considered. This result clearly shows that the biomass (rice straw) should be obtained from paddy fields without land-use change. The NER values for the bioethanol produced by the DiSC, RT-CaCCO and CaCCO processes were estimated to be 2.7, 2.1 and 1.0, respectively, and the total costs were estimated to be 102, 134 and 151 Yen/L ethanol, respectively (US $1 = 100 Yen). The use of the SC-rich rice straw contributes to a reduction of the environmental load and costs for the pretreatment, enzyme production, and enzymatic hydrolysis processes. Therefore, the use of SC-rich rice straw for bioethanol production reduces the total cost of production, reduces CO_2 emissions, and improves the NER. Our results suggest that the DiSC and RT-CaCCO pretreatment processes are promising pretreatment techniques and that SC-rich rice straw is a promising resource for bioethanol production.

1. Introduction

The interest in bioethanol as an alternative to fossil fuel for transportation has been increasing, and lignocellulosic biomass, such as agricultural waste, woody biomass, and lignocellulosic energy crops (e.g., switchgrass), is expected to be the new second-generation bioethanol resource (Galbe and Zacchi, 2007; Merino and Cherry, 2007; Goh et al., 2010). In general, these lignocellulosic materials contain two polysaccharides in the fibers: cellulose and xylan. These polysaccharides can be degraded into fermentable monomeric sugars (i.e., glucose and xylose) using cellulolytic and xylanolytic enzymes. However, the polysaccharides are tightly packed in their native form. Moreover, these polysaccharides tend to be surrounded by lignin, and the resulting structures are highly resistant to chemical, physical, and biological attack (Grabber, 2005; Han and Anderson, 1974). The advent of bioethanol production from lignocellulosic biomass may raise concerns about the effects on CO_2 emissions, the high cost of the process, and the value of the energy resource. Recently, it has been reported that certain

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http://dx.doi.org/10.1016/j.eaef.2015.01.007

varieties of rice straw contain soft carbohydrates (SCs) (Park et al., 2009), which are defined as carbohydrates that are readily recoverable via direct extraction or enzymatic hydrolysis in the form of free glucose, free fructose, sucrose, starch, and β-1,3-1,4-glucan (Nagata et al., 2002). Park et al. (2011) proposed a simple process called DiSC (direct saccharification of culms) for bioethanol production from SC-rich rice straw. Because SC-rich rice straw does not require strong pretreatment or the use of cellulase for saccharification, SC-rich rice straw will reduce the CO_2 emissions, energy requirements, and total cost of bioethanol production. So, the DiSC process, dealing exclusively with hexoses in SC-rich rice straw, is an extremely simple and environmentally-friendly system without harsh pretreatments (Park et al., 2011). For common rice straw, the new bioethanol production methods using enzymatic saccharification have been developed including CaCCO (calcium capturing by carbonation) (Park et al., 2010) and RT-CaCCO (room temperature-CaCCO) (Shiroma et al., 2011). The CaCCO process is applied to almost herbaceous biomass, which has many cellulose and hemicellulose. The main advantage of the CaCCO over other processes is its simplicity because neither a solid—liquid-separation step nor a washing step of the solid portion is needed. Therefore, the process could successfully liberate xylose, starch, and sucrose in a reaction vessel (Park et al., 2010). RT-CaCCO (improved CaCCO process) was developed by its incorporation with a step of lime pretreatment at room temperature. The RT-CaCCO could provide with not only a novel method for preserving feedstock but also a room temperature alkali-pretreatment method for lignocellulosic fractions that would save the cost of heat energy (Shiroma et al., 2011). The commercial plant, however, has not been constructed for these processes. In order to promote an action for the construction of commercial bioethanol plant, the costs, CO_2 emissions, and energy ratios for bioethanol production should further be evaluated. Orikasa et al. (2009) reported on the costs, CO_2 emissions, and energy ratios for bioethanol produced from common rice straw using sulfuric acid saccharification (NEDO, 2006), and Roy et al. (2012a) also reported on the net energy consumption, CO_2 emissions and production costs for bioethanol produced from rice straw using the RT-CaCCO process. In general, the expansion of cultivation of biomass resource for bioethanol results in land-use changes. Land-use change occurs by changing the way of using land and can have positive and negative effects on carbon stocks (Sterner and Fritsche, 2011). Several review studies have shown that important aspects, such as the soil carbon emissions from land-use change for the GHG balance of biofuels, have not garnered sufficient attention, even in recent biofuel life-cycle studies (Van der Voet et al., 2010; Whitaker et al., 2010; Malça and Freire, 2011). Moreover, the CO_2 emissions (i.e., the factors above) associated with enzymatic saccharification, including land-use changes and crop production processes, have not yet been reported, and the effects of SC-rich rice straw on these factors are not yet known. In this study, we conducted a scenario-based analysis of the CO_2 emissions, energy ratios, and total costs of bioethanol production from SC-rich rice straw, with common rice straw as a reference. The effects of the amount of SCs in rice straw on energy production, the abatement of CO_2 emissions and the total costs were also compared with the corresponding performance characteristics for bioethanol production from common rice straw.

2. Methods

2.1. Functional unit

The purpose of the functional unit (FU) is to provide a reference unit that can be used to normalize the inventory data. The FU in this study was defined as 1 L of bioethanol from rice straw.

2.2. System boundary

Fig. 1 shows the system boundary of this study, which included changes in land use. The process of bioethanol production from SC-rich rice straw (cv. *Leafstar*) by the DiSC process was compared with that using common rice straw (cv. *Koshihikari*) with the RT-CaCCO and CaCCO processes. In this study, the quantities of SCs, cellulose, and xylan in the rice straw were based on the report of Park et al. (Park et al., 2009), which listed the components of the carbohydrates in *Leafstar* and *Koshihikari* (Table 1).

2.3. Land-use change and crop production

The CO_2 emission associated with land-use change per 1 L bioethanol, *LUG* (kg-CO_2/L ethanol), was calculated using the following equation (IPCC, 2006):

$$LUG = \frac{PLUC - LLUC}{T \times Y_D \times H} \times \frac{44}{12}, \quad (1)$$

where *PLUC* is the carbon stock of the previous land use (t-C/MJ), *LLUC* is the carbon stock of the latest land use (t-C/MJ), *T* is the allocation year (=20 year), Y_D is the amount of rice paddy (=4.64 t dry/km^2) (MAFF, 2007), and *H* is the heat quantity of bioethanol (=21.2 MJ/L). The carbon stocks of each land-use category, which were consisted of living biomass stocks, carbon stocks of dead plant, carbon stocks of litter, and carbon stocks of soil for each land use category (GIO, 2012), are shown in Table 2.

To evaluate the effect of the crop production process on the total CO_2 emissions for bioethanol production using the DiSC, RT-CaCCO and CaCCO processes, the CO_2 emissions of the crop production process were allocated economically to brown rice and rice straw. The prices of the brown rice and rice straw were set to 241 Yen/kg-wet and 13.0 Yen/kg-wet, respectively (MAFF, 2010). Regarding soil-associated greenhouse gas emissions, CH_4 is emitted from flooded paddy fields (Yagi et al., 1997; Naser et al., 2007). Because the rice straw, which is normally incorporated into paddy soils, becomes the substrate for soil-based CH_4 emissions, the CH_4

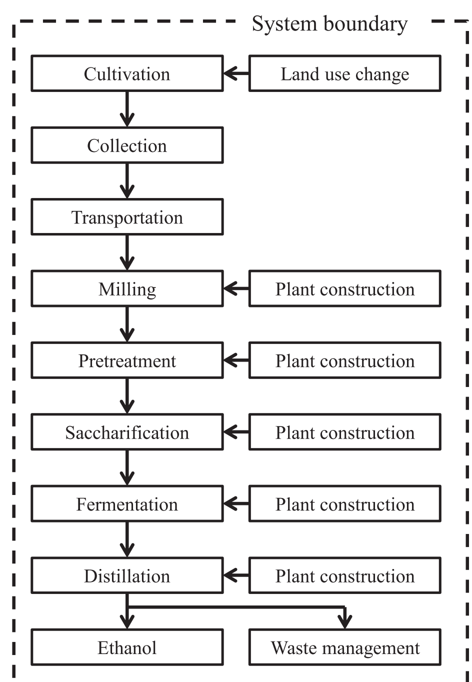

Fig. 1. System boundary of this study.

Please cite this article in press as: Orikiasa T, et al., Evaluation of the life cycle of bioethanol produced from soft carbohydrate-rich and common rice straw in Japan with land-use change, Engineering in Agriculture, Environment and Food (2015), http://dx.doi.org/10.1016/j.eaef.2015.01.007