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Research Paper

Effect of bioethanol conversion efficiency and ratio of rice paddy area to flatland on energy consumption and CO_2 emission of rice straw transport process in Japan

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In Japan, rice straw is recognised as the most promising biomass for bioethanol production based on the amount and availability. This study examined the energy consumption and the CO_2 emissions of the rice straw transport process. Specifically, we investigated the effects of the ethanol conversion efficiency (ε) and the ratio of the rice paddy area to flatland (γ) on the CO_2 emission and energy consumption of the rice straw transport process. The energy consumption and the CO_2 emissions (ε: 0.60–1.0; γ: 0.050–0.20) were determined to be 0.17–0.37 MJ L^{-1} and 0.012–0.025 kg L^{-1}, respectively. The predicting model for the energy consumption and the CO_2 emissions of the rice straw transport process was constructed, and the energy consumption and the CO_2 emissions were proportional to the ethanol conversion efficiency raised to the −1.5 power and γ raised to the −0.5 power. These results showed that the lower γ, the higher the energy consumption of the rice straw transport process. Furthermore, the energy consumption of the rice straw transport process increased at large-scale plants because of the higher value of average transportation distance.

1. Introduction

Researchers have been interested in producing ethanol fuel made from biomass (bioethanol) as an alternative to fossil fuel for transport because bioethanol has an advantage in its carbon-neutral nature as a fuel (Cardona & Sánchez, 2008; Ragauskas et al., 2006; Sánchez & Cardona, 2008). The global production of bioethanol raised from 17,106 ML in 2000 to

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72,782 ML in 2009 (F. O. Licht, 2009). Bioethanol is commercially produced from edible feedstocks, such as cornstarch and sugarcane juices, and these bioethanol production systems pose a concern because of competition with food and feed supplies (Park, Arakane, Shiroma, Ike, & Tokuyasu, 2010). To avoid this competition, non-edible lignocellulosic sources of biomass, such as rice or wheat straw, woody biomass, and lignocellulosic energy crops, are expected to be the new second generation bioethanol resource (Galbe & Zacchi, 2007; Goh, Tan, Lee, & Bhatia, 2010; Merino & Cherry, 2007).

In Japan, rice straw has attracted interest as a potential source for bioethanol production (Ogino & Kondo, 2009; Matsumura, Minowa, & Yamamoto, 2005; Ueda, 2011). Asano and Minowa (2007), and Imou (2008) reported that 6.7 Mt of wet rice straw (water content is about 15% wet basis) could potentially be converted to 1.7 GL of bioethanol every year in Japan. Bioethanol made from rice straw, however, has not been commercially produced in Japan because studies concerning the rice straw bioethanol production process are scarce. Lignocellulosic biomass, such as rice straw and other agricultural wastes, is not densely concentrated in the agricultural field. Therefore, the transport process of the agricultural wastes tends to have high financial and energy costs. Thus, the necessity for evaluating the efficiency of the rice straw transport process has increased. The energy consumption and the CO_2 emissions of the rice straw transport process influence not only the total levels of energy consumption and the CO_2 emission but also the total cost of bioethanol production. The report of the energy consumption and the CO_2 emissions of the rice straw transport process, however, are fewer than that of the bioethanol production process (e.g., Park, Shiroma et al., 2010; Shiroma et al., 2011). For example, Saga et al. (2008) reported that 16.6% of selling price of a baled rice straw was the transport cost. Kanai, Takekura, Kato, and Kobayashi (2010) reported that the fuel consumption of biomass transport process occupied to 1.3% of the caloric value of produced bioethanol. In estimation of energy consumption, CO_2 emission, and total cost of bioethanol production process, the transport distance and plant capacity differences are major uncertain factors to determine an optimal condition.

In this study, therefore, we focused on the effects of the feedstock transport process on ethanol production in relation to the conversion efficiency and the ratio of the rice paddy area to flatland (flatland is defined as the amount of area of farm land, grass land, roads, land for building and others), which influences the transport distance and quantity of rice straw required. This study had three objectives:

1. To investigate the effects of the ethanol conversion efficiency and the ratio of the rice paddy area to flatland on the energy consumption and the CO_2 emissions of the rice straw transport process in Japan.
2. To establish a model to predict the energy consumption and the CO_2 emissions of the rice straw transport process.
3. To discuss the relationship between the bioethanol plant size and the energy consumption of the rice straw transport process.

2. Materials and methods

2.1. Major parameters for analysis

This study investigated the energy consumption and the CO_2 emissions of the rice straw transport process from the rice paddy to the bioethanol plant. The purpose of the functional unit (FU) is to provide a reference unit that can be used to normalise the inventory data, and the FU of this study was defined as 1 L of bioethanol. We assumed that the rice straw generated from rice paddy cultivation was dried to around 15% wet basis in the cultivating area and collected from the paddy with a roll baler. The mass, the diameter, and the height of the bale were assumed to be 300 kg, 1.2 m, and 1.1 m based on the literature (Imou, 2008), respectively. The crop yield of 546 t km^{-2} was calculated from the amount of rice straw produced in Japan in 2005 (9,291,000 t) (Imou, 2008) and the acreage of rice paddy in Japan in 2007 (17,020 km^2) (MAFF, 2007). The Ministry of Agriculture, Forestry and Fisheries (MAFF) has committed to produce bioethanol (15,000 kL $year^{-1}$ per plant) from abundant rice straw in Japan. Therefore, the annual bioethanol production and the number of operation days at the bioethanol plant were set at 15,000 kL and 300 days, respectively (50 kL day^{-1}).

2.2. Biomass collection area

The biomass collection area was determined from the amount of rice straw required for bioethanol production. The radius of the biomass collection area was calculated using the following Equation (1) (Huang, Ramaswamy, Al-Dajani, Tschirner, & Cairncross, 2009):

$$L = (M_D/(\pi \cdot \gamma \cdot Y_D))^{0.5} \quad (1)$$

where L is the radius of the biomass collection area (km), M_D is the amount of rice straw to be processed (= the amount of biomass required to produce bioethanol) (t), γ is the ratio of rice paddy to flatland in Ibaraki prefecture, Japan (=1:7.8, from MAFF (2007), and GSI (2013)), and Y_D is the amount of dry crop per 1 km^2 rice paddy (t km^{-2}). The area of the rice paddy (= biomass collection area) per bioethanol plant was estimated from the ratio of the crop acreage of rice paddies (786 km^2 (MAFF, 2007)) to the area of flatland in Ibaraki prefecture, Japan (6095 km^2 (GSI, 2013)) ($\gamma = 0.128$ (Kanai et al., 2010)). The data was analysed by the assumption that the bioethanol plant was located in the Ibaraki prefecture. As in the Equation (1), the distance of biomass transportation increased with decreasing the γ value.

2.3. Transport of the feedstock

We assumed that the baled rice straw was transported to the biomass stock satellite from the rice paddy in a 4 t truck and then transported to the bioethanol plant in a 10 t truck. The capacities of the 4 t and 10 t trucks were calculated to be 8 bales and 18 bales, respectively, and the loading ratios of the 4 t and 10 t trucks were 60% and 54%, respectively. The biomass stock satellite was assumed to be a simple facility, with a roof to provide shelter from the rain and no electrical equipment (e.g., no refrigeration facilities for the long-term storage of the rice straw).