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ALCOHOL FROM BANANAS

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Abstract
Laboratory studies were conducted to assess the ethanol production potential from waste bananas. Over a 10-day ripening period, there was a 9% loss of fresh weight by day 6 and a 15% loss by day 10. Ethanol yields from normal ripe bananas were: whole fruit—0.091, pulp—0.082, and peel—0.006 l/kg of whole fruit. Ripeness effects on ethanol yield were measured as green—0.090, normal ripe—0.082, and overripe—0.069 l/kg of green whole bananas. Enzymatic hydrolysis was necessary for maximum yields. Dilution water was not essential for effective fermentation. Waste parameters of the banana stillage were measured. © 1996 Elsevier Science Ltd.

Key words: Alcohol fuel, alternative energy, bananas, biomass energy, ethanol, stillage.

INTRODUCTION

FAO (1990a) estimated worldwide banana production at 45 845 000 tonnes in 1990. Waste bananas have been estimated to range from 25 to 50% of total harvested production of the over 125 000 banana-producing hectares in South and Central America (Clavijo & Maner, 1974). Waste bananas are those that do not meet export standards due to size variation or blemishes or are the excess resulting from overproduction. Although the common practice of handling waste bananas is to dispose of them as garbage, they represent a potential energy feedstock which may be especially suited for ethanol production. Bananas grown for export are typically harvested and transported to a packing shed for grading. The grading rejects then require disposal. Because they have already been collected and brought to a centralized location, the waste bananas are a low-cost, concentrated biomass feedstock.

The composition of bananas is shown in Table 1. Bananas contain mostly carbohydrates, with only small amounts of fiber. The high nonstructural carbohydrate (NSC) and low fiber contents make bananas a good feedstock for ethanol production. The carbohydrate is nearly all starch when the bananas are harvested green, but rapidly converts to sugar during ripening (Clavijo & Maner, 1974). The primary sugars in bananas are glucose (19–22% of total sugars), fructose (12–17% of total sugars), and sucrose (62–68% of total sugars). At the same time, there is a loss of fermentable material due to native metabolic activity. By allowing the bananas to ripen before fermentation, enzymatic hydrolysis could possibly be eliminated, leading to a reduction in energy and input costs.

The NSC content of the bananas suggests that the fruit could be fermented without adding dilution water. Ideally, the sugar content of the unfermented

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Table 1. Banana composition from several literature sources

Parameter	Pulp[a]		Peel[a]		Pulp[b]		Whole fruit[c]	
	%ww	%dm	%ww	%dm	%ww	%dm	%ww	%dm
Dry matter	24.3		16.2		28.4		20.0	
Ash	0.8	3.3	1.9	11.7	0.8	2.8	1.0	5.0
Ether extract (fat)	0.2	0.8	1.4	8.6	0.3	1.1	0.2	1.0
Crude protein	1.1	4.5	1.0	6.2	1.2	4.2	1.0	5.0
Crude fiber	0.5	2.1	1.6	8.6	0.6	2.1	1.0	5.0
NFE (carbohydrates)	21.7	89.3	10.3	63.6	25.5	89.8	16.8	84.0

[a]NAS, 1972.
[b]FAO, 1990b.
[c]Clavijo & Maner, 1974.

mash should be about 15–25% (w/w); this will produce a beer of about 8–12% ethanol (v/v). Conversion of the structural carbohydrates to energy will probably not be feasible because of the small amounts contained within the fruit.

The objective of these studies was to assess the ethanol production potential from bananas and to study the parameters associated with ethanol production using bananas as feedstock.

EXPERIMENTAL DESIGN

The studies included determining the chemical characteristics of both the banana feedstock and the stillage remaining after fermentation.

First, dry matter and fresh weight changes and losses in bananas during a 10-day ripening period were examined. Bananas were sampled green (day 0), normal ripe (day 6) and overripe (day 10).

Secondly, the ethanol yield of ripe bananas and their components—pulp and peel—was investigated. The purpose of this was to assess the ethanol production capabilities from normal ripe bananas. Three replicates of whole banana and pulp fermentations were run, and one batch of banana peel was fermented. Ethanol yield from whole bananas at three stages of ripeness (green, normal ripe and overripe) was also investigated. There were two replications of green and overripe bananas and three of normal ripe bananas.

Thirdly, effects of enzyme addition on the ethanol yield from whole overripe bananas were determined. Three treatments were used: the standard enzymatic process (addition of alpha- and gluco-amylase), no enzyme addition but sterilizing the feedstock (using the standard cooking process described below but without adding enzymes), and no enzyme addition and no sterilization. For comparison, the same treatments were applied to whole green bananas. Two replications of each treatment/feedstock combination were run with two exceptions. Green/no enzyme, no sterilization had three replications, and overripe/no enzyme, no sterilization had one replication.

Finally, the last study focused on the effects of dilution water on ethanol production. In the standard fermenting process, dilution water was added to decrease the viscosity of the banana slurry and to ensure that glucose and ethanol inhibition did not limit the ethanol yields. However, based on the moisture and carbohydrate content of bananas, a banana slurry without the addition of dilution water would result in a posthydrolysis mash containing approximately 20% sugar, which is the maximum desired sugar concentration for optimum ethanol content in the beer. Three replicates of normal ripe bananas were fermented without the addition of dilution water and compared with the fermentations using the normal process with the dilution water.

METHODS

The bananas used during these studies were purchased at a local grocery store as needed. The bananas were selected according to the required degree of ripeness needed at the time of purchase. Occasionally, the bananas continued to ripen at room temperature until the proper degree of ripeness was obtained.

Banana characteristics

Several bananas were selected at random to be analyzed. The whole fruits were weighed and peeled. The pulp and peel were then weighed. The components were hand chopped, sampled and immediately frozen until analyzed. The components were tested for dry matter (DM), ash and volatile solids (VS) using procedures in *Standard Methods* (APHA, 1992). The characteristics of the whole fruit were calculated as a weighted average of the component parts based on their fraction of the whole fruit. Three to five replicates for each stage of ripeness were analyzed.

Several stillage samples were analyzed to estimate the stillage disposal parameters likely to be encountered. Stillage samples were taken from the normal ripe banana fermentations (whole fruit, pulp and peel). After distilling the beer, the amount of water removed during the distillation process was replaced. The stillage was then sampled and immediately frozen until analyzed. Before analysis, the samples were diluted 10:1 and processed in a blender to homogenize the particulate matter and form a slurry. The stillage was tested for total solids (TS), volatile solids (VS), ash and chemical oxygen demand (COD) in the Agricultural Engineering Department at Texas A & M University using procedures in *Standard Methods* (APHA, 1992). The following minerals were analyzed in the Soil Testing Laboratory at Texas A & M University: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) and sodium (Na).

Ripening losses

Fourteen bananas were purchased green, on the day they arrived at a local grocery store. Each individual banana was weighed. Four bananas were peeled and their components sampled. On day 6 (normal ripe), the remaining bananas were weighed again, and five were peeled and sampled. The remaining five were weighed again on day 10 (overripe), peeled and sampled.

Fermentations

The bananas were enzymatically hydrolyzed and fermented. The alcohol was then removed by distilling until no ethanol remained in the distillate (as measured by a proof and tralle hydrometer). The

Table 2. Analyses of banana components for three stages of ripeness

	Fresh wt, % whole fruit	DM, %	Ash, %DM	VS, %DM
Green peel	39.4	8.5	17.3	82.7
Green pulp	60.7	23.5	5.2	94.8
Green whole fruit	100.0	17.6	7.5	92.5
Normal peel	29.0	10.6	20.0	80.0
Normal pulp	71.0	21.3	13.5	86.5
Normal whole fruit	100.0	18.2	14.6	85.6
Overripe peel	22.4	14.4	21.0	79.0
Overripe pulp	77.6	19.3	24.7	75.3
Overripe whole fruit	100.0	18.2	24.1	76.0

distillate was collected, and the ethanol content was determined by density measurement (proof and tralle hydrometer) and corrected to 15.56°C. The cooking, fermenting and distilling were all batch processes conducted in 1000-ml flasks using 400–600 g of feedstock per batch. Commercial enzymes (Solvay Enzymes, Inc., Elkhart, IN) were used for starch hydrolysis. The alpha-amylase used was Takatherm II L-170, and the gluco-amylase was Diazyme L-200. Distiller's yeast for the studies was obtained from Alltech, Inc., Nicholasville, KY.

The standard cooking procedure was as follows. First, the banana feedstock was hand chopped and mashed with a pastry cutter. Water was added at a rate of 0.4 kg water/kg feedstock, and 1 g Takatherm/kg feedstock was also added. The mixture was then heated to 93°C for 60 min while being constantly stirred. Next, the mixture was cooled to 60°C and the gluco-amylase enzyme was added at a rate of 1 g Diazyme/kg feedstock. The mixture was held at 60°C for 60 min. Finally, the mixture was cooled to 35°C and distiller's yeast was added at a rate of 1 g yeast/1000 ml mixture. Variations in this standard cooking and fermention process were made when the various parameters affecting the ethanol yield were investigated.

The amounts of enzymes and yeast used were approximately double the optimum amounts recommended by the manufacturer so that any yield reduction would not be due to their limitations. After cooking, the beer was fermented for 72 h at 35°C. In commercial ethanol production, 72 h is about the maximum time used for batch fermentations. This time was used in these studies so that yield reduction would not result from insufficient time for complete fermentation.

RESULTS AND DISCUSSION

In general, no major problems were encountered during the laboratory fermentations. The tendency of the beer to foam during vigorous distillation caused one batch to have to be repeated with a smaller amount of feedstock.

Banana and stillage characteristics

Table 2 shows the composition of bananas at three stages of ripeness. It also shows the percentage of the whole fruit contained in the pulp and peel. The dry matter (DM) content, expressed as a percentage of the component, for the normal ripe bananas is similar to that reported in the literature (Table 1). The ash content, expressed as a percentage of dry matter, of the bananas used in the laboratory fermentations is considerably higher.

Several trends may be deduced from Table 2. The percentage of dry matter for the whole fruit over a 10-day ripening period increased slightly, which reflects some drying during the ripening. The dry-matter content of the peel increased substantially, probably due to more rapid drying. For the pulp, there was a slight decrease in the dry-matter content. This decrease was possibly caused by a loss of carbohydrate due to metabolic activity during ripening. The increase in ash and decrease in volatile solids during ripening suggests a loss of organic material. The change in the fresh weight distribution between the pulp and peel during ripening most likely resulted from a more rapid drying of the peel than the pulp.

The results of the stillage analyses are shown in Table 3. The stillage from this batch process is a high-strength organic waste, based on the chemical oxygen demand (COD) levels, and will need appropriate treatment and disposal. The stillage composition resulting from a continuous distillation process without the addition of dilution water would be somewhat different. However, these results should supply at least an order-of-magnitude estimation of the stillage composition to be expected.

Ripening losses

Fresh weight and dry matter losses over a 10-day period are shown in Fig. 1. There was a 6% loss of dry matter (DM) by day 6 and a 12% loss by day 10. This loss of total dry matter is likely due to metabolic activity during ripening. There was a slight increase in the dry matter percentage of the whole fruit by day 6 (Table 2), indicating that the increase due to drying is greater than the decrease caused by

Table 3. Analyses of stillage from banana components and whole fruit

	Peel, mg/l	Pulp, mg/l	Whole fruit, mg/l
TS	39500	36800	43500
VS	29400	28600	34400
Ash	10100	8100	9100
COD	42300	49300	53700
N	970	1710	1530
P	110	165	150
K	3800	2810	3830
Ca	100	100	100
Mg	100	200	150
Zn	4	3	6
Fe	23	16	18
Mn	2	1	2
Cu	2	3	5
Na	520	425	380

metabolism. There was no significant change in the dry matter percentage between day 6 and 10 (Table 2). This indicates that the percentage loss due to metabolism is approximately equal to the percentage increase due to drying.

During the ripening period there was also a considerable change in the fresh weight. There was a 9% reduction by day 6 and a 15% reduction by day 10. The reduction in fresh weight was due to losses associated with both the drying of the banana and the internal metabolic activity.

Fermentations

Normal ripe bananas

Ethanol yields from the normal ripe fermentations of the whole fruit, pulp and peel are shown in Table 4. The yields are shown per unit of fresh feedstock and per unit of fresh whole fruit. The maximum ethanol yield was obtained by fermenting the whole banana. While the average ethanol yield for the pulp was 0.116 l/kg of pulp, only 0.082 l/kg of whole bananas was produced. This difference is because the pulp is only 71% of the whole banana (Table 2). A

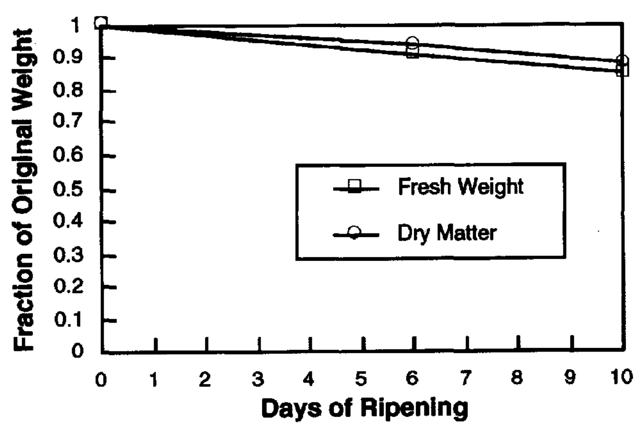

Fig. 1. Losses in dry matter and fresh weight in bananas (whole fruit) over a 10-day ripening period.

Table 4. Average ethanol yield from normal ripe bananas[a]

Feedstock	Whole fruit		Pulp		Peel	
	Avg	St. dev.	Avg	St. dev.	Avg	St. dev.
l/kg Fresh wt	0.091	0.005	0.116	0.017	0.019	
l/kg DM	0.499	0.027	0.543	0.080	0.181	
l/kg Whole fresh wt	0.091	0.005	0.082	0.012	0.006	

[a]Ethanol volume at 15.56°C.

greater yield of 0.091 l/kg of whole bananas resulted from fermenting the whole fruit. The yield from the peel was insignificant when compared to that of the whole fruit.

On a dry-matter basis, the yield from fermenting whole bananas was 0.499 l/kg dm, which is quite high compared to many other agricultural commodities. Badger *et al.* (1982) reported ethanol yields from a number of agricultural crops. Some typical ethanol yields (l/kg dm) they found were: corn—0.403, cull apples—0.406, cull irish potatoes—0.451, sweet potatoes—0.469.

Enzyme effects

The effects of enzyme addition and sterilization in green and overripe bananas (whole fruit) are shown in Fig. 2. The green bananas yielded poorly without the addition of enzymes. Actually there was a 65.4% difference between the standard process and the process without the enzymes. A large difference was expected since the majority of the carbohydrate in green bananas is in the form of starch. There was a further decrease in ethanol yield with the no enzyme/no sterilization treatment. The overripe bananas in the no enzyme treatment did ferment, but the yield was 13.4% lower than with the standard process. Again, very little ethanol was produced from the overripe bananas with the no enzyme/no sterilization process. A foul smell was produced when fermenting the overripe bananas, which indicated the growth of spoilage microorganisms. These results show that enzyme addition can result in significant improvement in the ethanol yield of both the green and the overripe banana feedstock.

Ripeness effects

Figure 3 shows the effect of ripeness and ripening losses on ethanol yield from the whole bananas. The maximum ethanol yield resulted from the green banana feedstock. Even though the yield per unit feedstock was slightly higher for normal ripe bananas compared to green bananas, the yield per unit weight of the original green bananas was higher when the bananas were fermented green. The yield of the overripe bananas was about 23% lower than that of the green bananas.

Dilution effects

The effect of dilution water on ethanol yield is shown in Table 5. The standard process used in the laboratory fermentations yielded slightly more ethanol per unit feedstock, but the difference was probably insignificant. These results show that effective fermentation of bananas can be achieved without the addition of dilution water. This would result in a higher concentration of ethanol in the beer and, therefore, a much lower energy input requirement for distillation. By not diluting the feedstock, the stillage volume would also be reduced. The concentration of the stillage components, however, would increase.

CONCLUSIONS

The highest ethanol yield, in terms of degree of ripeness, resulted from using green bananas as the feedstock. This is most likely due to the approximately 12% loss of dry matter and the 15% reduction of fresh weight during a 10-day ripening period. The highest ethanol yield, in terms of component of fruit, was obtained from fermenting the whole fruit. In order to obtain maximum ethanol yield, enzyme hydrolysis was required, even for overripe bananas. Dilution water was not required for effective fermentation. Banana stillage was found to be a

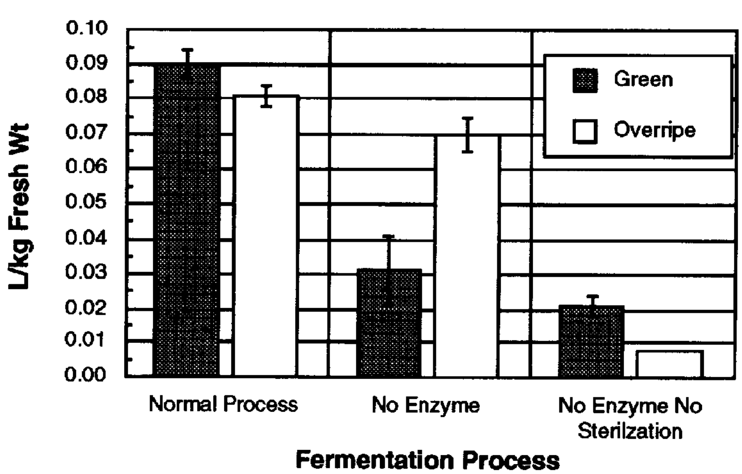

Fig. 2. Effect of enzyme addition on ethanol yield (ethanol volume at 15.56°C).

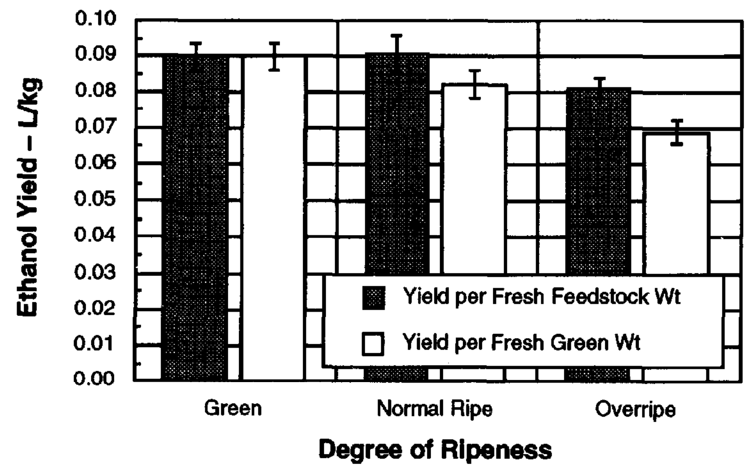

Fig. 3. Effect of stage of ripeness for ethanol yield (ethanol volume at 15.56°C).

Table 5. Average ethanol yield as affected by dilution water[a]

	Standard process		No dilution	
	Avg	St. dev.	Avg	St. dev.
l/kg Fresh wt	0.091	0.005	0.088	0.006

[a]Ethanol volume at 15.56°C.

high-strength organic waste, and concentrations would be higher if dilution water were not added.

Using waste bananas for ethanol production appears very promising. Ethanol yield (on a dry-weight basis) from bananas is higher than from most other agricultural commodities. The bananas currently are treated as a waste and, as such, represent a very low cost feedstock. They ferment well and have a high carbohydrate concentration. Waste bananas are already collected at packing areas, and therefore transportation/harvesting costs will be minimal. Dilution water requirements are very low, and fermentation results in a high concentration beer that would minimize distillation energy costs.

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