

AN UPDATE ON PROGRESS IN THE PRODUCTION OF ETHANOL FROM BAGASSE

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Abstract

There has been continued progress in the development of a fermentation for producing ethanol from xylose derived from bagasse. Cost estimates made so far with data from a process-development-unit have generated optimism for the future of this xylose-based process. Progress has also been made with techniques for pretreating bagasse and for subsequent enzymic conversion of its cellulose to fermentable glucose. Starting with steam-exploded bagasse from a furfural factory, and using a system of simultaneous hydrolysis and fermentation, it has been possible to convert 90% of the cellulose to alcohol at a concentration of 5%. This was achieved with an enzyme loading of only 5 units per gram of solids. A substantial improvement in the pilot scale production of the enzyme was made at the CSIR in 1984 but the enzyme is still a high cost component.

Introduction

In 1979 the Council for Scientific and Industrial Research (CSIR) initiated a national research programme with the objective of developing technology for the conversion of lignocellulose wastes to fermentable sugars. Bagasse was soon selected as the most promising substrate, and the Sugar Milling Research Institute (SMRI) became involved in the project. The process chosen for development involved the new technology of using cellulase enzymes to digest the bagasse and thereby to produce glucose as a fermentable end-product. It was necessary to develop techniques for enzyme production, bagasse pretreatment, bagasse hydrolysis and various fermentations. Thirteen different research groups have been involved and the project has now progressed to a point intermediate between pure laboratory studies and

pilot plant. A process-development-unit (PDU) has been commissioned at the SMRI so that the various process stages can be integrated and the technical requirements determined for use in preliminary costing studies. The results generated with the PDU are the main subject of this paper.

Process Alternatives

Various end products are possible (Figure 1) but the work so far has been aimed at producing ethanol. Normally, in producing ethanol, the fermentable substrate constitutes 55 to 60% of the final ethanol cost. A bagasse-based process however starts with the advantage of a relatively cheap raw material. The challenge is to convert it to an acceptably cheap fermentable material.

It can be seen from Figure 1 that the process of making glucose from the cellulose component of bagasse is complicated compared with the production of xylose from the hemicellulose component. Initially the production of xylose was not attractive because yeasts were not available for fermentation of the xylose to ethanol. Since 1981 however there has been steady development of xylose-based fermentations.

In 1981 the yeast *Pachysolen tannophilus* attracted most attention but it was superseded first by a strain of *Candida shehatae* isolated in South Africa (du Preez and van der Walt¹) and then by *Pichia stipitis*, which is presently the most promising yeast (du Preez and Prior²). When growing on xylose this organism has an ethanol yield coefficient similar to that of *Saccharomyces cerevisiae* growing on glucose but it ferments slowly and it cannot tolerate ethanol concentrations above about 3%. Thus fermentation of xylose to ethanol is still much less efficient than the fermentation of glucose but the development of a xylose fermentation is significant for the sugar industry because xylose can be produced reasonably cheaply from bagasse. Our research therefore now has two major directions:

- (a) xylose production by acid prehydrolysis of bagasse and
- (b) glucose production by enzyme hydrolysis of the residue remaining after extracting the xylose.

The major problem in producing glucose from bagasse via the enzyme route is the high cost of the enzyme. Again considerable international and local progress has been made in reducing this cost. The enzyme yields achieved at the CSIR since 1984 are amongst the best in the world (Figure 2).

If the enzyme process for glucose production never proves economical then an alternative is to prepare the bagasse for enzymic digestion and to feed it to a ruminant animal. The appropriate enzymes are available in the rumen and would cause extensive digestion of the pretreated bagasse. The pretreated bagasse could therefore be a valuable source of carbohydrate for ruminants.

If animal feeding is not viable then the residue, after acid prehydrolysis, could still be used as a boiler fuel. The dry mass of the residue would be about 66% of that of the original bagasse and the sulphur residue from sulphuric acid would be less than that in most coals.

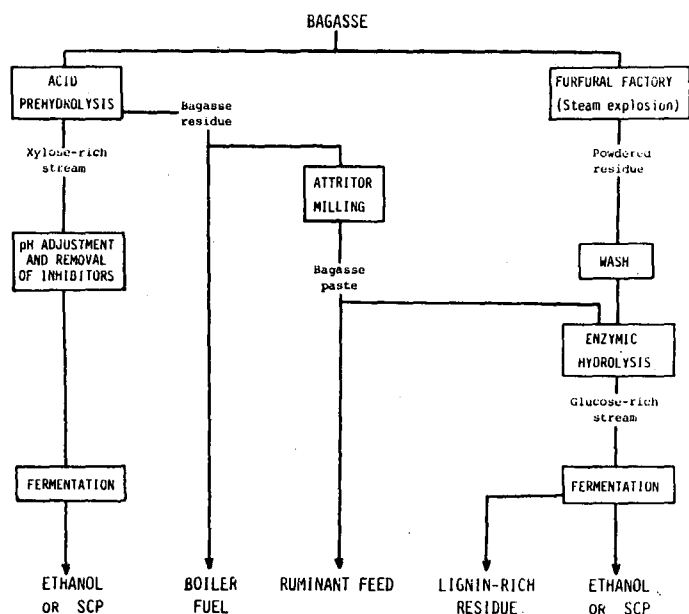


FIGURE 1 Process alternatives

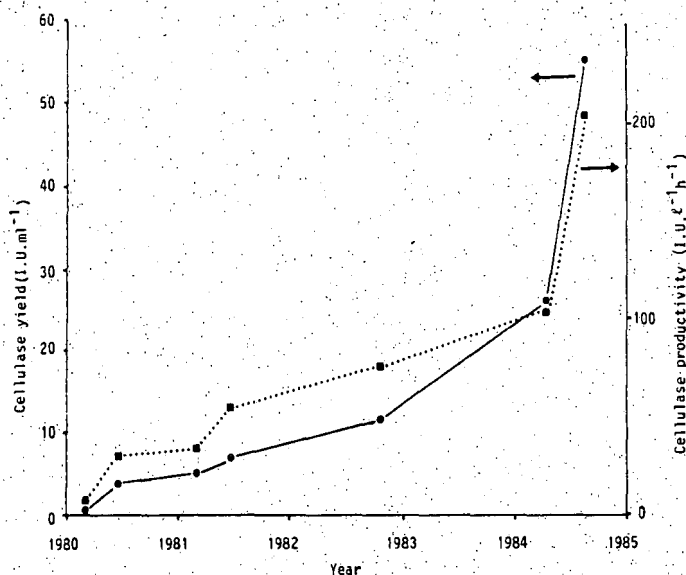


FIGURE 2 Historical trends in cellulase concentration and productivity in the CSIR pilot plant (Lessing and Watson³).

Single cell protein (SCP) can readily be made from xylose and is a potential alternative to ethanol.

The Xylose Route

Prehydrolysis

Approximately 33% of bagasse is hemicellulose. This component is relatively easily hydrolysed by dilute acid and it yields xylose as the main hydrolysis product. Data for the kinetics of this so-called prehydrolysis reaction have been generated for South African bagasse (Trickett²). These have indicated that the accumulation of toxic products (furfural and heavy metals) increases with increasing temperature. For the PDU it was therefore decided to operate at temperatures below 100°C, giving the added advantages of a non-pressurised reactor and less expensive materials of construction. Disadvantages include the relatively long reaction time and/or increased acid consumption.

The reactor simply percolates 5 kg (dry mass) batches of bagasse with 1 to 2% H₂SO₄ at 96 to 98°C for 4 to 8 h. The prehydrolysed bagasse is then dewatered to 65% between rubberised rollers and the liquid stream is recycled through fresh batches of bagasse to give a final xylose concentration of up to 8%.

Data generated with this reactor have been used to develop a computer model for predicting the performance of a full-scale continuous reactor under various conditions. From the model the acid consumption based on bagasse has been calculated to be 2,6%, 4,4% and 8,1% for 1%, 2% and 4% sulphuric acid solutions respectively.

The xylose generated in the reactor has been used for fermentation studies at the University of the Orange Free State. These studies have shown that acetic acid in the prehydrolysate is the major inhibitor of xylose fermentation. Techniques for removing the inhibitors are known and their use on a large scale is being investigated.

Costs

A firm of consultants was commissioned to estimate the cost of ethanol production from hemicellulose under South African conditions. Bagasse was not considered as a waste product but was costed at R22/t (dry) and no credit was passed for the residual bagasse (66% of original) after prehydrolysis.

The costing was based on the assumptions that the entire bagasse production (30 dry t/h) from a medium sized sugar factory would be prehydrolysed and the ethanol production facility would operate only during the crushing season (38 weeks each year). It would produce only 18 × 10⁶ litre/year. A selling price for ethanol of 70c/litre was assumed. It was also assumed that an ethanol concentration of 6% could be achieved in the fermenter but to date only 2,6% has been achieved.

The anticipated discounted ten-year cash flow for the project is shown in Figure 3, and some of the major capital cost items are shown in Table 1. The internal rate of return after tax is given as 18,5%. A sensitivity analysis shows that the project would benefit considerably from a high rate of inflation; a rate of 10% has been assumed. Considerable economy would be achieved if molasses could be made available for fermentation during the off-crop but this option has not yet been costed in detail.

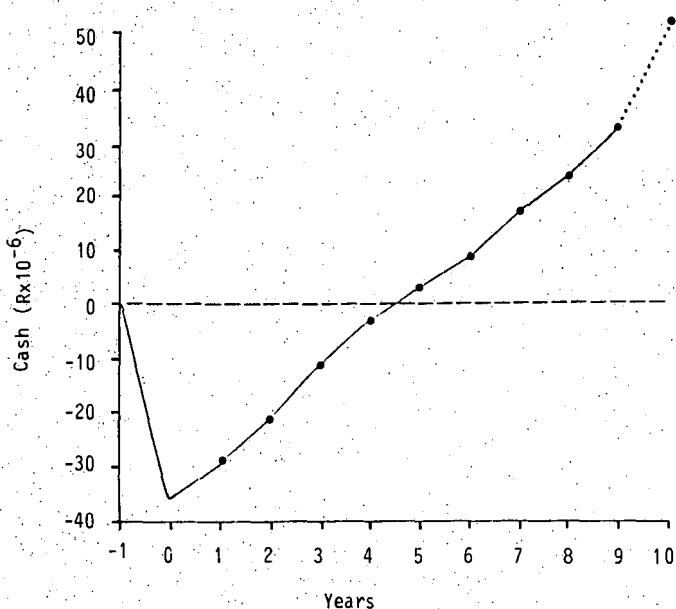


FIGURE 3 Anticipated cash flow for a factory making ethanol from xylose derived from bagasse

Table 1

Major capital cost items for the manufacture of ethanol from xylose derived from bagasse

Item	% of total cost
Prehydrolysis reactor	4
Vacuum belt filters	8
Fermentation unit	3
Distillation unit	13
Utilities (boilers etc.)	10
Effluent disposal	11

Attritor Milling and Steam Explosion

Bagasse must be pretreated in some way to make it reasonably susceptible to enzymic hydrolysis. Early in the project it was discovered that acid prehydrolysis caused bagasse to become brittle and susceptible to fine grinding. The grinding proved to be an effective pretreatment and so some effort has been concentrated on optimising a grinding procedure, particularly wet milling in a stirred bead mill (attritor mill).

After trials with small batch mills, a larger continuously fed machine was built for the PDU. The operation and performance of this machine are summarised in Table 2.

Table 2

Comparison of attritor mill performance when operated with different slurry concentrations

Slurry conc. in mill (%)	Feed rate (dry kg/h)	Mill power at 200 rpm (kW)	Specific energy input (kWh/dry kg)
15	25*	4,8-5,2	0,20
8-9	42*	4,4	0,10
8-9	32	3,4	0,11
8-9	18	2,8	0,15
6	42	2,7	0,06

* Maximum possible feed rates.

As a result of experience gained with the various mills a design concept for a mill with a throughput of 20 dry t/h has been developed. The cost of milling with such a machine, excluding overheads and labour but including electricity, depreciation and capital, was estimated to be R13/dry t. This is equivalent to 5,8c/litre of ethanol produced from the milled bagasse.

During the manufacture of furfural, bagasse is explosively decompressed from a steam pressurised reactor. The steam explosion shatters the bagasse and is a good alternative to attritor milling. The amount of powdered furfural factory residue (FFR) produced at Sezela is sufficient for the production of about 40×10^6 litres of ethanol, which is enough to have warranted PDU studies on the material. Compared to attritor milled bagasse the material has the advantages of greater susceptibility to enzymic digestion and easier handling at high solids concentrations. The disadvantages are its limited availability and the need to wash it to remove toxins generated during heating.

Enzymic hydrolysis and fermentation of pretreated bagasse

The economic viability of producing fermentable sugars from cellulose by enzymic conversions is still questionable but considerable improvements in the processs have been made recently. Research priorities in this area are determined by:

- (a) the need to reduce the cost and quantity of enzymes used in the process,
- (b) the need to produce as high an ethanol concentration as possible so as to minimise distillation costs, and
- (c) the need to reduce the long reaction times (48-64 hours) required for the conversion.

Sequential Enzymic Hydrolysis and Fermentation

The cellulose portion of the bagasse can be converted most simply to ethanol by a sequential batch procedure involving enzymic hydrolysis at 50°C followed by fermentation of the glucose at 30°C. The cellulase enzyme used by us (supplied by the National Food Research Institute, CSIR) is produced by the fungus *Trichoderma reesei*-C30 and is supplemented with a B-glucosidase enzyme (Novo Industries, SP 188). The fermentation is performed by the yeast *Saccharomyces cerevisiae*, CSIR Y718.

The rate of hydrolysis is dependent on the enzyme concentration used whilst the final concentration of glucose produced depends on the initial bagasse solids concentration fed to the reactor. The upper limit to the feed solids con-

centration is set by the viscosity of the material. It is not practical to use the milled bagasse at an initial solids concentration greater than 15%, or steam-exploded bagasse at a concentration greater than 20% (in each case these materials resemble thick pastes). Since the pretreated solids contain approximately 53% cellulose it is theoretically possible to obtain ethanol concentrations of 3,75% from milled bagasse and 5% from steam exploded bagasse.

Typical batch hydrolysis curves (Figure 4) show that the rate of glucose production is adversely affected by high concentrations of solids and by the accumulation of glucose. It is well established that the enzyme is inhibited by the glucose it produces.

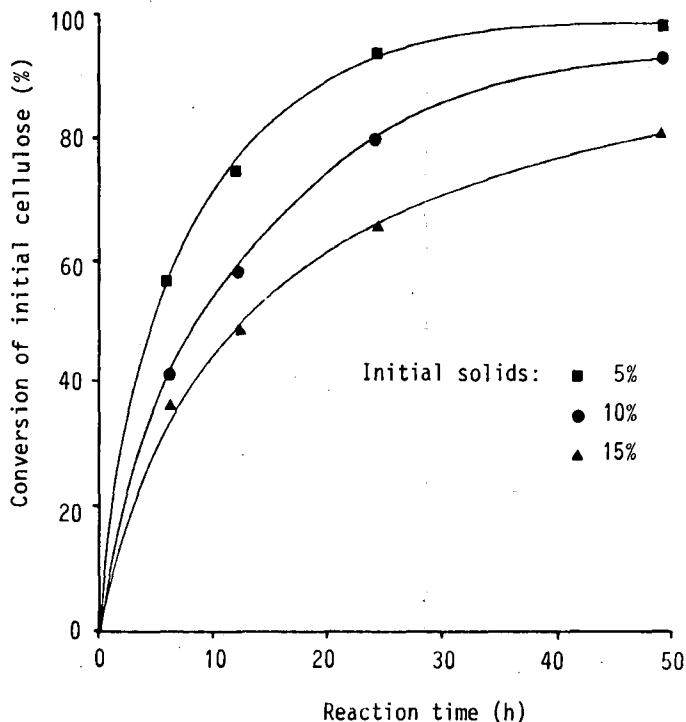


FIGURE 4 Typical batch hydrolysis curves for the enzymic conversion of furfural factory residue

These effects make sequential hydrolysis and fermentation unsuitable for the production of ethanol from feed solids concentrations above 10%. Batch reaction data have proved useful however in developing relationships between enzyme concentration, solids concentration, enzyme efficiency, reaction time and extent of cellulose conversion.

It has been established that enzyme productivity decreases markedly with increasing enzyme load, indicating the need to hydrolyse at low enzyme concentrations. Efficiencies exceeding 200 mg glucose per filter-paper-unit (fpu) of enzyme have been achieved by using an enzyme concentration of 1 fpu/g solids. However at this loading less than 50% of the cellulose was converted to glucose after 48 hours. An enzyme load of 5 fpu/g solids has been found to be close to the economic optimum. At this loading about 75% conversion of initial cellulose can be achieved from 15% steam exploded bagasse in 40 hours, giving an enzyme efficiency of 80 mg glucose/fpu. Performance on the milled bagasse is poorer than this.

Simultaneous Enzymic Hydrolysis and Fermentation

The concept of simultaneous enzymic hydrolysis and fermentation of lignocellulosic material (in a single vessel) was first introduced in 1977 by Takagi *et al.*⁴ Its advantage, in

comparison with sequential reaction, lies in the ability of the yeast to remove glucose as it is formed, thus reducing inhibition of the enzyme by accumulated glucose. This advantage is offset however by the fact that the reaction temperature is limited to the maximum temperature at which the yeast can ferment, which is well below the 50°C optimum for enzymic hydrolysis.

Our results with this scheme have shown that it is best to allow the material to hydrolyse for a period at 50°C before decreasing the temperature and inoculating with yeast. A typical reaction profile is given in Figure 5. Under these conditions, cellulose conversions exceeding 90% have been achieved from 20% steam exploded bagasse solids at an enzyme load of 5 fpu/g solids, giving an ethanol concentration of 5%.

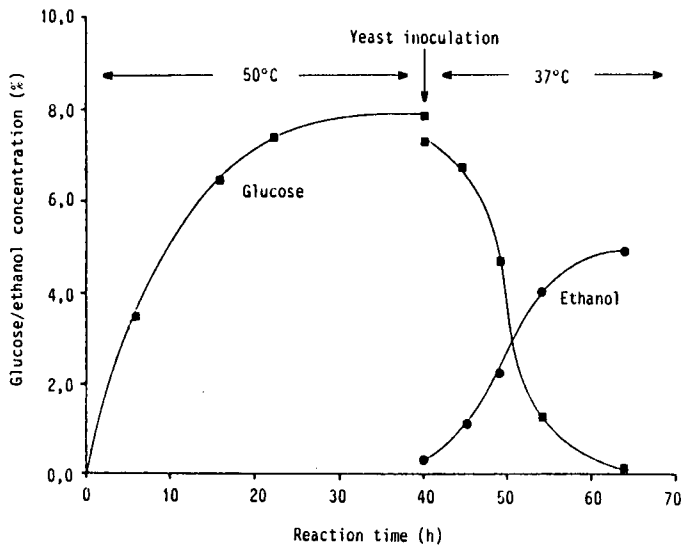


FIGURE 5 The dynamics of simultaneous hydrolysis and fermentation of 20% furfural factory residue solids.

Coupled Enzymic Hydrolysis and Fermentation

The successful production of a 5% ethanol stream is promising for the achievement of acceptably low distillation costs, but the problem of long reaction time still exists.

This has led to the consideration of a third reaction scheme (Figure 6) which involves simultaneous reaction in two separate vessels; allowing each reaction to run at its optimum temperature. Solid material is retained in the hydrolysis vessel, the yeast is immobilised in the fermenter and a liquid stream is cycled between the two vessels so that as glucose is produced by enzymic conversion it is fermented to ethanol.

Simulation of the hydrolysis reactor in this configuration has shown that a 44% decrease in reaction time should be possible. Future research will concentrate on developing this system.

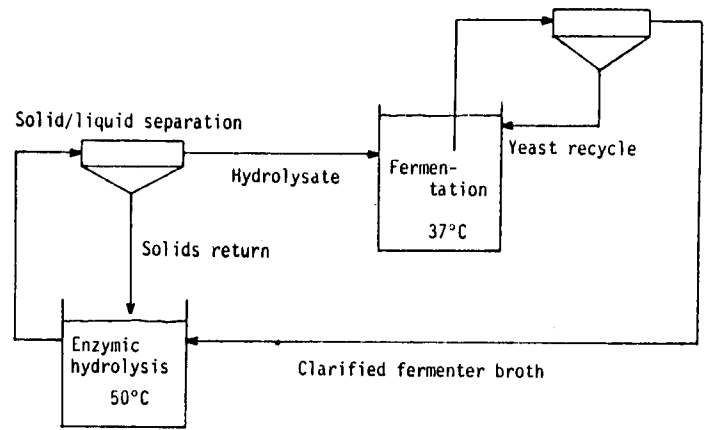


FIGURE 6 A simplified flowchart of the coupled hydrolysis and fermentation system.

Conclusions

In recent years considerable progress has been made in developing the technology for conversion of lignocellulose to ethanol. In the case of bagasse, the original concept of converting the cellulose component to fermentable glucose has been partially overshadowed by optimism for a process involving dilute acid prehydrolysis of the hemicellulose component and fermentation of the resulting xylose by newly selected yeasts. This route is particularly attractive to the cane sugar industry because of the high hemicellulose content of bagasse. A recent detailed economic analysis of the process gives cause for optimism. Novel biologically-based processes are usually amenable to considerable improvement and this applies to the xylose and the glucose routes from bagasse to ethanol. Expertise in the various process stages has accumulated locally as a result of the CSIR programme. This expertise should be useful in the continuing efforts to increase the value of bagasse.

Acknowledgements

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