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Effects of Biomass Composition and Pentose Fermentation on the Economics of Ethanol Production from Lignocelluloses Using Non-Sulfuric Acid Pretreatment

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Abstract – *For the purpose of climate change mitigation, we previously reported bioethanol production from lignocelluloses using non-sulfuric acid pretreatments such as hydrothermal and mechanochemical treatments. In that study, to estimate the economics of the process by sensitivity analysis, a simulator was constructed and used to determine the effects of plant capacity, feedstock cost, enzyme cost, and enzyme loading on ethanol production costs. In this study, the effects of biomass composition and ethanol fermentation performance were quantitatively considered using the simulator. It was quantitatively determined that the effect of the degree of pentose conversion for broadleaf trees was larger than for conifers. For conifers, the fermentation of pentose should be conducted at a high reaction rate. A reaction rate above approximately 112%/day was required; without that, the production cost increased even if the ethanol yield increased. For broadleaf trees, the production cost decreased when the reaction rate was above approximately 12.5%/day. The development of pentose fermentation with a high reaction rate will be important in order to realize an economical bioethanol production process.*

Keywords – Bioethanol, Non-sulfuric acid pretreatment, economic estimation, lignocellulosic biomass, process simulation.

1. INTRODUCTION

For the mitigation of climate change, the effective utilization of carbon-neutral and renewable biomass is very important. Biomass can be converted into various energies such as heat, power, syngas, liquid fuel and solid fuel by various conversion technologies [1]. In Japan, CO_2 emission from vehicles requires mitigation, as it accounts for approximately 20% of the total CO_2 emission [2], [3]. Therefore, the development of biofuel production for vehicles has been undertaken. Bioethanol, in particular, is attractive because it can be blended with gasoline, and gasoline-powered cars constitute the major part of the total passenger vehicles in Japan.

Bioethanol can be easily produced from first-generation biomass such as sugarcane and corn without troublesome pretreatment. However, competition with food production may become a serious problem. A stable supply of and increasing demand for bioethanol require ethanol production from lignocellulose derived from second-generation biomass. However, to produce ethanol from lignocelluloses, holocellulose must first be saccharized into sugar. Pretreatment is required to achieve saccharification of holocellulose. Additionally, the yeast used in the fermentation of pentose must be prepared by genetic recombination because wild yeast cannot ferment the saccharized pentose. These steps complicate the process and increase production costs. Therefore, addressing the pretreatment of holocellulose and the fermentation of pentose would have a great impact on cost.

Acid treatment was proposed as a pretreatment in the production of sugar from lignocelluloses. However, excessive decomposition of the product sugar becomes problematic and results in decreased ethanol yield. Additionally, because the excessive decomposition production hinders ethanol fermentation, the ethanol yield decreases [4], [5]. Acid recovery and wastewater treatment would also have negative environmental impacts.

For these reasons, ethanol production from lignocelluloses using non-sulfuric acid pretreatment was proposed [5]-[7]. In our research center, ethanol production using hydrothermal and mechanochemical treatments as non-sulfuric acid pretreatments was investigated. In our previous study, a simulator that could estimate economy of ethanol production process was constructed and used to determine the effects of plant capacity, feedstock cost, enzyme cost, and enzyme loading on ethanol production costs by sensitive analysis [8]. However, we did not discuss the effects of biomass composition and the fermentation of pentose to ethanol. In this paper, these subjects were quantitatively considered using the simulator.

2. PROCESS SCHEME AND PRECONDITIONS

2.1 *Ethanol Production Process*

The schematic flow of the process is shown in Figure 1. The process consists of pre-cutting, hydrothermal treatment, mechanochemical treatment, enzymatic saccharification, ethanol fermentation, distillation, and onsite cultivation of the enzyme. The main equipments in the process and details of the simulation have been omitted because these have been described in the previous study [8].

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2.2 *Preconditions*

The process simulation was conducted using the simulator devised in the previous study, which could estimate heat and mass balance, initial cost, and running cost for the production of bioethanol. The preconditions used herein were nearly identical to those in the previous study [8]. Therefore, only the main preconditions are described here.

a. The daily operation time was 24 h. The annual operation period was 300 days.
b. The feedstock was wood chips. The daily amount of feedstock was 100 dry tons/day. The moisture content was 30%.
c. Conifers and broadleaf trees were used; their compositions are listed in Table 1. Conifers contained 50% cellulose, 20% hemicellulose, 29% lignin, and 1% ash. Of the hemicellulose, 20% was $C_5H_8O_4$ and 80% was $C_6H_{10}O_8$. Broadleaf trees contained 50% cellulose, 25% hemicellulose, 24% lignin, and 1% ash. In this case, all of the hemicellulose was $C_5H_8O_4$.
d. Wood chips were precut until 2 mm in size.
e. The hydrothermal treatment was carried out at a temperature of 160°C and a pressure of 2.0 MPa.
f. The enzyme saccharification was carried out at 45°C for 2 days, at which time the saccharification conversion reached 80%.
g. The enzyme loading was 4 FPU/g-wood.
h. The fermentation conversion of hexose reached 90% at 1 day. The fermentation of pentose began after the fermentation of hexose was completed.
i. The maximum size of the tank for saccharification and fermentation was fixed at 5,000 m^3. Another tank was required as a buffer tank.

The number of trays in the distillation column was fixed at 30. The recovery rate of the produced ethanol was 99% and the concentration of the ethanol was 83 mol% (92.5 wt%).

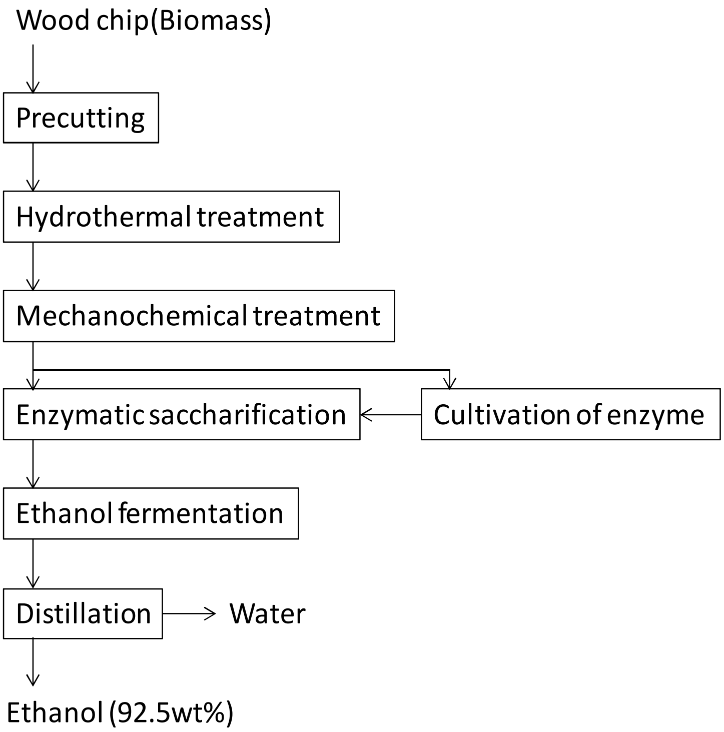

Fig. 1. Schematic of the solar assisted heat pump dryer.

Table 1. Composition of biomass

Component	Conifer	Broadleaf tree
Cellulose	50%	50%
Hemicellulose	20% ($C_5H_8O_4$: 20%)	25% ($C_5H_8O_4$: 100%)
Lignin	29%	24%
Ash	1%	1%

3. RESULTS AND DISCUSSION

3.1 *Effect of Biomass Composition on Ethanol Yield*

Figure 2 shows the ethanol yield versus the degree of pentose conversion by fermentation for conifers and broadleaf trees. For conifers, the ethanol yield was 33.1 kL at a degree of pentose conversion of 25%. In contrast, for broadleaf trees, the yield decreased to 27.8 kL at the same degree of conversion due to the lower amount of $C_6H_{10}O_5$. However, the yield from broadleaf trees exceeded that from conifers at a degree of conversion of approximately 70%. For conifers, the effect of the degree of pentose conversion was small. For broadleaf trees, which contained a high percentage of $C_5H_8O_4$, pentose conversion greatly affected the yield. Therefore, it is considered that improvements in the degree of conversion and the reaction rate would significantly affect the production costs of ethanol from broadleaf trees.

3.2 *Effect of Pentose Fermentation Rate on Process Economy*

The yield of ethanol increased as the fermentation time was extended, as long as fermentation continued, even if the reaction rate was low. However, in this case, to achieve the same throughput with a slow reaction rate, larger tank sizes would be required, which in turn would result in higher tank costs. Therefore, the effect of the fermentation time on the process cost became a trade-off between increases in the yield versus the tank cost. The relationship of this trade-off was investigated.

The production cost for a 1-d fermentation time (when the fermentation of hexose was complete and the fermentation of pentose was beginning) was defined as the base cost, and consisted of fixed unit costs and energy costs. Figures 3a and 3b show break-even curves for pentose fermentation. In these figures, the upper part of the curve indicates an improvement in the economics of the process and lower part of the curve indicates worsening. For conifers, an increase in the fermentation time could not greatly increase the yield due to the low $C_5H_8O_4$ content (Figure 3a). Consequently, the break-even curve sharply increased, and the production cost increased when the rate of pentose fermentation was less than approximately 112%/day. Although the absolute value of the reaction rate changes with different compositions of biomass, the tendency toward the increase in production costs for low reaction rates does not change. That is, if pentose fermentation with a very high reaction rate were impossible, then pentose fermentation should not be performed from the standpoint of process economics.

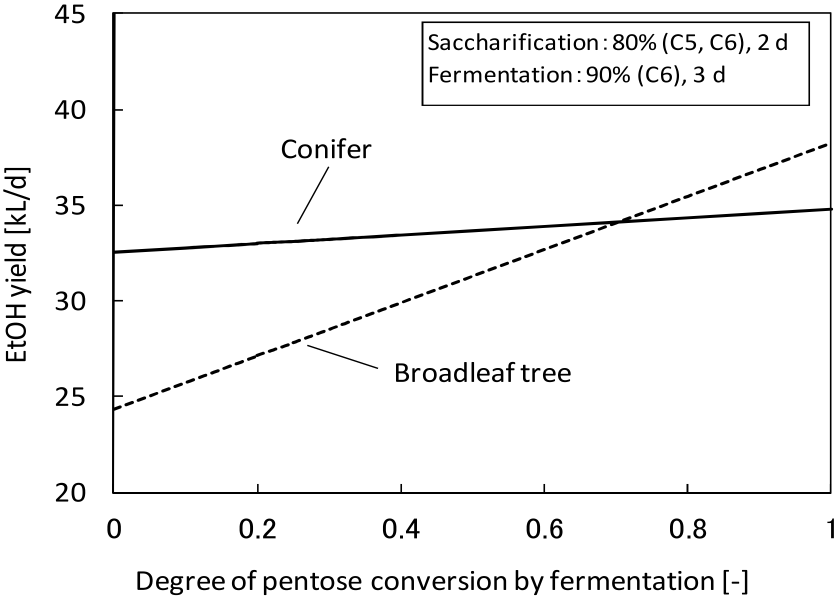

Fig. 2. Ethanol yield for degree of pentose conversion by fermentation in conifer and broadleaf trees.

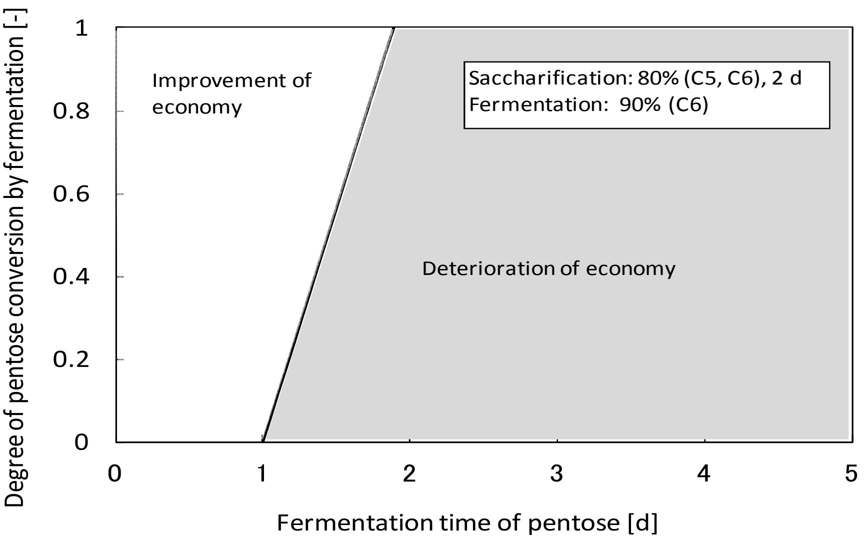

Fig. 3a. Break-even curve for the fermentation of pentose in conifers.

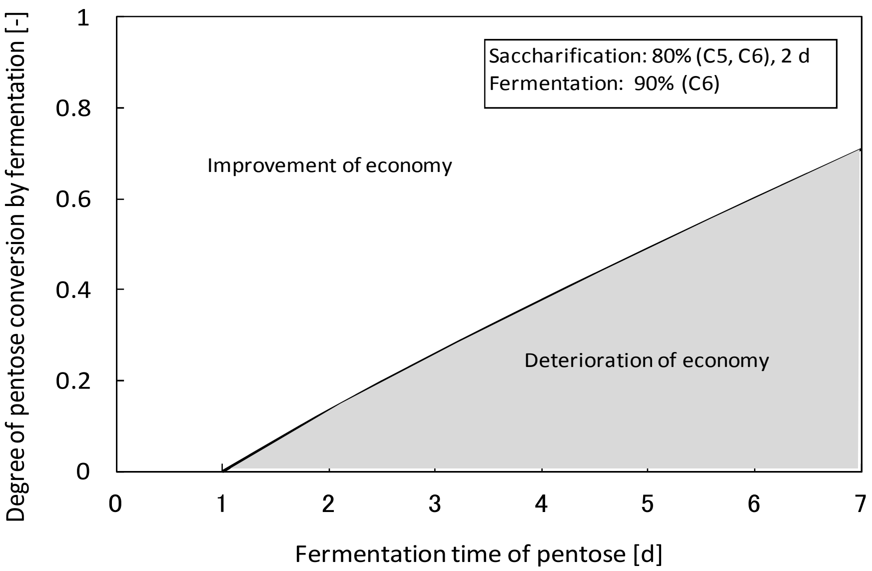

Fig. 3b. Break-even curve for the fermentation of pentose in broadleaf trees.

Due to the higher amount of $C_5H_8O_4$ in broadleaf trees than in conifers, the slope of the break-even curve was more gradual (Figure 3b). It is approximately 12.5%. The value is considered to be reasonable target compared with that in conifers. In both cases, although the fermentation of pentose is significant, a decrease in the production cost might be achievable for broadleaf trees.

From the preceding results, broadleaf trees were selected as a study focus and the effect of the pentose fermentation rate on the process economy was considered. Figure 4 shows the effect of the pentose fermentation rate on the production cost. At a reaction rate of 10.0%/day, the production cost increased with increasing fermentation time because increase of the tank cost greatly affected the production cost compared with increase of ethanol yield. This rate, therefore, is not viable for a reasonable process economy. When the reaction rate was 12.5%/day, the production cost increased until the third day of fermentation. On day four, the production cost returned to the same level observed on the first day, and continued to decline slightly with increasing fermentation time. For the reaction rates of 20.0%/day, 25.0%/day, and 50.0%/day, the production costs decreased with an increase in the fermentation time. Pentose fermentation should be performed at those reaction rates to improve the process economy, even if the fermentation time increases. In the case of a 20.0%/day reaction rate, the rate of production-cost decrease was approximately 2.40 JPY/day. Those at 25.0%/day and 50.0%/day were approximately 3.85 JPY/day and 11.19 JPY/day, respectively.

In Figure 4, the dotted lines indicate the degree of isoconversion. For a conversion degree of 25.0%, the dotted line intersected the *x*-axis at a fermentation time of 3 days. From this, it is found that pentose fermentation is beneficial when the fermentation time to achieve the conversion degree of 25% was within 3 days. In the case of the conversion degree of 50.0%, it was within approximately 5 days.

These results confirm that the pentose fermentation rate affects the economics of the bioethanol production process. In this paper, these effects were quantitatively determined. The development of pentose fermentation with a high reaction rate is required and will contribute to the realization of an economical bioethanol production process.

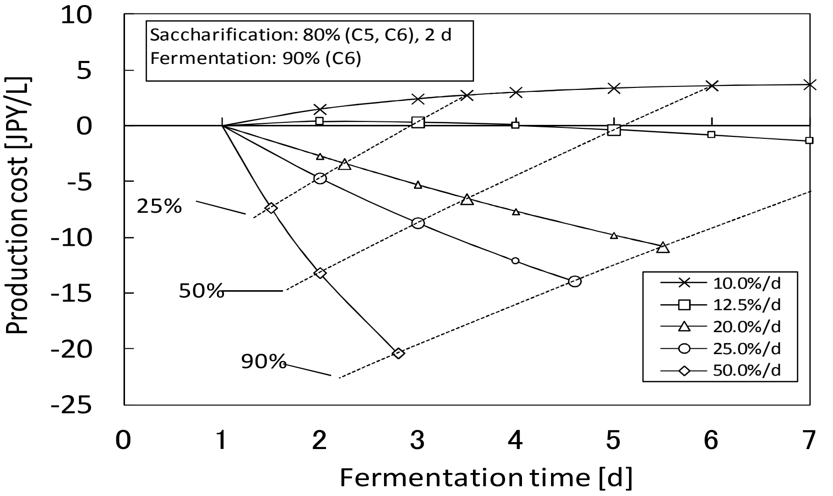

Fig. 4. Effect of pentose fermentation reaction rate on production cost.

4. CONCLUSIONS

For ethanol production from lignocelluloses using a non-sulfuric acid pretreatment that consisted of hydrothermal and mechanochemical treatments, a simulation was carried out using a simulator constructed in a previous study. The effects of the biomass composition and ethanol fermentation performance on the process economics, such as the production costs, were examined using case studies. The following results were obtained.

- For conifers, the effect of the degree of pentose conversion on the ethanol yield was small. In broadleaf trees that contain a high percentage of $C_5H_8O_4$, the conversion of pentose greatly affected the yield.
- For conifers, the fermentation of pentose should be conducted at a high reaction rate. A reaction rate above approximately 112%/day was required. Without this rate, the production cost increased even if the ethanol yield increased.
- For broadleaf trees, the production cost decreased when the reaction rate was above approximately 12.5%/day.

From these results, the pentose fermentation rate was found to affect the economics of bioethanol production, especially for broadleaf trees. In this paper, these effects were quantitatively determined. The development of pentose fermentation with a high reaction rate will be important in order to realize an economical bioethanol production process.

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