"a novel improvement in starch saccharification is the omission of the cooking step"

Alcohol Fermentation*

by

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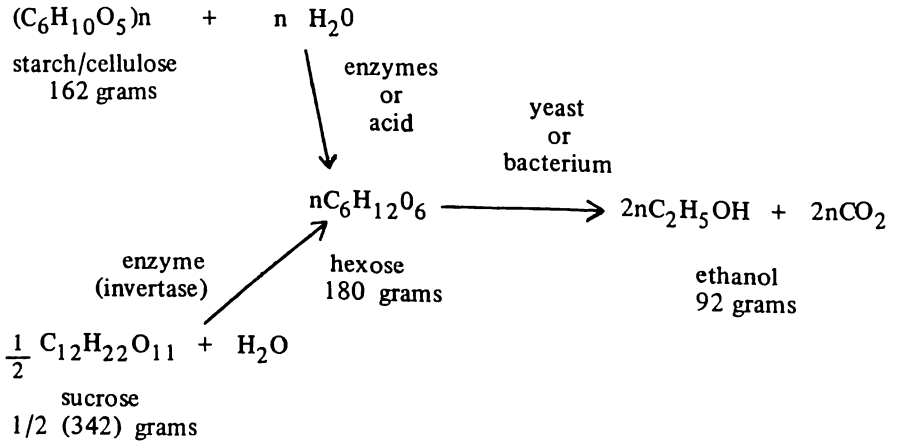
Theoretical Consideration

Man's ever-increasing energy needs have dramatically intensified the search for non-conventional energy sources. One of the most important of these sources is recently-photosynthesized biomass (plant biomass), as contrasted from fossilized photosynthetic products such as petroleum, coal and natural gas. Plant biomass is replenishable due to active photosynthesis. However, fossil fuels, which have been formed millions of years ago beneath the earth's crust, will run out perhaps in a not too distant future. Plants are able to photosynthesize a wide variety of fuel substances such as carbohydrates, lignin, vegetable fats (glycerides) and hydrocarbons. These fuel substances may be used directly or converted into other fuel forms by chemical and/or biological processes.

Fuels which are derived directly or indirectly from plant biomass are collectively called biofuels. One of the most important biofuels presently available is ethanol (or ethyl alcohol).

Ethanol may be produced from carbohydrates such as sugars, starch or cellulose as shown below:



SCHEME I

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The first step in Scheme 1 corresponds to the complete hydrolysis of either carbohydrate polymers, namely starch and cellulose, into glucose or of sucrose into glucose and fructose. This hydrolytic step is brought about by acids or the corresponding enzymes. The second step is called alcohol fermentation and requires the action of a microorganism such as yeast or certain bacteria such as *Zymomonas mobilis*. Some microorganisms such as *Saccharomyces cerevisiae* can convert sucrose into ethanol while others, such as *Schwanniomyces alluvius* can convert soluble starch into ethanol (Calleja et al., 1982).

The stoichiometric product yield coefficient $Y_{p/s}$ which is the mass ratio of the product (ethanol) formed to the substrate consumed, is calculated from Scheme 1:

$$Y_{p/s} = \frac{\Delta P}{-\Delta S} = \frac{92}{180} = 0.51 \quad \text{(based on glucose or fructose)}$$

$$Y_{p/s} = \frac{\Delta P}{-\Delta S} = \frac{92}{1/2(342)} = 0.54 \quad \text{(based on sucrose)}$$

$$Y_{p/s} = \frac{\Delta P}{-\Delta S} = \frac{92}{162} = 0.57 \quad \text{(based on starch/cellulose)}$$

The conversion efficiency, either for the stepwise or overall process, is the ratio of the experimental product yield coefficient to the corresponding stoichiometric coefficient.

Suitable crops for ethanol production are of four types, namely (a) saccharine, (b) starchy, (c) cellulosic and (d) hemicellulosic. The first type contains simple sugars such as sugarcane or nipa sap while starchy crops include cassava and sweet potato. Cellulose is the most abundant organic substance in the world. It makes up approximately 50% of the cell wall material of wood and plants and between 25 to 50% (dry basis) of sugarcane, bagasse, rice straw, rice hulls, wood and other lignocellulosic materials Hemicelluloses include pentosans as well as hexane. The latter are polymers of hexoses other than glucose and are the major constituents of coconut meat residue 'sapal'. Cellulose is usually tightly complexed with hemicellulose and lignin. The latter, which is non-carbohydrate, hinders the hydrolysis of both cellulose and hemi-cellulose. Corn cobs contain about 30% xylan (polymer of the five-carbon sugar xylose).

Process Technology

1. *Saccharification Technology*

Alcohol production from starchy materials requires the additional and prior step of hydrolyzing starch into glucose. As shown in Scheme 1, this saccharification step is catalyzed by acid or enzymes. The latter are broadly classified as amylase and are of three types, namely, alpha-amylase, beta-amylase and glucoamylase. The conversion of starch into glucose consists of three steps: (a) gelatinization-dissolution of starch into a mash by steam

cooking, (b) liquefaction (dextrinization) – breakdown of the gelatinized starch into short fragments or dextrins by means of alpha- or beta-amylase or dilute acid, and (c) saccharification-complete conversion of the dextrins into glucose. Enzymes are favored over acid in starch hydrolysis since they are more selective and the product yields are higher. After the starch is completely hydrolyzed into glucose the technology employed for alcohol production is identical to that using saccharine materials.

Recent developments in the starch-to-glucose conversion technology include the availability of heat-resistant and highly-active enzymes. A heat-resistant alpha-amylase derived from *Bacillus licheniformis*, which is presently produced by Novo Industri A/S (Denmark), can tolerate up to 90°C and is suitable for the dextrinization of gelatinized starch. A continuous process for enzymatically converting starch into ethanol is schematically shown in Figure 1. The milled starchy material is slurried in water in a feed tank, with or without adding pre-liquefaction amylase, and pumped into a tube cooker. Steam is introduced at the cooker inlet in order to heat the slurry to cooking temperature (130-160°C). At the cooker outlet the slurry is flash cooled at 90-80°C before post-liquefaction amylase is added to the mash. Starch liquefaction takes place at 80-90°C in a tube converter and the mash is cooled before introduction into the fermenter. The saccharification and fermentation are normally done in a batch fermenter.

A novel improvement in starch saccharification is the omission of the gelatinization or cooking step. The granular starch is converted into ethanol in the presence of alpha-amylase and glucoamylase. Although alcohol production from ungelatinized starch is slower, this is compensated for by increasing the level of granular starch in the slurry. The cold saccharification process has been tried by Novo Industries A/S and was shown to result in reduced energy consumption equivalent to 10% of the energy content of the product alcohol (Lützen, 1980). It was also found suitable for continuous processing with starch and yeast recycle. Research reports by several groups of researchers (Ueda and Koba, 1980; Hayashida and Flor, 1982; Taguchi, 1982; Park and Rivera, 1982) have also shown that raw uncooked starch could be saccharified and fermented into alcohol. The omission of this cooking or gelatinization step would reduce the energy requirements and processing cost for producing alcohol from starchy crops.

Extensive laboratory and industrial work has been done on the acid saccharification of wood (Wenzyl, 1970). Although the acid process is presently done on an industrial scale only in the Soviet Union, it may be run economically in capitalist countries using waste cellulose and in large-enough scale (Grethlein, 1978). Aside from wood and wood wastes, coconut meat aqueous process residue ('sapal') and sugarcane bagasse are promising materials for the production of sugar as shown in Table 1. The tabulated data, which were obtained in the author's laboratory, also include the sugar composition of acid hydrolyzates as well as efficiencies of hexose fermentation into alcohol. Although rice straw and rice hulls are *not* good source of hexoses, they may be hydrolyzed with acid to yield pentoses which can be used as substrate for the production of *Candida* yeasts for animal feeds (Cayabyab et al., 1977). Alternatively, selected microorganisms may be used which can ferment pentoses into ethanol.

The enzymatic hydrolysis of cellulose has been actively studied worldwide and has been the subject of several technical symposia (Hajny and Reese, 1969; Wilke, 1975; Badley et al., 1975; Gaden et al., 1976; Ghose, 1978; Ghose, 1981). Unlike the acid process, enzymatic saccharification requires milder conditions of pH (4-5) and temperature (45°C). However, long reaction times (> 12 hours) and a high liquid-to-solid ratio (20:1 v/w) are employed in order to obtain high sugar yields. Cost estimates of producing glucose from newsprint using the enzyme cellulose were made by Wilke et al. (1976) and a comparison of the unit costs of acid and enzymatic hydrolysis of newsprint was done by Grethlein (1978). Although the enzymatic hydrolysis of newsprint has been shown to be more expensive than the acid process, substantial improvement in the enzymatic process has been recently reported. An improved strain of *Trichoderma viride*, namely Rut-C-30 was found superior to the QM-9414 strain in terms of enzyme production (Wilke et al., 1980). It is expected that with further genetic improvement of existing cellulase producers, or the discovery of highly cellulolytic microorganisms, the enzymatic saccharification of cellulose should be made economical in the near future.

2. *Alcohol Fermentation Technology*

Batch Fermentation

Yeast fermentation of sugar solutions into ethanol has been traditionally carried out as a batch process using cylindrical fermenter vats. A flow diagram of the batch process is presented in Figure 2. The molasses is pumped through a "masher" in which it is diluted with water to 16-18 Brix (containing approximately 11% total sugars) before being charged to the fermenters. The resulting wort is supplemented with a source of nitrogen, such as urea, as well as other nutrients and its pH is adjusted to about 4.5 by adding sulfuric acid.

The pure yeast inoculum is successively increased in amount starting from the test tube slant through "build-up" using containers of increasing size from which the large fermenters are inoculated. Fermentation in the large vats usually takes more than 20 hours and the final "beer" contains approximately 6% alcohol by volume and 4.3 – 4.5 Brix.

Ethanol is recovered from the "beer" through continuous distillation with the aid of steam using two or three distilling columns (Figure 2). Preheated "beer" enters the top of the first column with distillate (40-50% alcohol by volume) and slops as the products of the first distillation process. The alcohol distillate is then introduced into the successive columns where it is purified and concentrated to 95% alcohol by volume.

In Brazil, the "Melle-Boinot process" of batch alcohol fermentation is employed using open air, topless vats of 100-200 m^3 capacity ($1m^3$ = 1000 l). This process involves yeast recycling which allows a reduction in fermentation time to 6-8 hours and a cycle time of 10-12 hours which includes filling, emptying and cleaning of the vats (Lindeman and Rocchiccioli, 1979). A block diagram of the Brazilian ethanol process is presented in Figure 3. Four distillation towers are employed in the production of anhydrous ethanol. The first tower separates the solid materials and drives aldehydes overhead. The second tower concentrates the fusel oils (higher alcohols) for removal and concentrates the alcohol to the azeotrope, which contains 95.6% by weight

ethanol. The last two towers are required for dehydration of the alcohol beyond the azeotropic composition. The most popular dehydration process uses benzene to extract ethanol. The last tower is a stripper which recovers benzene from the benzene-water phase formed in the decanter.

Current alcohol production in the Philippines is beset by many problems which contribute to the high cost of alcohol.

Some of these problems are:

(a) inferior yeast strain used,

(b) contaminated and low-quality molasses,

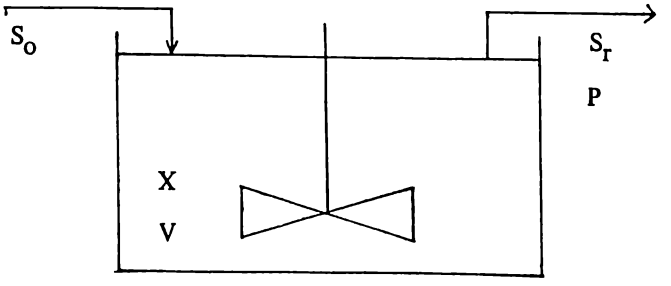
(c) inadequate temperature control during fermentation, and

(d) lack of proper distillery waste management procedures.

The first problem is very important because the selection of an excellent yeast strain can overcome the succeeding two problems. A suitable yeast strain is characterized by a high specific ethanol productivity and can tolerate up to 40°C and alcohol concentrations of 10% by volume. By using a heat-tolerant yeast, cooling costs are minimized and the use of contaminated molasses becomes a minor problem. The latter problem normally causes low fermentation efficiencies, which are less than 80% for most distilleries in the country. This is explained by the formation of by-products other than ethanol by the contaminants in the molasses. The utilization of distillery slops for the production of biogas, single-cell protein or fertilizer serves two purposes, namely reduction of the pollution load of the slops and corresponding decrease in alcohol production costs.

Continuous Flow Fermentation

In the continuous process the sugar solution is continuously pumped into the fermenter while the fermented product 'beer' is withdrawn such that the volume of the fermenting liquid remains constant, as shown below:



Scheme 2

The complete mass balance equation for the sugar during continuous alcohol fermentation is given by the equation (Wang et al., 1979):

Sugar	– Sugar	– Biomass	– Maintenance	– Ethanol	= Sugar
in	out	produced	requirement	formed	accumulated

$$DS_o - DS_r - \frac{\mu X}{Y_{x/s}} - mX - \frac{-Q_p X}{Y_{p/s}} = \frac{dS}{dt} \qquad (1)$$

The parameters and their units are defined as follows:

D (hr^{-1}), dilution rate (ratio of flow rate F to fermenter working volume V)

S_r (g/l), residual sugar concentration in the the 'beer'

r (hr^{-1}), specific growth rate

X (g/l), yeast concentration (dry basis)

$Y_{x/s}$ (g/g), biomass yield coefficient

$Y_{p/s}$ (g/g), product (ethanol) yield coefficient

S_o (g/l), feed sugar concentration

m (g/g-hr), specific maintenance rate

Q_p (g/g-hr), specific ethanol production rate

The biomass yield coefficient $Y_{x/s}$ is equal to the mass ratio of yeast produced to sugar consumed. The specific maintenance rate is expressed as grams of sugar utilized per gram of dry yeast per hour and represents substrate utilization for cell functions other than growth and ethanol production. These functions include turnover of cell materials, osmotic work to maintain concentration gradients and cell motility. The specific ethanol production rate Q_p is ratio of the volumetric productivity dP/dt to the cell concentration X and is expressed as grams ethanol produced per gram yeast per hour:

$$Q_p = \frac{1}{X}\frac{dp}{dt} \qquad (2)$$

It can be seen after rearranging Eq. (2) that the volumetric productivity dP/dt is directly proportional to both the yeast concentration X and the specific productivity Q_P.

Under steady-state conditions, sugar does not accumulate in the continuous fermenter and Eq. (1) may be simplified and rearranged as:

$$Q_s = \frac{D(S_o - S_r)}{X} = \frac{u}{Y_{x/s}} + m + \frac{Q_p}{Y_{p/s}} \qquad (3)$$

Q_s is the specific sugar uptake rate expressed as grams sugar assimilated per gram of yeast per hour.

The volumetric productivity of a continuous alcohol fermenter is greater than that of the batch fermenter because the latter has a lag time before the yeast can maximally produce alcohol while the continuous fermenter at steady state is always operating optimally. Furthermore, the batch process requires a "down time" or idle period for emptying, cleaning and filling of the fermenter in between the batch runs. At the same productivity, a continuous fermenter is equivalent to a bigger batch fermenter.

Equipment Design and Operation

The major equipment items for saccharification and alcohol fermentation include mixing and storage tanks, heat exchangers for sterilization/pasteurization and cooling, cylindrical fermenter tanks, distillation equipment and pumps. As shown in Figures 1 and 2 except for pumps and mixers, mostly stationary equipment is used. Unit operations for saccharine materials such as sugarcane molasses are liquid mixing, heat transfer, distillation and solid-liquid separation. Post-harvest operations for cassava, and to a large extent also for sweet potato, include peeling, washing, chipping and drying. Many of the equipment, especially tanks and distillation columns can be and are locally fabricated.

Recent Developments in Alcohol Fermentation Technology

Some of the promising innovations in alcohol fermentation technology include: (a) rapid fermentation using high yeast levels (Ghose and Tyagi, 1979; del Rosario et al., 1979; Ghose and Bandyopadhyay, 1980; Robinson et al., 1981), (b) use of rapidly-fermenting microbial types such as *Zymomonas mobilis* (Rogers et al., 1980; 1982) and micro-organisms that ferment pentoses into ethanol (Sliniger et al., 1982; C.S. Gong et al., 1983), (c) simultaneous alcohol fermentation and distillation (Maiorella et al., 1980; Alfa-Laval, 1982) and (d) direct microbial conversion of thinned starch into ethanol in a two-stage process (E.J. del Rosario and R.L. Wong, submitted for publication; Bugarin, 1983).

The use of high yeast concentrations results in rapid ethanol fermentation (less than six hours fermentation time). This may be achieved by using a continuous-flow process with cell recycle. Alternatively, a flocculent or immobilized yeast may be used. A high volumetric productivity is attained such that a small fermenter produces a large alcohol throughput. The savings in capital investment can be quite substantial when compared to the conventional batch process. Volumetric ethanol productivities using *Zymomonas mobilis* are even higher (greater than 100 g/l-hr) than those of yeast. Unfortunately, many strains of this bacterium can not ferment sucrose; this bacterium also produces levan as a by-product of ethanol fermentation. The use of the combined 'Biostil' fermentation-distillation process (Alfa-Laval, 1982) has been reported to result in a 5% increase in ethanol yield and a 70% reduction in volume of stillage or slops. The latter benefit is very important because of the pollution problem posed by this waste material.

The author's current researches on alcohol fermentation include the development of a rapid continuous-flow process using immobilized yeast in a column fermenter. The laboratory-scale process utilizing diluted and nutrient-supplemented molasses as substrate, is shown in Figure 4. The operation of the one-liter column fermenter (bioreactor) containing immoblized yeast has been tested for the continuous-flow fermentation of sugarcane molasses into ethanol. Diluted and nutrient-supplemented molasses was continuously passed through a pasteurizer and cooler and then through the column fermenter containing a heat-tolerant and yeast immobilized on wood particles maintained at 42°C. Yeast recycle was achieved by means of a yeast settler and recycle pump. Medium feed and yeast recycle were regulated by an automatic feed controller. The experiment was conducted continuously for 50 days and fresh yeast was added to the fermenter after 3 days and 20 days in order to compensate for cell death and washout. The average alcohol concentration in the 'beer' was 7.3% by volume while the residual sugar concentra-

tion was approximately 7% at an average residence time of 7.2 hours. The fermenter contained initially 2 x 10^9 yeast cells per ml.

The present process has solved the previous problem of contamination and allowed yeast viability to be maintained for up to one month. However, a relatively high residual sugar concentration was obtained in the 'beer' which, hopefully could be solved by higher yeast loading in the fermenter and/or a longer residence time.

A direct microbial process for the saccharification and ethanol fermentation of starchy materials is another interesting innovation. The alternative process, which is sometimes called the 'Amylo' process, does not employ added enzymes but uses enzymes produced *in situ* by an amylolytic microorganism. As early as 1914, Grove described a process for the commercial production of ethanol using amylolytic fungi. A recent report (Sreekantiah and Rao, 1980) has dealt with the conversion of starch from potato, sweet potato or cassava into ethanol using a mixed culture of *Rhizopus niveus* and yeast. This mixed-culture process is potentially simpler and more economical than the enzymatic process because the need for separately producing the amylolytic enzymes is obviated. However, the amylolytic and alcohol-producing microorganisms need not be combined in a fermenter for a single-stage process but can be placed in two separate fermenters. Such a sequential or two-stage process allows the first-stage microbial saccharification and second-stage alcohol fermentation to be separately optimized. Research done in the author's laboratory (E.J. del Rosario and R.L. Wong, submitted for publication) has shown that the sequential action of an amylase-producing mold and a yeast in a two stage continuous process effectively converted cassava starch into ethanol. A mixture of cassava root flour (15% by weight) and rice bran (6%) was thinned with either acid or alpha-amylase and served as culture substrate for *Aspergillus awamori*. After a residence time of 12.5 hours in the first fermenter, 88% of the starch was converted into sugars and the sugar concentration of the hydrolysate was 12.5% by weight. In the second stage of the process, the hydrolysate was fermented into alcohol by a non-flocculent yeast after a residence time of 5.6 hours. The resulting alcohol concentration was 5.3% by weight and the starch-to-ethanol conversion efficiency was 72.5%. Equally promising results have been obtained recently in the author's laboratory using sweet potato as substrate (Bugarin, 1983). A diagram of the two-stage process for cassava or sweet potato root flour is given in Figure 5.

Economic Considerations

Substrate and Energy Costs

The estimated yields of some agricultural crops and the corresponding ethanol yields are presented in Table 2. The crop yields were estimated for Philippine conditions and the lower limits were derived mainly from the data of the Bureau of Agricultural Economics. Nipa is the most promising crop for alcohol production and can yield up to 21,000 liters of alcohol per hectare per year. The actual yield of nipa sap from Philippine nipa stands in 1911 was estimated by Gibbs (1911) to be 87,000 l/ha/yr at a plant density of about 2,000 nipa plants per hectare. A rough calculation gives an ethanol yield approximately 7,800 l/ha/yr assuming a 14% sugar concentration in the sap. This conservative ethanol yield estimate is greater than the theoretical ethanol yields from the other crops on the basis of current crop yields. What is implied is that using suitable land and current farming

technology the cost of ethanol production would be lowest for nipa. This conclusion had been arrived at in 1911 by Gibbs, who also noted the case and rapidity of fermentation of nipa sap. A possible drawback for nipa is that it takes about four years for the seed to grow and bear fruit and tapping for sap is normally done after another year.

A useful comparison of some of the raw materials for alcohol production can be made using the present cost of the carbohydrate contained in these raw materials. Sugarcane molasses is presently the choice substrate in the Philippines and, presently, has a low price of less than ₱100/metric ton (ex-mill price). Since it contains about 55% carbohydrates, in the form of the sugars sucrose, glucose and fructose, the carbohydrate cost is calculated to be less than ₱0.18/kg (or ₱100/550 kg). Cassava and sweet potato contain approximately 25% carbohydrate mainly in the form of starch (fresh basis). At an assumed price of ₱1 per kilogram of the fresh crop, the carbohydrate cost is ₱4/kg (or ₱1000/250 kg). This presently high carbohydrate cost makes these two root crops impractical substrates for alcohol production. Assuming a raw material cost of 65% of the alcohol product cost, a starch-into-alcohol conversion efficiency of 75% and an alcohol cost of ₱5/liter of alcohol, the cost of fresh cassava or sweet potato should be ₱0.47/kg of the fresh material containing 25% starch. This demand price is presently too low for the Filipino root crop farmer. It should be pointed out that the estimated values in Table 1 are based on maximal conversion efficiencies.

Energy balance calculations for sugarcane, cassava and sweet sorghum under Brazilian conditions have been done by Pimentel (1980) and are presented in Table 3. The energy ratio E_{out}/E_{in}, which is obtained by dividing the total energy contained in the product alcohol divided by the energy consumed in the overall process, is highest for sugarcane and lowest for cassava. The energy ratio for cassava should be increased by improving cassava crop yields and reducing process energy consumption. The energy ratio for sweet potato, which was not included in the calculations, is expected to be slightly higher than that for cassava due to its shorter crop cycle and higher ethanol yields. However, sugarcane is still expected to be the most preferred crop for alcohol production due to simpler processing required and the production of sugarcane bagasse for fuel.

Overall Process Costs

A systematic cost evaluation of the overall ethanol process may be done using sensitivity analysis (Myers, 1982). This technique is useful in identifying the process parameters, a small change of which, produces a large change in the plant profitability. This is very useful during the research and development and project evaluation stages because it provides an insight into the specific process areas in which further research and development would most effectively reduce operating or capital costs and therefore increase profitability. In practice, a "base case" plant proposal is defined and the process parameters which affect the plant profitability are varied by a certain amount; the resultant change in plant profitability is then calculated relative to the base case.

The analysis is done by breaking down the calculations under three main groups namely Production Costs, Capital Costs and Revenue. These are presented in Tables 4, 5 and 6 for a 50 million liters per year ethanol plant. Profitability can be measured either as Return on Investment (ROI) or as Discounted Cash Flow Rate of Return (DCFROR). The latter, although more difficult to calculate than

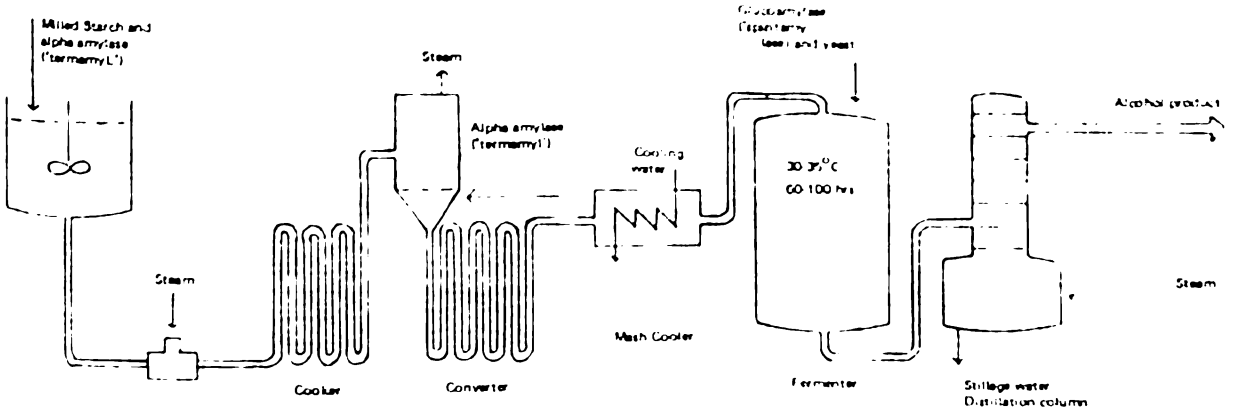


Figure 1. Continuous conversion of starch into ethanol (NOVO, 1976)

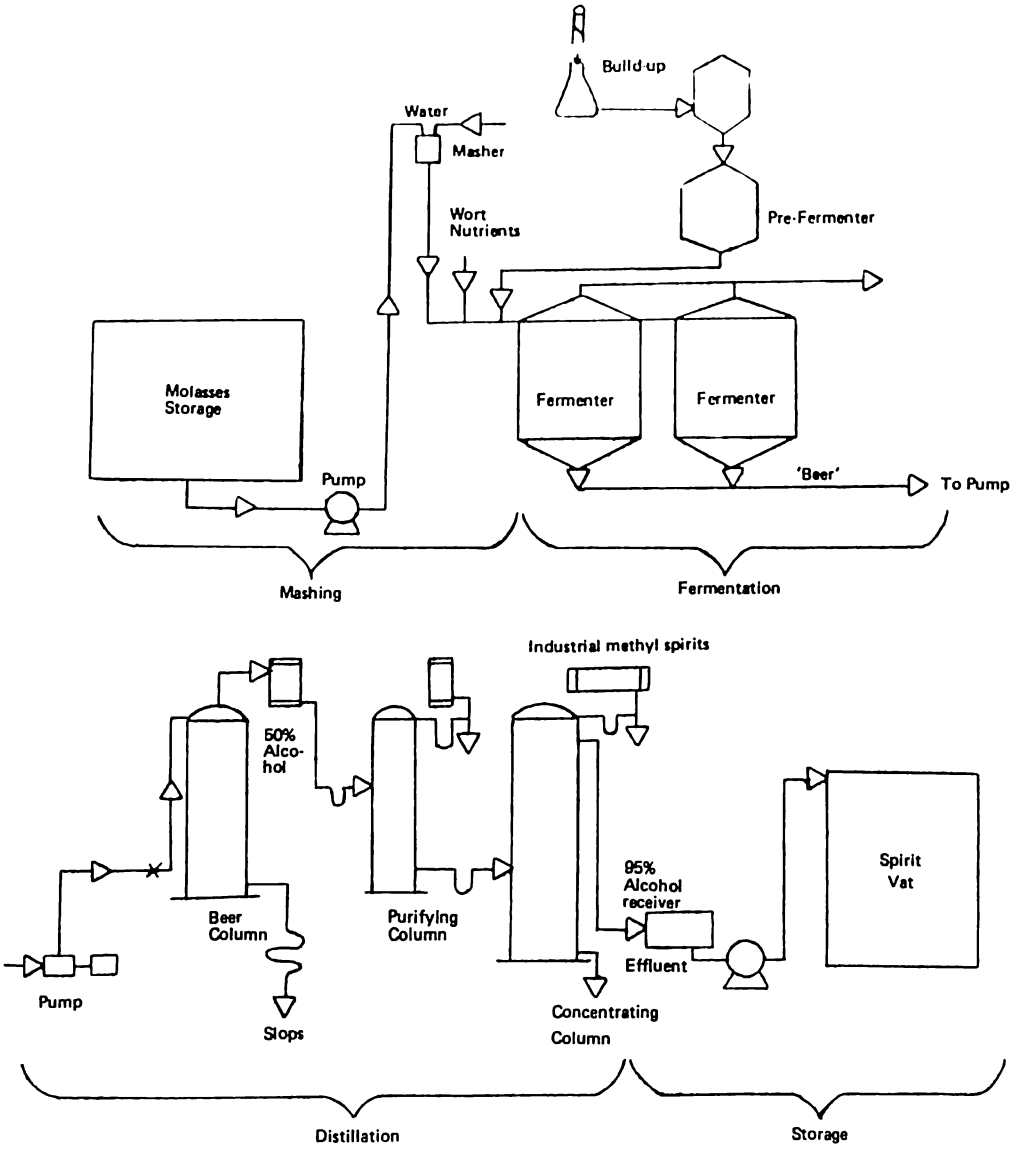


Figure 2. Flow diagram of the batch alcohol process.

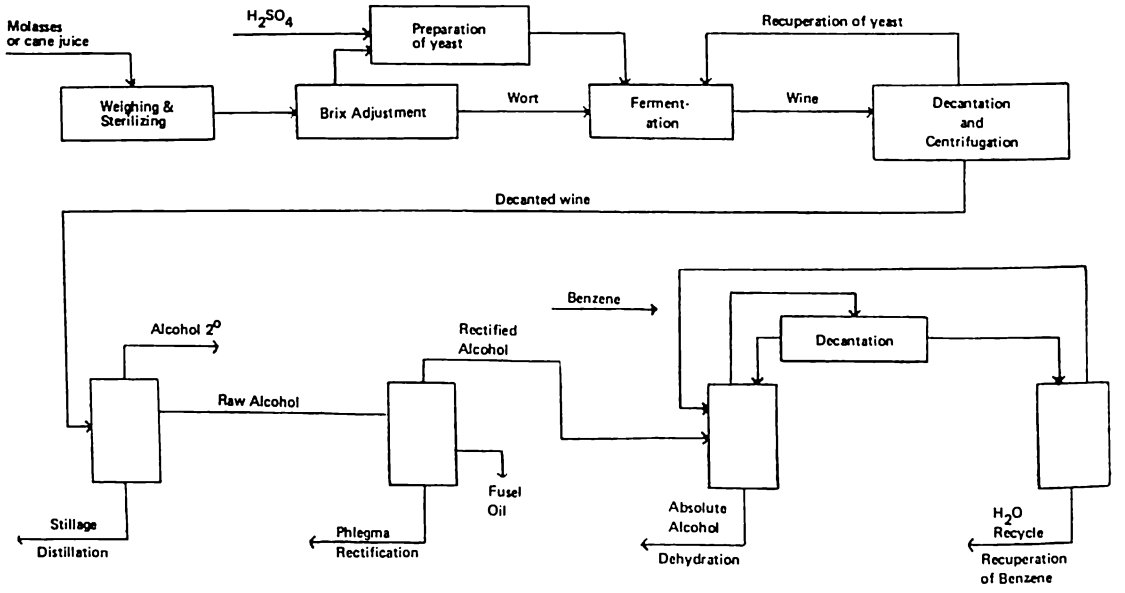


Figure 3. Block diagram of ethanol distillery (Lindeman and Rocchiccioli, 1979)

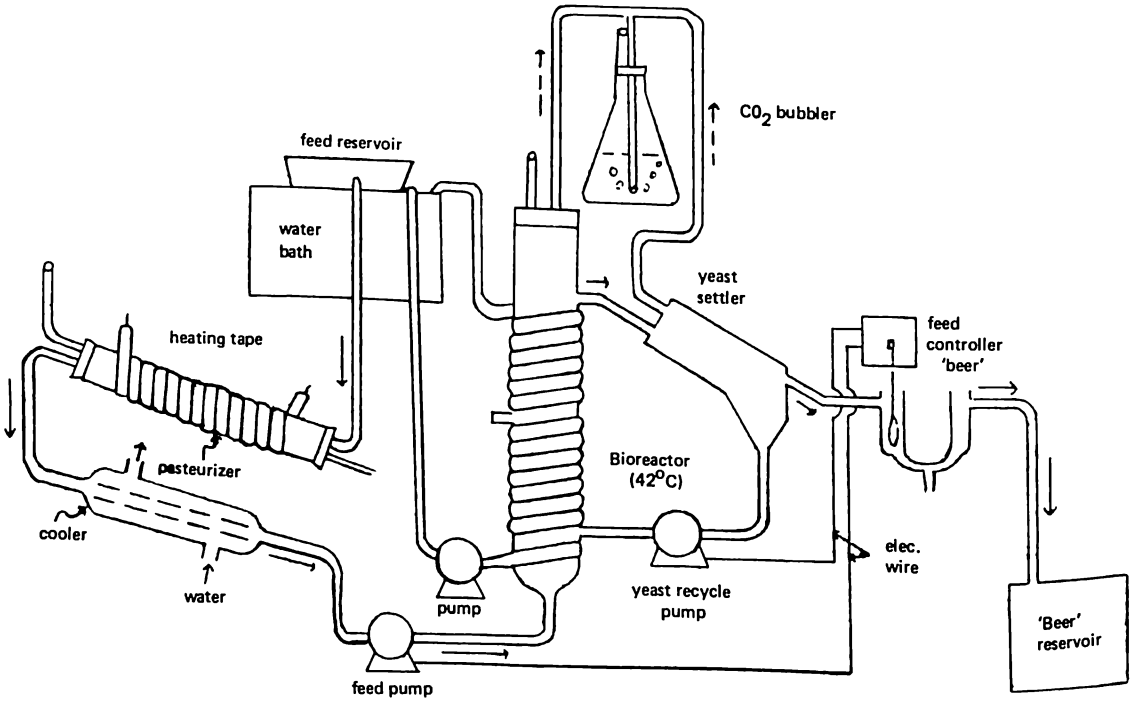


Figure 4. Set-up for continuous-flow ethanol fermentation

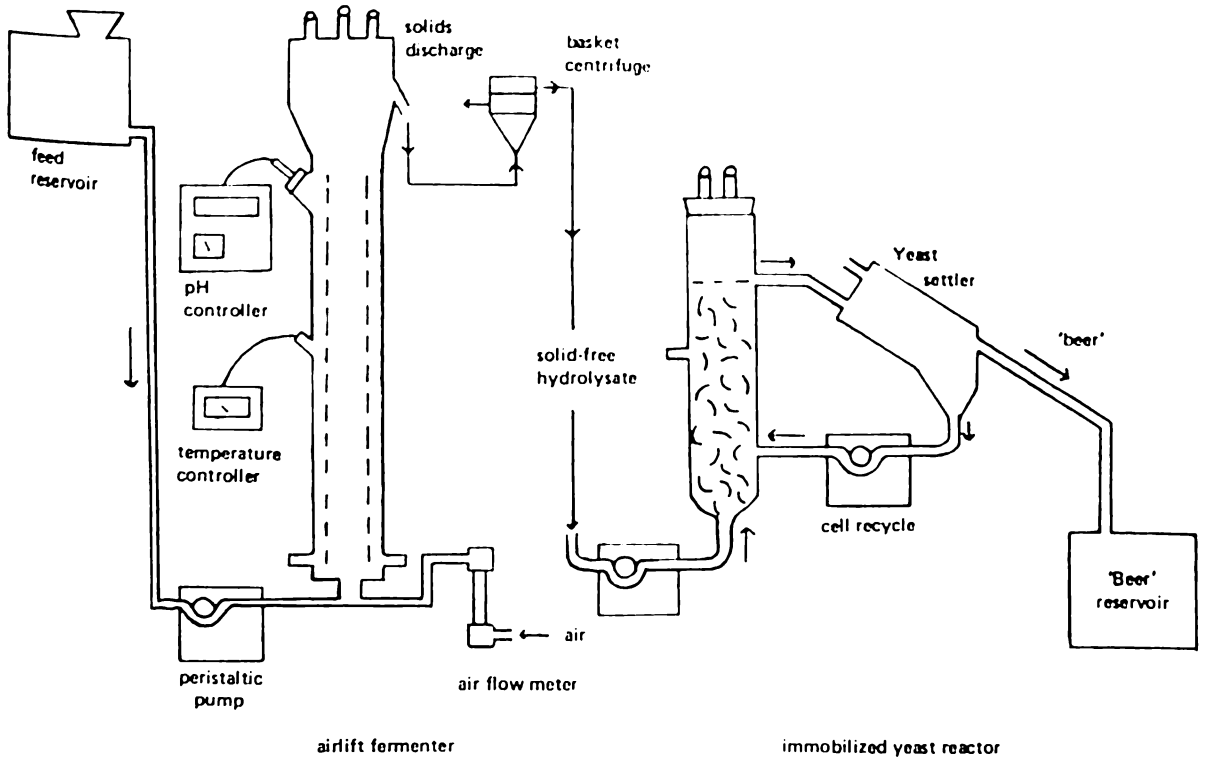


Figure 5. Two-stage process for ethanol production from alpha – amylase treated cassava or sweet potato root flour.

Table 1. Acid saccharification of some agricultural-by-products.

Material	Experimental Conditions	Yield of sugars (g/100g sample)	Ratio of sugars produced to polysaccharide content of material	Conc. of sugars in hydrolyzate (% /w/v)	Fraction of Sugars		Efficiency of hexose fermentation into alcohol (%)
					glucose & other hexoses	Pentose & other sugars	
coconut meat residue	5% H_2SO_4, 126°C, 3/1 ASR,* 1 hr.	54.3	0.6	17.4	0.75	0.22#	94
Sugarcane bagasse one-step	5% H_2SO_4, 126°C, 3/1 ASR, 1 hr.	39.0	0.6	12.0	0.29	0.61	–
sequential	2% H_2SO_4, 126°C, 3/1 ASR, 1/2 hr	22.5	0.3	9.2	0.25	0.69	–
	3/1 ASR, 1 hr	16.0	0.2	5.5	1.0	0.0	30
Rice straw	3% H_2SO_4, 126°C, 3/1 ASR, 1 hr	23.6	0.4	3.8	0.2	0.6	16
Rice hulls	2% HOl, 130°C, 3/1 ASR, 1/2 hr	24.5	0.4	22.4	0.2	0.8	78
Unripe banana fruits	2% H_2SO_4, 130°C, 2/1 ASR, 1/2 hr	55.8	0.8	21.0	0.70	0.25	97

*ASR = acid-to solid ratio (v/w)

#Di – and oligo-saccharides

Table 2. Yields of biomass and ethanol for some agricultural crops (estimated for Philippine conditions)

CROP	CROP CYCLE, days	Yield of FRESH CROP t/ha-season	t/ha-yr	ETHANOL YIELD* l/t	l/ha-yr
Saccharine:					
Sugarcane	360	50-100	50-100	67	3,350-6700
Nipa sap**			123-252	83	10,290-21,000
Coconut sap+			38-60	83	3,200-5,000
Sweet sorghum	120				14,000 ++
Starchy:					
Cassava	300	15-40	18-48	180	3,240-8,640
Sweet potato	100	15-40	54-144	125	6,750-18,000
Corn (maize)	110	1.0-5	3.3-16	400	1,320-6,400
Rice	120	1.8-6	5.4-18	420	2,270-7,560

*Based on complete ethanol recovery.

**Based on 700-1000 tappable fruit stalks per hectare, 0.7-1.0 liter of sap (14% sugar) daily per fruit stalk, continuous tapping for eight months each year.

+Based on 100-130 trees per hectare, 1.0-1.2 liters of sap (14% sugar) daily per tree and continuous tapping year round.

+ +Data for Texas and Lousiana conditions (Sachs, 1980).

Table 3. Balance of ethanol production (Pimentel, 1980)

Culture	Agricultural efficiency (ton/ha)	(ton/ha-yr)	Alcohol production (liter/ton)	(liters/ha)	(liter/ha-yr)
Sugarcane	72	54	66	4,752	3,564
Cassava	29	14.5	174	5,046	2,593
Sorghum	–	–	–	3,775	3,775

Energy produced (moal/ha-yr) alcohol	residues	Eout total	Energy consumed (moal/ha-yr) agricultural phase	industrial phase	Ein total balance	Energy ratio Eout/Ein
18,767	17,538	36,297	4,226	10,814	15,040 + 21,257	2.41
13,271	9,112	22,283	4,042	8,983	12,925 + 9,358	1.72
19,876	11,839	31,686	4,667	11,883	16,550 + 15,136	1.91

Table 4. Production costs for 50 million liters/year ethanol plant (Myers, 1982).

Item	Cost cents/liter	% of Production cost
Raw Materials	16.9	52.0
Utilities	4.6	14.1
Labor	3.0	9.3
Overheads	0.9	2.8
Maintenance	5.3	16.3
Packaging (Yeast by-product)	0.2	0.6
Marketing, Selling, Distribution	1.6	4.9
TOTAL PRODUCTION COST	32.5	100

Table 5. Capital cost breakdown for 50 million liters/year base case ethanol plant (Myers, 1982).

Item	Factor (%)	Cost ($ '000)
Purchased Equipment Cost (PEC)	100	10450
Installation	38	3971
Piping	31	3240
Instrumentation	13	1359
Electrical	10	1045
Building	29	3031
Plant Services	30	3135
Land	2	209
Site Improvements	5	523
TOTAL DIRECT COSTS (I)	258	26961
Project Management and Construction Expenses (Indirect costs)	54 of (I)	14389
TOTAL DIRECT PLUS INDIRECT COSTS (II)		41350
Contingency	20 of (II)	8250
TOTAL FIXED CAPITAL		49600

Table 6. Breakdown of ethanol selling price for case base 50 x 10^6 L/year ethanol plant (Myers, 1982).

	Item	Cost (cents/liter)
1.	Selling Price (Revenue) 20% ROI after tax	69.1
2.	Production Cost	32.5
3.	Profit before Tax	36.6
4.	Depreciation (7.5% of fixed capital	7.9
5.	Taxable Income (3-4)	28.7
6.	Tax (@46% of 5)	13.2
7.	Profit after Tax (return) (3-6)	23.4

Table 7. Parameters affecting the profitability of a 50 x 10^6 L/year ethanol plant (Myers, 1982).

Parameter		Variation in DCFR (%) from Base Case*	
		+20% parameter	−20% parameter variation
Production Costs	– overall production cost	−2.86	2.86
	– labor cost	−.26	.26
	– utilities cost	−.40	.40
	– maintenance cost	−.47	.47
	– raw material cost	−1.49	1.49
Capital Cost	– Fixed capital	−2.32	2.32
	– fermentation capital	−.10	.10
	– distillation capital	−.71	.71
Revenue	– Total revenue		
	– Ethanol selling price	5.31	−5.31
	– yeast selling price	− .14	−.14
Combined Areas	– plant scale	+1.04	−1.04
	– overall process yield	+3.39	−3.39
	– fermentation yield	1.73	−1.76

*The base case DCFR was calculated to be 15.66%

the former, takes into account the whole project life and the time value of money invested.

Results of sensitivity analysis for a 10^6 liters/year base case ethanol plant are given in Table 7 which shows the change in DCFR (or DCFROR) for a ± 20% change in a cost parameter. Thus, a 20% increase in production costs lowers the DCFR by 2.86% from the base case of 15.66% to 12.8%. The results show that the parameters most sensitive to project profitability are ethanol selling price, overall yield, distillation capital cost and plant scale. Research and development geared towards reducing costs in these areas would most effectively increase plant profitability. On the other hand, parameters which are not very sensitive are labor cost, utilities and maintenance costs, fermentation capital and yeast selling price. It is seen, therefore that sensitivity analysis is a useful and powerful tool for optimizing the economics of producing ethanol.

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