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Economic evaluation of synthetic ethanol production by using domestic biowastes and coal mixture

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ABSTRACT

Biowastes, such as cow manure, waste paper, and wood waste, are recognized as an essential source of renewable energy, and their importance increased significantly over time. However, the insufficient supply of biowastes for commercial thermochemical conversion processes is a major problem that needs to be addressed. Therefore, the co-utilization of biowastes and coal has been developed globally. In this study, we investigated the feasibility of biowaste and coal mixtures in an ethanol conversion process. A commercial-scale thermochemical process consisting of a dual fluidized bed gasifier, compressor, tar reformer, catalytic reactor, and auxiliary facilities was used and analyzed. In particular, the effects of material costs including both transportation and collection costs of biowastes and mix percentages on the economic value of synthetic ethanol were analyzed. In addition to the limitations of biowaste collection, the scale of co-utilization processes could be a critical factor for the commercialization of converting biowaste and coal mixtures to ethanol.

1. Introduction

Global energy demands have continued to increase because of the development of industries and societies in countries. Consequently, more fossil fuels are required to meet future demands. However, the increase in atmospheric carbon dioxide concentrations from the increasing usage of fossil fuels is changing the global climate, causing sea level rise and increases in the annual average global temperature. For these reasons, many countries have committed to reduce greenhouse gas emissions. In addition, sustainable sources of renewable energy are being actively developed to reduce carbon dioxide emissions and replace fossil fuels. Furthermore, a new generation of energy plants can capture carbon dioxide has been globally developed and adopted [1–3].

Biomass, which is derived from organic materials, is one of the more important potential sources for the production of green power and synthetic fuels. Biomass can be classified into forestry biomass (generated or produced in wood and wood products industries); agricultural wastes (generated as a byproduct of crops, agro-industries, and animal farms); energy crops (i.e., crops and trees dedicated to energy production); and municipal solid waste (generated in human society). Biomass resources are considered to be environmentally friendly fuel because there is no net increase in CO_2 as a result of burning biomass resources. Biomass has received increased public and scientific attention, driven by factors such as oil price spikes and the need for increased energy security. Moreover, biomass is often regionally available, and conversion into secondary energy carriers is feasible without high capital investments [4–6].

Biomass resources have been used as fuels for electricity production, heat generation, and chemical production. Additionally, biomass resources can be converted into biofuels, such as biodiesel or bioethanol [7,8]. Bioethanol, which has been commercially produced in the United States and Brazil, is a valuable energy resource that can partially replace gasoline [9,10]. In the United States, a renewable fuel standard sets the minimum requirements for the use of renewable fuels such as ethanol, and approximately 14 billion gallons of ethanol were added to the gasoline consumed in 2015. Moreover, bioethanol could be one promising option for meeting the 2015 Korean Renewable Fuel Standard [4,9].

The most common ethanol production processes today use yeast to ferment the sugars and starch in corn, sugar cane, or sugar beets. The starch in corn is fermented into sugar, which is then fermented into alcohol. Sugar crops are the most convenient resources for conversion into alcohol, because alcohol is created by fermenting sugar [9]. The increasing bioethanol production has led to the increased planting of these crops, even though the production of biomass resources is limited by the amount of available arable land, as well as the nutrient and land degradation. Additionally, competition with food resources has increased the price of these crops. Therefore, non-edible biomass resources, such as forestry biomass, agricultural wastes, energy crops, and municipal solid wastes, are considered as suitable substitute biomass

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resources for producing biofuels. Research on the energy conversion of non-food biomass resources has led to the modification of thermochemical conversion processes such as pyrolysis, combustion, gasification, and liquefaction. Compared with other thermochemical processes, gasification has been recognized as a key process for a new generation of energy plants that can produce electricity, chemicals, hydrogen, substitute natural gas, and synthetic fuels [11–16].

The shift from edible biomass to non-edible biomass for bioethanol production is challenging because an economically feasible thermochemical conversion process is required for the massive scale of non-edible biomass resources. Furthermore, the seasonal nature of biomass availability makes energy production from biomass-only thermochemical conversion processes difficult [4,11]. The massive fuel supplies necessary for commercial-scale production will incur significant collection costs, which is a major concern for biomass energy conversion. Additionally, there are many types of biomass resources, which are widely distributed and which have different harvesting periods. This makes it difficult to estimate the amount of biomass that will be available for energy production.

In order to overcome the fuel supply challenges facing commercial bioenergy plants, co-gasification of biomass and coal, petroleum coke, and combustible wastes can be considered as a reasonable solution [11–16]. In particular, the co-gasification of non-edible biomass resources and coal, which plays an important role in world energy supply, has been widely developed, because it reduces CO_2 emissions, and can even lead to net CO_2 reduction, if CO_2 capture is incorporated as a part of the process. In addition, biomass resources could help to reduce fossil fuel dependency [11,13,17]. Synthesis gas obtained from the co-gasification is further used for synthetic ethanol production, too.

Given the numerous applications of biomass and coal, collection costs remain the biggest hurdle for thermochemical biomass energy conversion. To commercialize biomass energy conversion, it is essential to evaluate the costs of collecting domestic biomass resources. By using a domestic biomass resource map, it is possible to quantify the usable biomass resources available in Korea [3]. Because of the broad distribution of biomass resources, an increase in plant scale would result in a shortage of raw materials and an increase in the cost of fuel.

In this study, we conducted a techno-economic evaluation of the domestic biowastes, that are annually generated in Korea, and coal mixture to synthetic ethanol conversion based on a published biomass resource map and database [2,3]. The economic evaluation of bioethanol production processes was carried out using data from the reports of the Ministry of Environment [18]. In particular, we evaluated the effect of biowaste-coal mixing ratios, biowaste collecting costs, and other variables on ethanol prices. Our economic feasibility analysis of synthetic ethanol production using domestic biowaste and coal mixtures could be used as valuable data for national energy resource planning, industrial development, and policy decision-making.

2. Process description and economic analysis

2.1. Description of synthetic ethanol production process

Fig. 1 shows a flow diagram for the proposed process for converting a domestic biowaste–coal mixture to synthetic ethanol, via gasification and alcohol synthesis. The synthetic ethanol production process introduced and analyzed by the National Renewable Energy Research Institute [19] and Gwak et al. [4] was modified and used for this study. Similar to previous studies, the proposed synthetic ethanol production process can be divided into drying, co-gasification, syngas cleanup, conditioning, alcohol synthesis, separation, and heat and power generation. The drying process involves the removal of moisture from domestic biowastes, delivery of dried biowastes, short-term storage of biowastes on-site, and preparation of feedstock for processing in the gasifier [4]. As shown in Fig. 1, coal is injected into the co-gasification process without drying. A dual circulating fluidized bed gasifier, suggested by Batel [20], is composed of a combustor, a gasifier, cyclone separators, and a scrubber. The gasification block converts the mixture of dry biowastes and coal into syngas and char. The mass balance from the gasification block operating at 1160 K and 1.58 atm is presented in Table 1. The mass flow rates and gas composition were calculated on the basis of a 2000 dry-ton/day scale. Similar to previous studies [4], the carbon conversion defined in Eq. (1) was fixed and used for mass flow in this study, because there was no available published data for the gasification of domestic biowaste–coal mixtures.

$$Carbon\ conversion\ efficiency = \frac{Moles\ of\ carbon\ in\ products}{Moles\ of\ carbon\ in\ raw\ material} \tag{1}$$

The syngas produced by the gasification process is refined and reformed before being compressed for injection into an ethanol synthesis reactor [19]. Undesired hydrocarbon materials such as CH_4, C_2H_6, C_2H_4, and tars in syngas are reformed to produce additional CO and H_2. Particulates are removed by quenching to increase the yield of ethanol. The tar reforming stage is composed of a bubbling fluidized tar reformer, a quench chamber, an acid gas scrubber, and a compressor. After the acidic gases (CO_2 and H_2S) are removed, the purified syngas should be compressed for ethanol synthesis. Hydrogen and carbon monoxide increase with a decrease in the undesired hydrocarbon materials in syngas. To convert reformed syngas into synthetic ethanol, the pressure of the reformed syngas should be increased to suitable pressure conditions for alcohol synthesis (68 atm). In this study, a modified molybdenum-disulfide (MoS_2) base with alkali metal salts was used because of its relatively high ethanol selectivity and linear alcohol productivity [4,19].

The product is then cooled, allowing the mixed alcohols to condense and separate from the unconverted syngas, which is recycled to the tar reformer. The methanol stream in the mixed alcohol products is used to back-flush the molecular sieve drying column, and is then recycled to the inlet. The ethanol and mixed higher-molecular-weight alcohol streams are cooled and sent to the product storage tanks. Because this process requires a lot of energy to produce synthetic ethanol, it was assumed that all byproducts (except synthetic ethanol) should be used to produce heat and power with the steam turbine/generator. The plant energy balance was managed to generate only the amount of electricity required by the plant [4,19]. The ethanol outputs for each condition are shown in Fig. 2. The final carbon conversion calculated in this study was approximately 33%, and the daily ethanol outputs ranged from 100 to 350 L/dry-ton. According to the IEA report, ethanol production ranges from 120 to 160 L/dry-ton [21] and ethanol production in various technologies ranges from 110 to 300 L/dry-ton according to the International Renewable Energy Agency report [22]. Therefore, the ethanol production calculated in this study was reasonable and could be used for the techno-economic evaluation of commercial plants.

The ultimate and proximate analyses results for the biowastes and coal used in this study are presented in Table 2. Korean waste paper (WP), waste wood (WW), and cow manure (CM) were selected, because the daily production of these biowastes exceeds 2000 ton/day and they are enough to be used in commercial biowaste-to-synthetic ethanol production processes if they are gathered throughout the country. Because of the lack of approximate analysis result based on moisture-free condition, this study used the properties of air-dried cow manure. To overcome the drawbacks of biowaste, bituminous coal imported to Korea was selected and used for the techno-economic evaluation. In Table 2, the proximate and ultimate analysis results of coal indicate that its carbon content is higher than that of other biowastes. In this study, the mixing ratios of coal to biowastes defined in Eq. (2) are 0, 0.25, and 0.5.

$$Mixing\ ratio = \frac{Coal\ weight}{Biomass\ weight + Coal\ weight} \tag{2}$$