

PERSPECTIVES IN THE PRODUCTION OF ETHANOL FROM BAGASSE

By B. S. PURCHASE

Sugar Milling Research Institute

Abstract

Given economic incentive the South African sugar industry could probably produce a bagasse surplus of about one million tons (dry). Research on the conversion of this material to ethanol, via sugar, was initiated in South Africa in 1979 and developments to-date suggest that the cheapest sugar would be xylose produced by dilute acid hydrolysis of the bagasse. Progress is being made in developing a fermentation process for converting xylose to ethanol. Success with this would have particular relevance to the sugar industry because of its unique potential for producing low cost xylose. Furthermore, the bagasse residue after xylose removal is amenable to attritor milling which prepares the cellulose for enzymic hydrolysis. Glucose yields equivalent to at least 75% of the cellulose can be expected and the yields can be increased by the use of non-enzymic additives. Enzyme production and hydrolysis are the highest cost areas but are also areas with maximum scope for improvement.

Introduction

If ethanol is made from sugarcane juice it is estimated (Ravnö¹ and Lima²) that 50–65% of the production cost is due to the cost of the juice. Thus, whereas new technologies for fermentation and distillation may reduce ethanol production costs, the reductions are relatively small in comparison with the cost of the raw material, and unless cheaper raw materials become available there is no economic incentive in South Africa for fuel ethanol production by fermentation. In attempts to reduce the cost of the raw material, alternative fermentable substrates are being sought.

Agricultural residues are a potential source of fermentable substrate. They are generally inexpensive but require collecting and modification before they are suitable for fermentation. With most agricultural residues (e.g. maize stover and forest trimmings) the cost of collection is prohibitive. Bagasse is unique in that it collects at central points at which there are already infrastructures for manufacturing activity. This suggests that sugarcane industries will have an advantage in applying technology which upgrades the value of lignocellulosic wastes. The South African sugar industry has a further advantage in that its cane has a higher fibre content (15–16%) than in most countries (11–12%), and it operates only 17 factories so the bagasse collects at relatively few points. Furthermore, approximately 48% of the total bagasse is produced at 8 factories concentrated within 100 km of either Stanger or Tongaat, and this concentration could be advantageous.

At present there are only limited markets for surplus bagasse in South Africa; thus giving added incentive for investigating technologies for the conversion of bagasse to fermentable sugars.

Bagasse Surpluses

If there was a market for bagasse then it is not easy to specify how much surplus could be generated because this would depend on the type of equipment installed in factories (e.g. high-pressure boilers). Large surpluses could be generated but there is cost involved so the amount of surplus would depend on the market value of bagasse.

Some indication of potential surpluses is available from the Taiwan Sugar Corporation (Sang and Yen³) where financial incentive caused them to steadily convert from zero surplus to a surplus equivalent to almost 10% of the initial cane mass (Fig. 1). In the modernised Taiwanese factories the bagasse consumption is only 16 t (wet) per 100 t cane processed. In South Africa 100 t of cane produces 32–34 t of wet bagasse, so there is potential for generating a significant surplus. Direct comparison with Taiwan should not be made, however, because the Taiwanese data do not include the bagasse required for sugar refining and because comparatively more imbibition water is used in South Africa. If there was financial incentive then one might assume that most South African factories could eventually save one third of their bagasse. This would be approximately 2 000 000 t of wet bagasse (1 000 000 t dry).

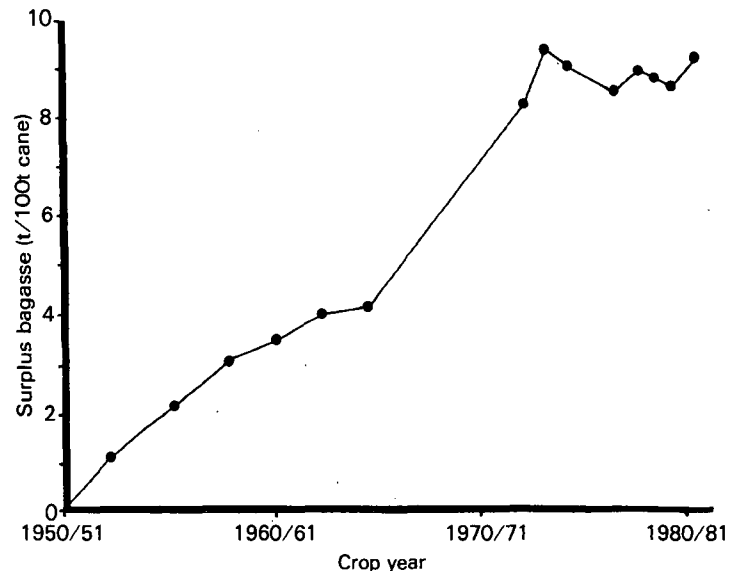


FIGURE 1 Surplus bagasse generated in Taiwan in response to financial incentive (Sang & Yen³).

Bagasse Hydrolysis

The major components of bagasse are cellulose (40%), hemicellulose (33%) and lignin (22%). The cellulose consists of glucose molecules and so it can yield fermentable glucose if it is hydrolysed (split). Hydrolysis is not easy because the cellulose has a stable crystalline structure and is protected by lignin.

Acid hydrolysis of cellulose was applied on a large scale during the World Wars but it is not presently economical. When dilute acid is used, a high temperature is required and this causes some of the glucose to decompose thereby limiting the yield of glucose to approximately 50% of the initial mass of cellulose. Substances which inhibit subsequent fermentation may also be produced. Higher yields can be achieved with concentrated acid but the cost of the acid is prohibitive.

During World War II the troublesome decomposition of cellulosic textiles was investigated by American scientists. The investigation eventually led to the realisation that enzymic hydrolysis of cellulose might be a viable alternative to acid hydrolysis (Augustine⁴). This possibility has received considerable research attention since 1975 and in South Africa the Council

for Scientific and Industrial Research (CSIR) initiated a national coordinated research effort on the subject in 1979.

The reasons for concentrating on enzymic hydrolysis rather than acid hydrolysis were (a) low temperatures are involved so end-product degradation is not a problem and high yields of glucose, free from inhibitors, are theoretically possible, (b) corrosion problems associated with acid are avoided and (c) because the concept is relatively new there is more scope for progress.

Bagasse was chosen as the raw material for study and ethanol was seen as the most promising end-product. It was soon realised that one third of bagasse is hemicellulose and that the research effort should not be confined to cellulose. Hemicellulose in bagasse is relatively easy to hydrolyse with dilute acid. Xylose is the main hydrolysis product but until recently this sugar was considered unsuitable as a substrate for ethanol production because there were no known yeasts capable of mediating the necessary fermentation. Various organisms, including a few yeasts, have now been discovered with promising potential for ethanol production from xylose. None of the organisms is yet suitable for industrial application but future developments in this area will be relevant to the sugar industry because the industry could probably produce xylose at a cost low enough for profitable ethanol production. Again this technology has particular application in the sugarcane industry because bagasse contains more xylose than do most other lignocellulose wastes and the bagasse is in a disintegrated form making it readily accessible to acid for hydrolysis. The South African industry could have an added advantage in that the diffusion process, which is popular in the industry, produces bagasse at a temperature of about 70°C thus reducing the heat required for subsequent acid hydrolysis.

Recent Progress in Bagasse Hydrolysis and Fermentation

Hemicellulose hydrolysis

In the past three years considerable data on the dynamics of hydrolysis of hemicellulose in South African bagasse have accumulated (Trickett⁵ and Neytzel-de Wilde & Lussi⁶). A reliable mathematical model for predicting rates of xylose accumulation under a wide range of temperature and acid concentration was developed and a pilot-scale continuous hydrolysis reactor was constructed and operated at temperatures up to 130°C. The accumulation of acetic acid, heavy metals and furfural (a breakdown product of xylose) was measured under various conditions and the rate of acid consumption has been established.^{5, 6} Most of this work was done at temperatures above 100°C and a tentative conclusion is that hydrolyses at lower temperatures should be more thoroughly investigated because at lower temperatures corrosion would be reduced and the hydrolysate would contain lesser amounts of heavy metals, furfural and other toxic substances. Less expensive materials of construction could be used.

The possibility of running the hydrolysis in dumps of bagasse without special containers is soon to be investigated. Laboratory tests have shown that a temperature of 55°C for 14 days may be adequate for our purpose. The long reaction time is not a major disadvantage because facilities for bagasse storage will have to be provided to ensure a supply of bagasse during the four months when sugar factories are closed.

Xylose fermentation

Progress in this field has taken place mainly in Canada and the Northern States of America where xylose is available from paper factories and cereal crop residues. Numerous organisms can grow on xylose but only a few are able to ferment it to ethanol. *Pachysolen tannophilus* is a yeast which probably has most potential but its ethanol productivity and tolerance are too low for industrial ethanol production. Rapid progress is

being made in increasing its productivity by optimising fermentation conditions (Detroy et al⁷). The search for suitable xylose fermenting organisms is continuing and it is likely that organisms better than *P. tannophilus* will be found. A potential source of such organisms is the effluent system at Union Cop because this has received hemicellulose hydrolysate from cooked wattle bark for many years.

Any new xylose fermenting organism is likely to need mutation and adaptation to high ethanol concentrations before it is suitable for industry. An alternative approach is to use an enzyme to isomerise xylose to xylulose and then to use an existing industrial ethanol producing yeast (*Saccharomyces cerevisiae*) to ferment the xylulose. The appropriate enzyme is presently used on a large scale to make high fructose corn syrup, and the potential of this approach has been demonstrated but the process is not efficient. Attempts are being made to modify the yeast genetically so that it produces the necessary xylose isomerase enzyme itself. Success in transferring the necessary genes has just been reported (Batt et al⁸). The genes express themselves in the yeast but do not enable it to grow on xylose as a sole source of carbon.

Bagasse pretreatments for cellulose hydrolysis

The cellulose in raw bagasse, and in bagasse which has been treated to remove hemicellulose, is not very susceptible to enzymic hydrolysis. Some form of pretreatment is necessary to make it accessible to the enzyme. Various effective chemical pretreatments are known but most of them are too costly or they tend to remove part of the cellulose (Neytzel-de Wilde and Lussi⁹). Physical pretreatments such as milling may also be effective but are generally too costly in terms of energy requirements.

Work at the SMRI has involved the study of pretreatments. Whilst working with prehydrolysed bagasse (i.e. bagasse from which most of the hemicellulose has been removed) it was noticed that, in comparison with normal bagasse, there was a substantial reduction in the energy required for milling. This suggested that prehydrolysis followed by milling might be the most suitable pretreatment for bagasse. After optimising milling conditions in a stirred bead mill (attritor) it was found that a milling duration of only 10 minutes was adequate (Fig. 2). This suggests that milling could be done on a continuous basis by a single pass through a large attritor. With a small-scale indirect drive batch attritor the energy consumption was 0,39 kWh kg⁻¹ of prehydrolysed bagasse. When steel balls were used in the attritor they introduced severe inhibition effects if the optimum milling duration was exceeded. High-density ceramic balls of 6 mm diameter have proved most successful for routine milling (Purchase¹⁰).

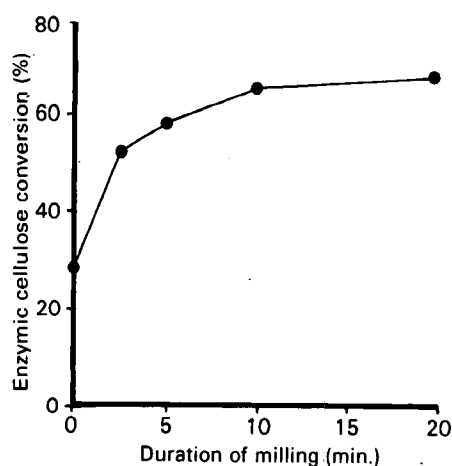


FIGURE 2 Cellulose conversions as affected by duration of milling with 6 mm ceramic balls at 300 rpm.

The success of this pretreatment has been assessed by subjecting the pretreated cellulose to enzymic hydrolysis. If enough enzyme is used then almost 100% conversion is possible but with realistic enzyme concentrations the expected conversion is about 75% (Fig. 3).

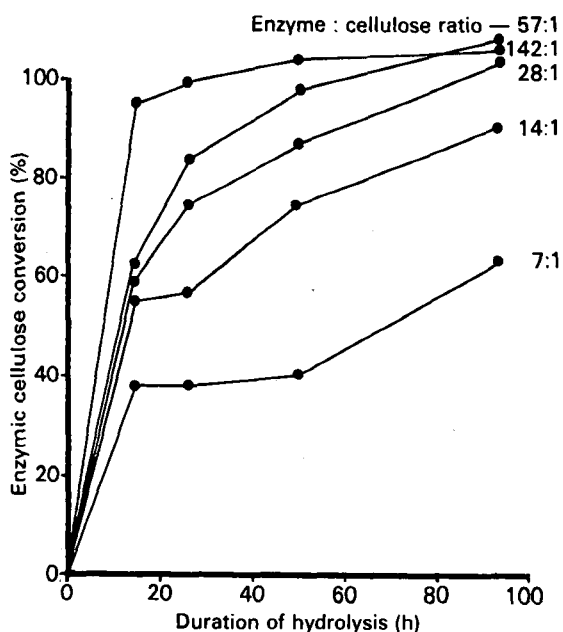


FIGURE 3 Hydrolysis dynamics for attritor-milled bagasse with different enzyme (filter paper units): cellulose ratios.

Furfural is made from bagasse by steaming the bagasse at a temperature high enough to hydrolyse the hemicellulose and convert the xylose to furfural. After steaming, the bagasse is explosively decompressed. Steaming followed by explosive decompression is normally a good pretreatment but when the steamed bagasse from a furfural factory was subjected to enzymic hydrolysis the conversion yields were only about 30%. It was suspected that the harsh steaming conditions generate phenolic compounds which interfere with the enzyme. To test this possibility, a chemical which binds phenolic compounds (polyvinylpyrrolidone (PVP)) was added to the bagasse prior to adding the enzyme. The PVP had a substantial beneficial effect (Fig. 4). Even without attritor milling, the cellulose conversion exceeded 60%, and where milling was applied only 5 minutes was necessary for maximum effect. When a surfactant

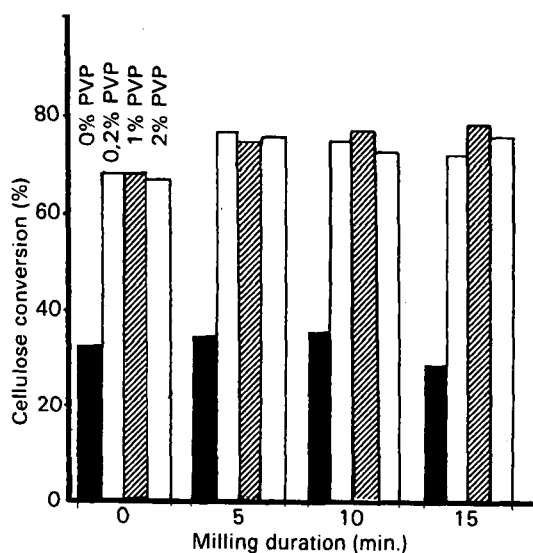


FIGURE 4 Enzymic cellulose conversions as affected by duration of milling and supplementation with various PVP concentrations.

(Triton X-100) was also added then the conversion of cellulose to glucose often exceeded 80%.

Although PVP is too expensive for this use on a commercial scale the results show that if interference from phenolic compounds can be removed then the bagasse residue from a furfural factory is a promising substrate for glucose production by enzymic hydrolysis. It can give good yields with very little additional pretreatment and enough will be available at Sezela to produce approximately 15 million litres of ethanol annually.

Acid (or high pressure steam) prehydrolysis followed by attritor milling seems promising and appropriate for pretreating bagasse because (a) as yet there is no organism which will simultaneously ferment xylose and glucose so there is a need to separate the two sugars, (b) the separation step (prehydrolysis) removes about 35% of the bagasse and leaves a residue which can be milled with reasonably low energy input, (c) relatively inexpensive energy is usually available at sugar factories and (d) after saccharification of the milled slurry the residual lignin-rich material can be recovered for use as a fuel. It dries to coal-like lumps and contains at least 30% of the fuel value of the original bagasse.

Enzyme production and enzyme efficiency during hydrolysis

The high cost of the enzyme used for cellulose hydrolysis is a major barrier to commercialisation of the enzymic process. Recently considerable progress has been made in improving enzyme productivity by selecting improved strains and optimising fermenter conditions (Cuskey et al¹²). High productivities are being achieved in a pilot plant at the CSIR and this plant is able to produce all the enzyme required for small pilot-scale studies on bagasse.

The high cost of the enzyme has prompted studies on improving the enzyme efficiency. With our pretreated bagasse the addition of PVP and a surfactant has led to significant improvement in the enzyme efficiency, particularly when the hydrolysis is run in fed-batch mode (Fig. 5). These results suggest that additives help by preventing irreversible binding of the enzyme to components in the bagasse and they show that there is scope for improving enzyme efficiency during hydrolysis.

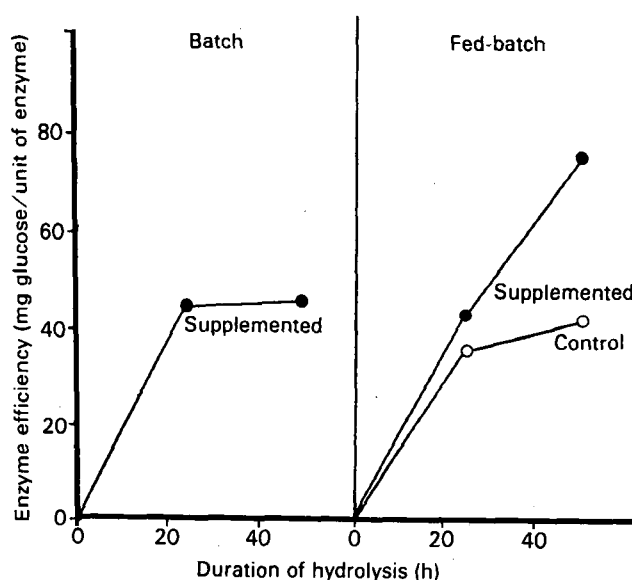


FIGURE 5 Enzyme efficiency during batch and fed-batch hydrolyses supplemented with 0,1% Triton X-100 plus 0,2% PVP. (The fed-batch system received additional bagasse after 24h)

Economics and process perspective

A preliminary economic assessment of a bagasse-to-ethanol process consuming 300 t (dry) bagasse per day was recently

completed by chemical engineers at the University of Cape Town (Flack¹⁴). The process is clearly uneconomical at this stage but the analysis gives useful perspective and direction for future research. Table 1 shows how capital and running costs are distributed between the various sections.

TABLE 1
Preliminary indications of high cost areas

Plant section	Costs as % of total	
	Capital	Production
Bagasse		8
Pretreatment	16	21
Enzyme production	39	33
Hydrolysis	34	30
Fermentation	5	3
Ethanol recovery	1	2
Waste treatment and steam generation	5	3

(Data from Flack¹⁴)

The figures show that over 60% of the cost is related to enzyme production and hydrolysis. These are areas of relatively new technology with most scope for improvement. No by-product credits have been allocated and it was assumed that xylose has no value. Again this shows that there is considerable potential for cost reduction because successful xylose fermentation seems a real future possibility and would add about 50% to the ethanol yield without adding any enzyme and hydrolysis costs.

The figures also show that the normal tendency to aim for final ethanol concentrations of at least 6% may not be logical for this process. Enzyme efficiency declines as the concentration of final product increases and because ethanol recovery is relatively much less costly than enzyme production it is enzyme efficiency which must be optimised. Supplementation of dilute glucose solutions with molasses would be one way of optimising ethanol recovery without adversely affecting enzyme efficiency.

If an efficient xylose fermentation process could be developed then instead of diverting only one third of the bagasse to ethanol production it might be better to prehydrolyse all of the bagasse and then burn the resulting residue. The prehydrolysis would remove about one third of the bagasse and 60% of this would be fermentable without involving enzymic hydrolysis. Assuming a yield of only 25% ethanol on xylose, the ethanol yield from three tons of bagasse would be about 190 litres, which is similar to that obtainable from one ton of bagasse if its xylose and glucose were to be fermented. This xylose route from bagasse would give ethanol at a cost of about R0,40¹

Conclusions

Hydrolysis of bagasse is a technology which could be particularly relevant to the South African sugar industry. At present this technology is not economically attractive but there is

considerable potential for cost reduction. The developing technology for fermentation of xylose is of particular interest because xylose could probably be produced at a cost low enough for profitable fuel ethanol production. Some facilities and expertise have been established in South Africa for pilot-scale production of cellulase enzymes and for pretreatment of bagasse prior to enzymic hydrolysis. Progress in these areas of research could substantially reduce the cost of fermentable glucose from bagasse. The research has reached a stage where a small process-development-unit is being considered.

Acknowledgement

Financial support from Cooperative Scientific Programmes of the Council for Scientific and Industrial Research is gratefully acknowledged.

REFERENCES

1. Ravnø, A. B. (1979). Perspectives in ethanol manufacture. *SASTA Proc.* 53: 6-9.
2. Lima, J. E. (1982). Sugar cane as an energy resource for the Caribbean area. *Sugar y Azucar* 77: 62-71.
3. Sang, S. L. and Yen, Y. (1981). An improvement of thermal efficiency in Taiwan cane sugar industry. *Taiwan Sugar* 28: 152-157.
4. Augustine, N. R. (1976). Technology transfer from military requirements to public need. *Biotechnology and Bioengineering. Symposium 6.* John Wiley and Sons, New York. 316 p.
5. Trickett, R. C. (1982). Utilisation of bagasse for the production of C₃ and C₆- sugars. M.Sc. Thesis, University of Natal.
6. Neytzell-de Wilde, F. C. and Lussi, M. (1982). Dilute acid hydrolysis of bagasse hemicellulose in a batch and continuous reactor to produce C-5 sugars. Report to National Materials Programme, Council for Scientific and Industrial Research. 65 p.
7. Detroy, R. W., Cunningham, R. L., Bothast, R. J., Bagby, M. O. and Hermans, A. (1982). Bioconversion of wheat straw cellulose/hemicellulose to ethanol by *Saccharomyces uvarum* and *Pachysolen tannophilus*. *Biotechnol. Bioeng.* 24: 1105-1113.
8. Batt, C. A., Taylor, M. and Lee, K. M. (1983). Development of a strain of *Saccharomyces cerevisiae* that can catabolise xylose. Paper at meeting of American Society for Microbiology, New Orleans, March, 1983.
9. Neytzell -de Wilde, F. C. and Lussi, M. (1981). Chemical delignification of sugar cane bagasse using caustic soda or ammonium hydroxide and the effect of some treatment methods on the enzymatic hydrolysis of the cellulose in bagasse. Report to National Materials Programme, Council for Scientific and Industrial Research. 13 p.
10. Purchase, B. S. (1983). Attritor-milling as a pretreatment for bagasse prior to enzymic hydrolysis. *ISSCT Proc.* 18, in press.
11. Perrow, S., Purchase, B. S. and Proudfoot, S. (1983). Enzymic hydrolysis of bagasse - progress report 6. Technical Report No. 1337, Sugar Milling Research Institute.
12. Cuskey, S. M., Frein, E. M., Montenecourt, B. S. and Eveleigh, D. E. (1981). Over-production of cellulase - Screening and selection. *FEMS Symposium* 13, Eds. Krumphanz, V., Sikyta, B. and Vanek, A., Academic Press. 731 p.
13. Watson, T. G. and Anziska, G. (1982). Pilot scale production of cellulase in the bioconversion of cellulosic materials to glucose and ethanol. *South African Food Review* 9: 102-104.
14. Flack, L. (1983). Ethanol from bagasse. Report to National Materials Programme, Council for Scientific and Industrial Research.