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Xylose Fermentation

An Economic Analysis

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ABSTRACT

The economic impact of conversion of xylose to ethanol for a wood-to-ethanol plant was examined, and the maximum potential reduction in the price of ethanol from utilization of xylose is estimated to be $0.42 per gallon from a base case price of $1.65. The sensitivity of the price of ethanol to the yield, ethanol concentration and rate of the xylose fermentation was also examined, and the price of ethanol is most affected by changes in yield and ethanol concentration, with rate of lesser importance. Current performances of various xylose conversion biocatalysts were analyzed, and *C. shehatae* and *P. stipitis* appear to be the best yeasts.

Index Entries: Xylose; economics; lignocellulose; ethanol; biomass.

INTRODUCTION

Wood is an attractive feedstock for ethanol production because it is available at low cost and in large quantities. The primary constituents of wood are cellulose, hemicellulose, and lignin. Cellulose, the most abundant constituent, comprising about 50% of the dry weight, is a source of glucose. The abundance of cellulose has provided incentive for research aimed at improving the hydrolysis of cellulose to glucose and the subsequent fermentation of glucose to ethanol for fuel. However, economical use of wood for liquid fuel production depends on utilization of the hemicellulose and lignin components as well (*1*).

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The hemicellulose component of hardwood represents about 25% of the dry weight of wood, with *D*-xylose as the major sugar constituent. Unfortunately, conventional yeasts cannot ferment xylose to ethanol, and in early processes the xylose was assumed to be sent to costly waste disposal or burned as boiler fuel. However, over the past few years, several yeasts, fungi, and bacteria have been discovered that can ferment xylose (*2–4*). In addition, xylose isomerase can be used to produce xylulose from xylose, and the xylulose can be fermented to ethanol with certain yeasts (*5*). All of these biocatalysts offer a means for producing ethanol from hemicellulose hydrolyzates.

In this paper, we studied the conversion of xylose-to-ethanol and examined the effects on the overall economics of a wood-to-ethanol plant. For the plant design considered, the maximum potential reduction in the price of ethanol resulting from xylose utilization was established. In addition, the current xylose conversion capabilities of several yeasts, fungi, bacteria, and a xylose isomerase–yeast combination were examined and the potential economic effects of using these biocatalysts were determined. Finally, sensitivity of the price of ethanol to changes in key xylose conversion paramaters was assessed in order to develop a rationale for future work aimed at improving xylose conversion biocatalysts. The key parameters examined were yield, ethanol concentration, and productivity.

METHODS

A base case, without xylose fermentation, and alternative cases, with xylose fermentation, were examined, with the overall processes for these cases shown in Fig. 1. All cases were based on a feed of 73, 831 kg h^{-1} (162,729 lbs/h) of dry wood. For the base case and the alternates, wood is partially hydrolyzed via a dilute acid pretreatment step to produce cellulose, lignin, and xylose. A liquid stream, containing xylose, is separated from a cellulose/lignin stream, and the liquid stream is then neutralized. After removing gypsum, the neutralized xylose stream is ready for further processing. For the base case and alternates, the neutralized liquid stream contains 60 g L^{-1} xylose, which seems to be the highest concentration that can reasonably be obtained using dilute acid pretreatment without a xylose concentrating step.

The cellulose/lignin stream from the liquid–solid separation step must be diluted before being fed to the simultaneous saccharification and fermentation (SSF) step. Dilution could be carried out by the addition of water, but this would result in a significant net increase in the amount of water carried through the process. This, in turn, would have severe negative effects on the capital and operating costs associated with downstream operations. Consequently, in the base case, the neutralized xylose stream is combined with the cellulose/lignin stream to dilute the cellulose/lignin stream to 10% cellulose. Using this procedure, no new water is added to the process, and the capital and operating costs of downstream operations

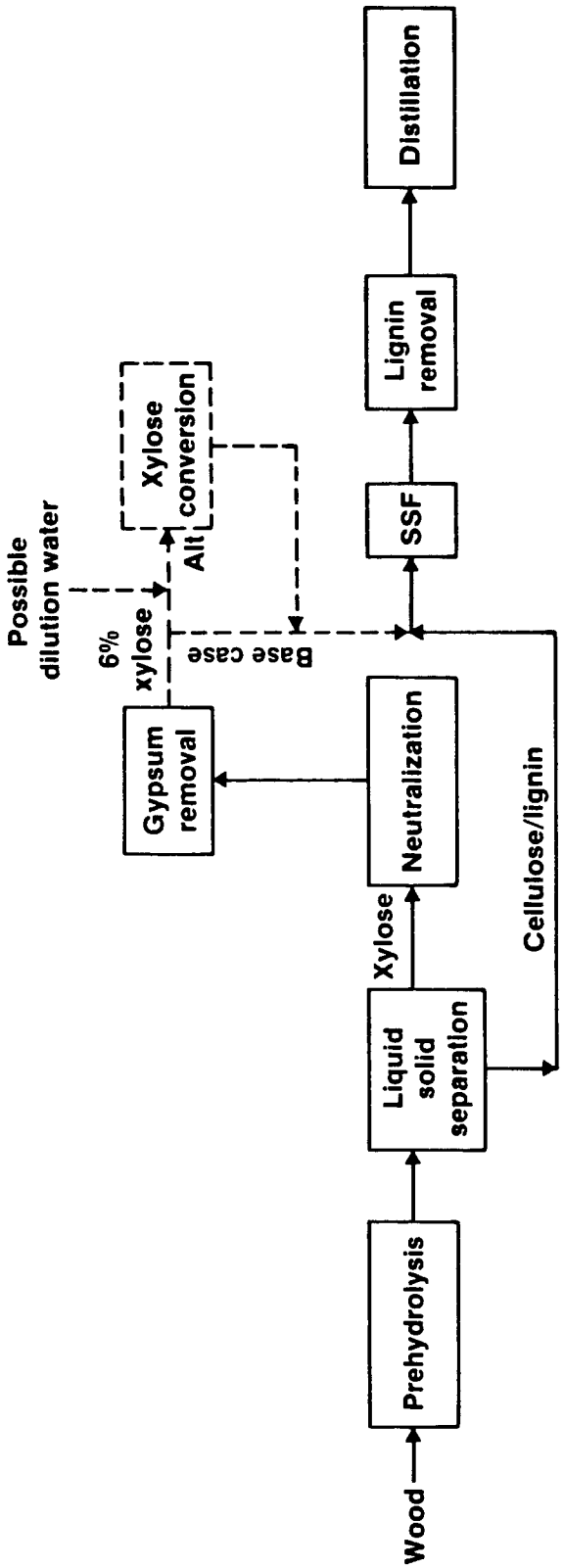

Fig. 1. Wood-to-ethanol processes examined in this study. For the base case, xylose is not converted to ethanol. Rather, the 6% xylose stream from the gypsum removal step is combined with the cellulose/lignin stream, and this combined stream is fed to the simultaneous saccharification and fermentation (SSF) unit. For the alternate cases, xylose is converted to ethanol. For these cases, output from the xylose conversion unit is combined with the cellulose/lignin stream and this combined stream is fed to the SSF unit.

are minimized. The combined stream is then sent to SSF where ethanol is produced from cellulose. Following SSF, lignin is removed, and the remaining solution is sent to distillation, where the ethanol is separated from water and xylose. The lignin is dried and sent to the boiler as fuel. The water/xylose stream is concentrated, and the xylose and other organics are sent to the boiler as fuel.

In the alternative cases where xylose is fermented, the neutralized xylose stream is converted to ethanol via xylose fermentation utilizing yeast, bacteria, fungi, or combined enzyme-yeast system. The resulting ethanol solution is then combined with the cellulose/lignin stream to dilute this stream to 10% cellulose content without adding additional water to the process. Even though the output from the xylose conversion unit is being fed to SSF, the SSF ethanol concentration never exceeds the ethanol tolerance of industrial yeasts. The remainder of the process is as described in the base case, except that there is no xylose to be sent to the boiler.

In the alternate cases, it may be necessary to dilute the feed stream to the xylose conversion unit in order to achieve the maximum potential yield. Whether dilution water is required and the amount used depends on the ethanol tolerance of the xylose conversion biocatalyst. For example, assuming a feed containing 60 gm/L xylose, a potential yield of 100% theoretical, and an ethanol tolerance of 3%, the maximum yield achieved would be 100%. However, with the same feed and potential yield but with an ethanol tolerance of only 1%, the maximum yield would be only 33%. To achieve a maximum yield of 100% for the latter case, it is necessary to dilute the feed with two volumes of water for every one volume of feed so that the feed to the xylose conversion unit contains 20 gm/L xylose.

It is important to note that, although hardwoods do contain the five carbon sugar arabinose, the typical xylose-to-ethanol biocatalyst systems do not readily convert arabinose to ethanol. Accordingly, in the process considered in this study, arabinose was not converted to ethanol. Rather, it was assumed that arabinose ends up in the stillage of the distillation unit. Since the stillage is subsequently concentrated and sent to the boiler as fuel, a credit was taken for the arabinose as boiler fuel.

The design and performance of the prehydrolysis section was as described by Torget et al. (*6*). The liquid-solid separation step, neutralization, and gypsum removal were carried out as described in a process evaluation study by Badger Engineers, Inc. (*7*). The xylose conversion unit and the xylose isomerase unit were designed using batch reactors. A study by Raphael Katzen and Associates (*8*) was utilized in the design of the xylose conversion unit. The overall performance of the xyose conversion unit was a function of the biocatalyst system employed. The design and performance for the SSF process and the remainder of the plant was as described by Wright et al. (*9*). Capital cost estimates were produced with the ICARUS computer aided cost estimating program and have an accuracy of ±10% for a completely defined process (*10*). A SERI economic

Table 1
Annual Operating and Capital Charges (cents/gallon of ethanol produced) for the Base Case Wood-to-Ethanol Process[a]

	Cent/gal
Raw materials	
Wood	70.38
Sulfuric acid	2.16
Lime	1.16
Chemicals	1.72
Utilities	
Water	0.75
Steam	0.00
Labor	6.62
Overhead and maintenance	31.46
Byproducts	
Furfural	0.00
Lignin	0.00
Electricity	−4.62
Annual operating cost	109.63
Capital charges	55.41
	165.04

[a]For this case, cellulose is converted to ethanol but xylose is not converted.

model was used to calculate material and energy balances, operating costs, and ethanol selling price.

The design presented should not be viewed as that from a real operating plant but as our best estimates of current technology. The model accurately reflects the sensitivity of the process to the key parameters associated with the xylose conversion unit, but uncertainty in the basic design means that the absolute ethanol selling price cannot be accurately estimated. Therefore, although great care was exercised in preparing the model and economics, caution must be used when comparing the results of this study to other authors who may have used different cost estimating, economic methodologies, or other technologies.

RESULTS

Maximum Economic Effect Caused by Xylose Conversion

For the base case, in which none of the xylose is converted to ethanol, the price of ethanol is $1.65/gallon. The annual operating costs and annual capital charge for this case are shown in Table 1. The cost of enzyme(s) is not included in the chemicals cost. Rather, it is contained in the capital and operating costs of the enzyme production unit(s).

The economic effect of xylose conversion depends on three key xylose conversion parameters: yield, ethanol concentration, and productivity. The highest yield obtainable is 100% theoretical or 0.51 gm of ethanol per gm of xylose. In addition, the highest ethanol concentration attainable in the xylose conversion unit from a 6% xylose feed is 3% ethanol. Furthermore, for a given yield, the xylose conversion capital cost per annual gallon of ethanol produced from xylose is a function of productivity, and for this study, the capital cost per annual gallon for high productivity values was found to have a minimum value of $0.25/annual gallon. Accordingly, the maximum potential reduction in the price of ethanol was calculated using yield at 100% theoretical, ethanol concentration at 3%, and capital cost per annual gallon at $0.25. Using these values, the price of ethanol with xylose conversion is $1.23/gallon, which represents a $0.42/gallon or 25% reduction in the price of ethanol from the base case.

Economic Effect of Using Current Xylose Conversion Biocatalysts

Values for the three key parameters that are associated with various current xylose conversion biocatalysts were obtained from the literature (yeast (*11–35*); fungi (*32,36–40*); bacteria (*4,41–44*); xylose isomerase–yeast (*45–47*). All values were for batch fermentation. If the fermentation time, or volumetric productivity, was not given, the fermentation time was assumed to be 4 d. (As will be discussed in the next section, xylose fermentation time has a minimal effect on the price of ethanol and the value assumed is not critical.) The ethanol prices calculated for each set of performance parameters associated with a given type of biocatalyst were averaged to obtain a representative ethanol price for the biocatalyst type. In addition, a representative ethanol price was calculated for certain biocatalyst types using only performance data where the initial xylose concentration was close to 60 gm/L, which is the undiluted xylose concentration in the feed to the xylose conversion unit in this study. These latter prices did not differ significantly from those calculated from all available performance data.

A considerable amount of performance data exists for three types of xylose fermenting yeasts, i.e., *P. tannophilus, C. shehatae,* and *P. stipitis.* Representative ethanol prices associated with the use of these yeasts are shown in Fig. 2. For *C. shehatae,* the representative price is $1.36 per gallon, for *P. stipitis* the price is $1.37 per gallon, and for *P. tannophilus* the price is $1.48. Thus, *C. shehatae* and *P. stipitis* perform better than *P tannophilus.* Moreover, the ethanol price for *C. shehatae* and *P. stipitis* represents a reduction in the price of ethanol from the base case of $0.29–$0.30 per gallon, which is 70% of the maximum potential reduction of $0.42 per gallon. The average performance parameters for *C. shehatae* were yield at 70%, ethanol concentration at 2.7%, and a fermentation time of 6.7 d. Performance data for other yeasts is scanty, but none of those yeasts performed better than the average performance of *C. shehatae* or *P. stipitis.*

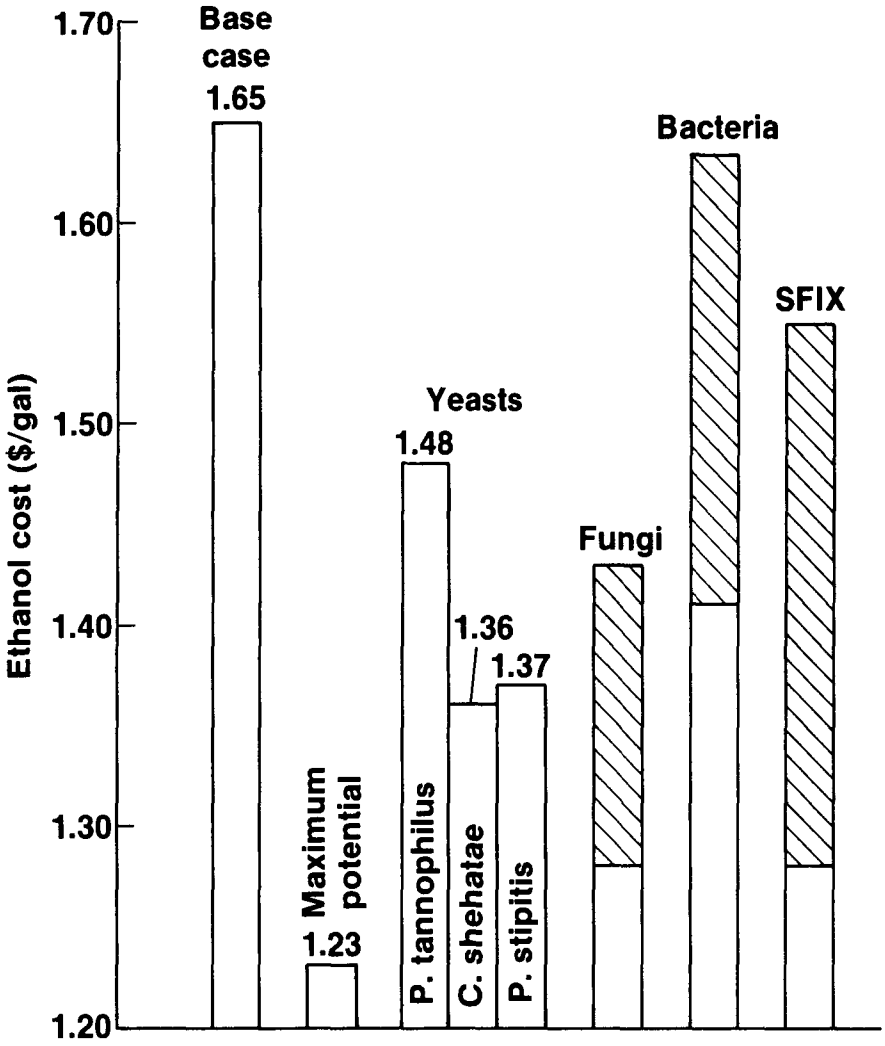

Fig. 2. Price of ethanol for cases examined in this study. For all cases, cellulose is converted into ethanol. For the base case, no xylose is converted to ethanol. For the maximum potential case, xylose is converted to ethanol using the following performance parameters: 100% yield, no ethanol inhibition, and high productivity. For the remaining cases, xylose was converted to ethanol with published performance parameters for each type of biocatalyst. The prices of ethanol shown for each of the yeasts are the average prices calculated for these biocatalysts. For fungi, bacteria, and the xylose isomerase-yeast combination (SFIX), the range of calculated ethanol prices is shown.

Data for fungi, bacteria, and the xylose isomerase-yeast combination is limited and, therefore, it is difficult to assess their economic performance with the same degree of confidence as can be done with yeasts. The range of ethanol prices calculated for these types of biocatalysts is shown in Fig. 2. In general, the data for these biocatalysts does not suggest that they are currently capable of either attaining or surpassing the performance of the best yeasts.

Sensitivity of Ethanol Price to Changes in Key Xylose Conversion Parameters

The sensitivity of the price of ethanol to changes in the three key xylose conversion performance parameters was examined in order to develop a rationale for future work aimed at improving xylose conversion biocatalysts. The percent theoretical yield was varied between 20–100%. For a given yield, the maximum allowable ethanol concentration was varied between the maximum possible for the yield and lower values by varying the amount of dilution water added to the 6% xylose feed stream. The range of maximum allowable ethanol concentration was 1–3%, with 3% being the highest that can be achieved with the 6% xylose feed stream.

The capital cost per annual gallon is a function of fermentation time, which, for a given yield and equipment configuration, is a function of volumetric productivity. The capital cost per annual gallon for a conversion plant that includes a xylose isomerase unit and that for a plant without the enzyme unit varies between about \$0.25–\$1.00 for reasonable fermentation times. Accordingly, in this study, the xylose conversion capital cost per annual gallon of ethanol from xylose was varied between \$0.25–\$1.00.

It was found that changes in the capital cost per annual gallon have relatively minimal impact on the price of ethanol. A fourfold improvement in capital cost per annual gallon from \$1.00 to \$0.25 reduces the price of ethanol \$0.05 per gallon. On the other hand, changes in yield and ethanol concentration have a major impact on the price of ethanol. The effects of changes in the yield and ethanol concentration on the price of ethanol (with capital cost per annual gallon set at \$0.25) are shown in Fig. 3. This figure shows that a fourfold improvement in yield from 20% to 80% at 3% ethanol concentration reduces the price of ethanol by \$0.20 per gallon and a threefold improvement in ethanol concentration from 1% to 3% at 100% yield reduces the price of ethanol \$0.35 per gallon.

DISCUSSION

This study has shown that for the wood-to-ethanol plant described, conversion of xylose to ethanol in a batch system results in a maximum reduction in the price of ethanol of \$0.42 from a base case cost of \$1.65 per gallon, which is a 25% reduction. The current performance of various xylose conversion biocatalysts were also analyzed. Of the xylose fermenting yeasts, *P. stipitis* and *C. shehatae* appear to be best, since they are currently capable of achieving 70% of the maximum possible ethanol price reduction. To equal this performance, other types of biocatalysts must have a yield of about 70% and be capable of producing an ethanol concentration of about 2.7%. Data for fungi, bacteria, and the xylose isomerase–yeast combination is limited and, therefore, it is difficult to assess their

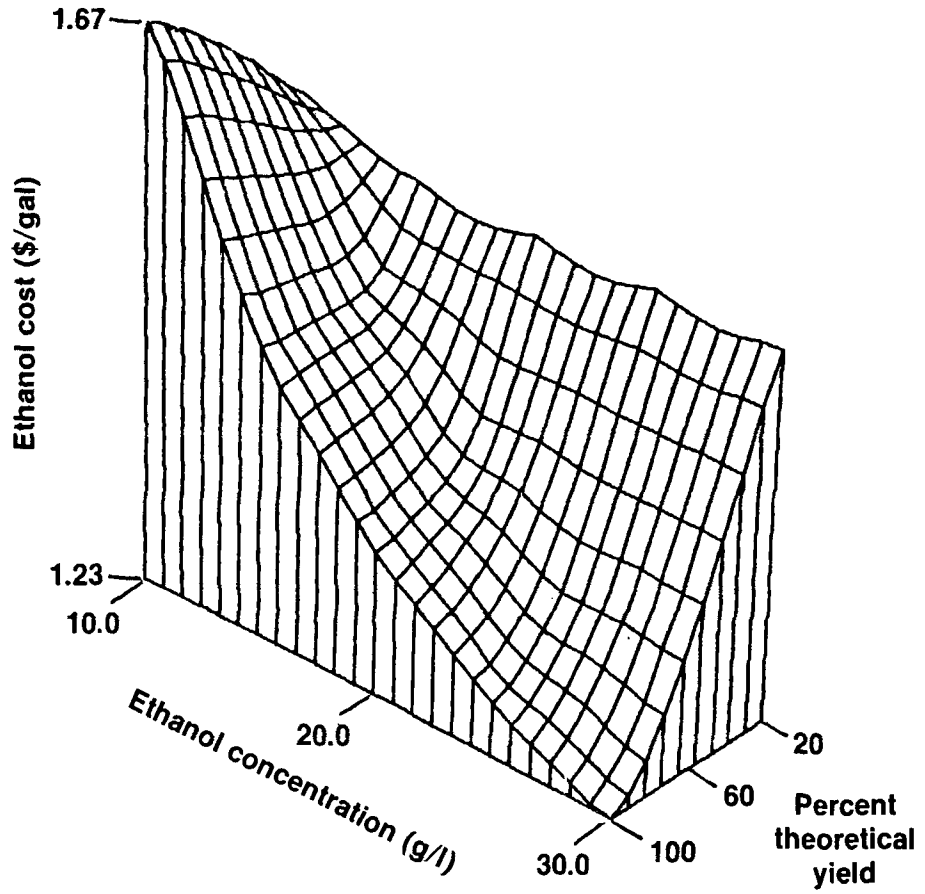

Fig. 3. Ethanol price as a function of key xylose conversion parameters. The xylose conversion capital cost is set at $0.25 per annual gallon of ethanol from xylose.

economic performance with the same degree of confidence as can be done with yeasts. However, at present they do not appear to be capable of attaining or surpassing the performance of the best yeasts.

The three key parameters associated with xylose conversion that impact the economics of a wood to ethanol plant are yield, ethanol concentration, and productivity. This study has shown that yield and ethanol concentration are the most important, whereas productivity has a relatively minor impact. Yield has importance because at a given wood feed rate, each increase in yield translates directly into an increase in revenue. Allowable ethanol concentration has importance because if the allowable concentration is not high enough, it is necessary to add dilution water to the feed stream to the xylose conversion unit in order to achieve the maximum potential yield. Unfortunately, whereas the addition of water permits the maximum potential yield to be achieved, addition of water increases the size of SSF, distillation, the concentration unit, and the waste

treatment unit. Moreover, the load on the utility systems also increases. Productivity is of minor importance because it only impacts the size of the xylose conversion unit, which is a relatively small percentage of the total capital cost of the plant. Given the relative effects of the three parameters on the price of ethanol, it seems clear that future work aimed at improving xylose conversion biocatalysts should focus on improving yield and ethanol tolerance with less emphasis on improving productivity.

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