tion exists for converting the grain to anhydrous, fuel-grade ethanol.

Use of potatoes, sugarbeets, sugarcane, or molasses also results in energy output-to-input ratios quite close to 1.0. Characterization and utilization of the fermentation by-product from sugarcane and molasses will probably improve their energy ratios. Additional energy-saving innovations, including use of feed by-products in wet form increases the energy ratio to 1.0 to 1.5 for the grains, potatoes, and sugarbeets.

The most favorable energy balance occurs with use of cellulosic residue as the feedstock, largely because no energy is charged for crop production and because usable by-products are obtained from the hemicellulose and lignin. With the attractive energy balance feature of this approach, commercialization will depend on adequate pilot-scale demonstration and economic feasibility.

Since it is fossil energy input that is critical and, thus, counted in the energy balance for ethanol production from biomass, any use of renewable, nonfossil fuel would improve the energy balance. Other researchers have shown that recovering 50 percent of the corn field residue (stalks, cobs, and husks) for their energy value could supply a conversion energy input of 83,000 Btu per gallon of ethanol produced. If this practice could be made economically feasible for year-round operation, and if soil quality were not affected, use of corn field residues would improve the ethanol energy balance considerably. Based on our analysis, 50 percent of field residue could supply the energy requirement for feedstock preparation, distillation, by-product recovery, and miscellaneous. Thus, the ratio of energy output to input (fossil) for corn would increase to a range of 1.8 to 3.1.

Sugarcane juice or molasses as the feedstock would provide the opportunity to use sugarcane bagasse for fuel. In normal processing of sugarcane to refined sugar, sufficient bagasse is available to produce steam for a plant to convert the molasses to ethanol. For the time bagasse is available to provide steam for a molasses-to-ethanol plant, the energy output-to-input (fossil) ratio would be 1.1 to 2.0. If the sugarcane were used directly to produce ethanol via sugar juice, the bagasse could provide enough steam for the conversion process. Thus, the energy output to input (fossil) ratio would increase to 2.0 to 4.0.

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Crop feedstocks for fuel alcohol production

Roy M. Sachs

Ideally, economic analyses and decisions concerning complex agricultural-industrial systems, as represented by crops to fuel alcohol, should be made from systems in operation and not merely from computations found in this article. Currently fuel-grade, fermentation ethanol sells for about $1.75 per gallon in the United States. The computed costs in table 3 are considerably below this value and, hence, must be examined closely in systems in operation. Such important data were not available to the author at the time of manuscript preparation, and interested readers are urged to inquire further.

Ethyl alcohol is now produced in the United States by fermentation of high-starch-containing crops, foremost among which are the cereal grains and especially corn. Other good sources are potato, sweet potato, yam, Jerusalem artichoke, and cassava (used in Brazil). Sugarcane, sugarbeet, sweet sorghum, and fodder beet (mangold) give higher alcohol yields per acre than the starch crops, but grains have been the main source of alcohol.

Alcohol itself may be regarded as a by-product. The "food and fuel" concept is predicated on the fact that the overall nutritional value of crops is improved even as their carbohydrate content is reduced in the fermentation process. Most of our corn, many other grains, and many crop by-products are used for animal feed. When the bulk of the readily digested carbohydrates are removed from the grains, the residual spent grain, with increased protein concentration and other benefits derived from the yeast organism, finds it way into the feed market at prices almost equal to those of high-protein seed meals. Carbohydrate supplements to animal feeds are then derived from lower priced hay or forage crops. Malt and yeast supplements also work well in human nutrition, and brewer's spent grains may find use in breads and other products.

The crops

Almost all yield data in this presentation come from the California Crop and Livestock Reporting Service. These are average yields for 1978; they are well below those which many growers achieve and below those used by many analyses for biomass-to-fuel computations.

The data for Jerusalem artichoke, fodder beet, and sweet sorghum are from small-scale trials in Canada, New Zealand, and Texas/Louisiana, respectively; they should be compared, in all justice, with high-value data for other crops grown under similar conditions. The high values for fodder beet do not seem unreasonable, even though we have little information on the inputs required to obtain these yields. They are the averages for nonirrigated trials with 20 different cultivars, and one expects the yields to be significantly greater with irrigation. Four small irrigated plots of Jerusalem artichoke in Davis have yielded as much as 33 tons per acre (average 26.5 tons per acre) of tubers in about 110 days with a July 1 planting date. We expect to obtain higher yields with an earlier planting date.

Among the widely grown crops in California, the sugarbeet has by far the best potential alcohol yield—600 to 700 gallons per acre. Irish potatoes and corn follow at 400 and 360 gallons per acre, respectively. Grain sorghum may yield much more in some areas and would then be competitive with corn. The alcohol yields were computed by assuming that 13.6 pounds of fermentable materials will yield 1 gallon of alcohol (147 gallons per ton fermentables), a yield used by the Battelle Institute, a private research organization in Columbus, Ohio, and somewhat higher than that used by the U.S. Department of Agriculture and other laboratories.

If sweet sorghum were introduced into California, it could make a strong, perhaps the best, contribution to fuel alcohol production. Most varieties are quick crops, maturing in 110 to 130 days in Texas and Louisiana, and would presumably perform equally well in many California locations. The alcohol yield of nearly 500 gallons per acre is far better than that for corn, and the potential by-product credits are significantly greater, too.

By-products

By-products loom large in the use of food crops for alcohol production. Very large quantities will be produced if we pass more of our grain crop through the fermentation process. Beet pulp and brewer's grains from the sugar and beer industries are already produced in large amounts in California. They draw a good price.

It is likely that adding the single-cell protein (largely from the yeast) to the fermentation residue (stillage) after beet press juice fermentation would make the stillage quite valuable. Stillages remaining after fermentation of sugarcane and sorghum press juices are estimated at $60 per ton.

These stillages have high salt concentrations and require special handling if they are dried or, if wet, must be sold close to the fermentation plant. Thus there are significant problems and research opportunities in developing by-product markets for stillage with or without the added yeast.

Yeast production will increase enormously if fuel alcohol from fermentation becomes a major industry. Its human nutritional value is unquestioned, but for the present we have very little idea of how much the market could absorb. As much as 108 pounds of yeast (dried) will be produced per ton of fermentable sugars.

Fibers from sweet sorghum can be used in the paper and fiberboard industries. If the crop is successful in California, very large quantities of fibers will be produced, nearly 8 tons per acre of fibers suitable for paper and 9 tons per acre for fiberboard. Another 12 tons per acre of silage will be produced, which will become useful as a feed supplement if more of our grain supplies are passed first through a fermentation process. Thus, the by-product credits for sweet sorghum may exceed the credit for the alcohol produced.

By-product values for fodder beet, Jerusalem artichoke, potatoes, and sweet potatoes may be expected to reflect the protein content of the pulp and stillage from the press juice (or starch hydrolysate) and be similar to the value for sugarbeets. Distiller's grain has at least twice and up to three times as much protein as beet pulp or stillage. But the important values concern the increased protein concentrations found within a crop after it has passed through the fermentation (press juice) process. Protein concentration increases at least twofold in the grains and sixfold in sugarbeet pulp. Jerusalem artichoke pulp should contain

TABLE 1. Average Crop Yields and Characteristics, 1979

Crop	Yield* Calif. total	Per acre	Moisture†	Fermentables‡	Fermentables per acre	Alcohol production Per acre	Per ton
	1,000 tons	*tons*	%	%	*tons*	*gal*	*gal*
STARCH CROPS							
Dry grains: warm season							
Corn	991.4	3.52	12.9	70.3	2.47	363	103
Sorghum	367.8	1.98	12.8	69.8	1.38	202	102
Rice	1,312.4	2.63	9.7	67	1.76	259	98
Dry grains: cool season							
Wheat	1,374.8	1.91	10.6	71.6	1.37	201	105
Barley	1,094.0	1.43	9.6	66.9	0.96	140	98
Oats	91.4	0.768	7.7	60.7	0.47	69	90
Tubers, tuberous roots							
Potato	892.7	15.6	79	17.3	2.70	396	25.4
Sweet potato	68.0	8	71	24.7	1.98	291	36.4
Jerusalem artichokes§	—	23.2	78.7	18	4.17	613	26.5
SUGAR CROPS							
Sugarbeet	4,778.0	24.5**	78	15.5-16.5	3.80-4.04	559-594	22.8-24.3
Fodder beet (mangold)	—	49.9††	85	10.5	3.80	770	15.5
Sweet sorghum	—	39.8‡‡	64	8.3	3.3	485	12.2

*As much as possible, average yields for California are given. Assumption: 13.6 pounds fermentables required per gallon of alcohol produced.
†All data derived from J. H. Martin and W. H. Leonard, 1967, *Principles of Field Crop Production*, 2nd edition, New York: The Macmillan Company.
‡Variety of sources.
§Composite values: yields from an experiment at U.C. Davis: moisture percentage from Martin and Leonard.
**State average.
††Experimental high value, New Zealand.
‡‡Experimental high value, Louisiana.

TABLE 2. By-products with Economic and Nutritional Values

Product	Amounts produced in alcohol production	Market value/ton	Nutritional qualities Moisture	Ash	Protein	Fiber	Digestible carbohydrates	Fat
		$	%	%	%	%	%	%
Brewer's, distiller's grains	0.33 ton/ton grain (corn)	130	7.9	4.1	20.7	17.6	42.5	7.2
Dried grains (all grain crops)	—	—	7.7	4.3	25.4	16.0	40.3	6.3
Yeast	0.054 ton/ton fermentable carbohydrates (all crops)	—	5	6	39.3	—	39.3	1.1
Stillage	1 ton/ton press juice	60	9	25	15	—	39	—
Beet pulp (also sugarbeet, potato Jerusalem artichoke	0.1 - 0.3 ton/ton sliced beets	120-140	9.2	3.2	9.3	20.0	57.5	0.8
Sweet sorghum								
Rind fiber (stalks)	0.2 ton/ton crop	40						
Pith fiber (stalks)	0.2 ton/ton crop	30						
Silage (grain, leaves)	0.31 ton/ton crop	40						

TABLE 3. Sample Costs of Crop Production and Computed Costs per Gallon of Alcohol, 1978-1979

Crop	Production cost/acre	Crop yield/acre	Alcohol yield/acre	Cost/gal. alcohol (feedstock)	By-product credit/acre	Cost/gal. alcohol With by-product credit	With manufacturing costs of $0.60/gal*
	$	*tons*	*gal*	*$*	*$*	*$*	*$*
Corn	425	3.5	361	1.18	140	0.78	1.38
Grain sorghum	395	2.5	256	1.54	100	1.17	1.77
Rice	500-600†	3.1	305	1.64-1.97	—	—	2.24-2.57
Wheat (irrigated)	345	2.0	210	1.64	84	1.25	1.85
Barley (dryland)	115	1.35	133	1.02	56.70	0.44	1.04
Potato	2,465	18.75	477	517.00	—	—	—
Sweet potato	1,820	7	255	7.14	—	—	—
Sweet sorghum	400-600‡	39.8	485	0.83-1.24	300	0.21-0.62	0.81-1.22
Sugarbeet	675§	30§	728**	0.93	360-420	0.36-0.45	0.96-1.35

*Manufacturing costs of $0.60 per gallon are assumed to apply for large-scale alcohol production facilities of 10 million gallons per year and above, as well as for much smaller scale operations of about 50,000 gallons per year. If the alcohol production facility is attached to an existing sugar mill, manufacturing costs for alcohol production from sugarbeets may be reduced substantially to $0.40 per gallon or less.
†Butte and Glenn counties.
‡Estimated.
§Madera County.
**At 16.5 percent fermentables.

about 15 percent protein (compared with 2.5 percent for the fresh tuber) and, for that reason, will probably have a higher market value than sugarbeet pulp.

Production costs

Labor, material, equipment, fuel, management, and harvest costs differ among crops. Some representative values for selected areas in California indicate that these costs are the largest part of the cost of alcohol produced. A Battelle Institute report on sugarbeets for alcohol uses a 35-ton-per-acre yield at $595 for production in a California coastal valley, presumably Monterey County, whereas we have used 30 tons per acre at $675 for Madera County. This difference in location makes a substantial impact on the cost of alcohol if one assumes the same percentage of fermentables in the beets. The higher overall yields were accompanied by somewhat less fermentable sugars, such that the computed alcohol yields are only 6 percent greater (772 compared with 728), but at $595 per acre instead of $675, the per-gallon feedstock cost of alcohol is now 22 percent less—$0.77 instead of $0.99.

Since 1974, production costs have more than doubled for potatoes, corn, sorghum, wheat, and rice, but changed very little for barley and sugarbeets. Special practices or labor-intensive operations for some crops but not others may ultimately be of major significance in determining what feedstocks will be used for fuel alcohol.

The high costs per acre for Irish and sweet potatoes must reflect the fact that considerable labor is invested at harvest in sorting and selecting fresh-market-quality potatoes. The culls, an unknown fraction of the reported yield, would be used for alcohol production.

The computed costs of alcohol are based on several computed values—not necessarily on systems in operation. Average yields, average percentage of fermentables, estimated by-product credits, and estimated production costs contribute to a very uncertain final price. A production cost of $0.60 per gallon can be found for very large and relatively small production facilities. For this reason the values given must be regarded as "conversation prices" only—ballpark figures. Nevertheless, they clearly indicate that rice and potato (Irish or sweet) will not find their way into the fuel alcohol feedstock market unless production costs decline markedly, yields are substantially higher, or both.

If Jerusalem artichoke and fodder beet production costs are similar to those for sugarbeet—a reasonable assumption—they are both good candidates for fuel alcohol feedstock.

We can produce about $1.00-per-gallon alcohol with sugarbeet and barley as feedstocks. Sweet sorghum may be equally good. Corn at $1.38 per gallon is still a promising candidate—particularly as liquid fossil fuel prices rise.

TABLE 4. Energy Inputs for Crop Production and Caloric Value of Crop Produced

Crop	Input (dried)	Output (caloric content of crop)	Output/input
	1,000 Kcal per ton		
Corn	1,027.3	3,338.4	3.25
Grain sorghum	1,188.3	3,011.84	2.53
Rice	1,289.3	3,293	2.55
Wheat	563.3	3,020.9	5.36
Barley	479	3,166	6.6
Oats	776.7	3,541	4.56
Potatoes	325.4	689.46	2.12
Sugarbeets	850.9	3,492.6	4.1

TABLE 5. Fruit and Vegetable Crop Production and Potential Alcohol Production

Crop	1977 Calif. production	Cull	x Fermentables =	Fermentables	Alcohol
	1,000 tons	*1,000 tons*	*%*	*1,000 tons*	*1,000 gal*
Apples	260	26	11.7	3.04	447
Apricots	123	12.3	12	1.48	218
Berries (bush)	4	0.4	13	0.05	7.35
Carrots	430	43	6-8.2	2.58-3.53	380-519
Cherries	14	1.4	12.8	0.18	26.5
Dates	22.5	2.25	63.4	1.43	210
Figs	27.7	2.77	20.3	0.56	82.3
Grapes (table, raisin)	2,179	217.9	16.5-17.4	35.95	5,280
Melons	666	66.6	4-5	2.66	391
Nectarines	148	14.8	9	1.33	196
Oranges	1,575	157.5	8.6-9	13.54	1,990
Peaches, whole	815.5	81.55	8.4	6.85	1,010
Nectar			12.4		
Pears	288.2	28.82	13.9-15.3	4.01	589
Plums	154	15.4	11.5-16	1.77	260
Potatoes	892.7	89.3	17.3	15.45	2,270
Prune-type plums	131	13.1	18.6	2.44	358
Strawberries	256.9	25.69	8	2.06	303
Sweet potatoes	68	6.8	24.7	1.68	246
Tangerines	56	5.6	8.6	0.48	71
Tomatoes	7,018.5	702	4.3	30.2	4,664
TOTALS	15,130.0	1,513		128.68	18,900

Energy input/output

There should be no question that we are seeking to replace fossil fuels with renewable fuels—*we want a system that gives a net gain in liquid fuels*. Ethyl alcohol produced by fermentation of crops meets this objective well if, and only if: (1) minimum inputs are used in crop production, (2) advanced designs are used in the fermentation/distillation facility, and (3) biomass and other solar sources are used, insofar as possible, to fuel the system.

Selecting crops as feedstocks for fuel alcohol on the basis of minimum liquid or gaseous fossil fuel consumption is a reasonable objective. Large differences exist among the major field crops in fuel requirements for production; barley is once again a leading candidate.

Additional fossil fuel requirements for transporting crops to fermentation facilities and for by-product recovery are very difficult to estimate for all crops. If biomass residues are used to fuel some of the preparation/distillation operations in the corn-to-alcohol system, 1 gallon of liquid fuel is gained for every 2 gallons consumed. In this instance, the energy content of the distiller's grain (expressed as liquid fuel), required to grow an equivalent amount of corn for feed, is included in the computation.

Use of biomass residues to fuel farm operations will further reduce fossil fuel requirements for production. It seems clear that replacing fossil fuels with renewable ones requires a systems approach to the utilization of biomass.

Culls as feedstock

Fruit and vegetable production practices in California cannot deliver 100 percent of the crop to market. Selection for quality necessarily rejects at least 10 percent of the reported production. Both in the field and at the packing sheds relatively large quantities of high-sugar- and starch-containing cull fruit and vegetables are a potential, low-cost feedstock for fuel alcohol. Considerably more than 10 percent of some crops, such as potatoes, melons, and tomatoes, is lost in the field or at the packing/processing plant; probably no waste is available in other crops, such as grapes and pears, because the wine and liqueur industries already scavenge for discards.

The price of culls will vary considerably; some may be gratis but it is likely that, if a fuel-alcohol industry develops in California, this resource will be quickly recognized and prices will increase sharply. Moreover, the resource may disappear!

Whatever the feedstock price, the potential alcohol production from culls is well over 10 million gallons annually. Although this represents no more than a tenth of a percent of the liquid fuels consumed in California, it can make a large contribution to fuel supplies in some counties.

Summary

Which are the candidates for fuel alcohol?—Current: barley, sugarbeet, corn, cull fruit and vegetables. Potential: sweet sorghum, fodder beet, Jerusalem artichoke.

What is the computed price per gallon?—$1.00 to $1.50.

How much alcohol can be produced annually at $1.00 to $1.50 per gallon in California?—100 million gallons from barley, 100 million gallons from corn, 120 million gallons from sugarbeet, plus more than 10 million gallons from cull fruit and vegetables at a much lower cost.

How much does this represent of total gasoline consumed in California?—Taking the total for barley, sugarbeet, and corn, more than 3 percent.

Does fuel alcohol production from these crops detract from food supplies?—No! Animal feed mixtures will be altered; sucrose will come from other sources.

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The distillation of alcohol for fuel

Lynn A. Williams

Alcohols are simple chemical compounds consisting of carbon and hydrogen (hydrocarbon) chains that contain one or more added hydroxyl (hydrogen plus oxygen) groups.

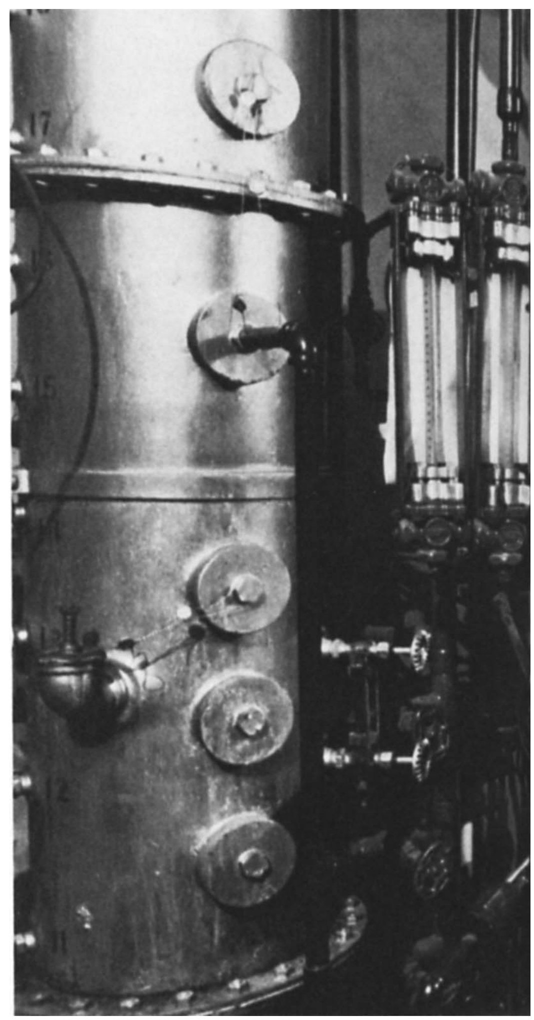
Methanol, the simplest alcohol, was previously distilled from wood but is now produced entirely chemically by the catalytic reforming of gaseous carbon monoxide and hydrogen. Most of the feedstock now comes from partial oxidation of methane (natural gas), but in the future methanol probably will be produced from coal or perhaps woody biomass by a process requiring capital-intensive high technology.

Ethanol production is one of the oldest chemical processes known to man. Early in this century the main source of industrial (nonbeverage) ethanol was fermentation, but nearly all is now produced by chemical processes under heat and pressure; the processes are based on ethylene, a petrochemical derived from natural gas or heavier petroleum fractions.

Fermentation

Fermentation is a simple biological conversion of sugar into ethanol and carbon dioxide. The basic materials for ethanol production are simple sugar molecules, such as glucose or fructose, found in most fruits. They are readily fermented by yeast to alcohol. Sucrose (table sugar) is a more complicated type of carbohydrate found in sugarcane or sugarbeets, but also is readily fermented.

Starch, the storage carbohydrate found in seeds, grains, and tubers, has a more complex structure and must be cooked and then broken down by enzymes or mild acid treatment before fermentation. Cellulose, an abundant carbohydrate, is more difficult than starch to break down because of the lignin content. It can be done, although the economics of cellulose breakdown are at present somewhat unsettled.



Pilot-scale continuous column still at U.C., Davis, operated here by Lynn Williams.