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Preprocessed Barley, Rye, and Triticale as a Feedstock for an Integrated Fuel Ethanol-Feedlot Plant

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ABSTRACT

Rye, triticale, and barley were evaluated as starch feedstock to replace wheat for ethanol production. Preprocessing of grain by abrasion on a Satake mill reduced fiber and increased starch concentrations in feedstock for fermentations. Higher concentrations of starch in flours from preprocessed cereal grains would increase plant throughput by 8–23% since more starch is processed in the same weight of feedstock. Increased concentrations of starch for fermentation resulted in higher concentrations of ethanol in beer. Energy requirements to produce one L of ethanol from preprocessed grains were reduced, the natural gas by 3.5–11.4%, whereas power consumption was reduced by 5.2–15.6%.

Index Entries: Cereal grains; preprocessing by abrasion; ethanol yield; mass balance; energy.

INTRODUCTION

High-yielding Canadian Prairie Spring (CPS) wheat varieties are used as raw material for fuel ethanol production in Western Canada. Local availability and a high starch content make CPS wheat the feedstock of choice. However, in 1995–96, the decline in the world wheat reserves and predictions of low winter wheat yields in the United States pushed prices of wheat to US $4.70/bu (1). Thus, wheat became too expensive for fuel ethanol production.

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Other cereal grains, triticale, rye, and barley, are traditionally lower priced than wheat; their 1995–96 prices ranged from US $110 to $120/tonne *(1)*. Two of these grains, triticale and rye, are comparable in starch content to wheat, whereas barley is substantially lower because of the presence of hull *(2)*.

Preprocessing of wheat was reported to remove bran fiber and to concentrate starch for fermentation *(3)*. The present investigation describes preprocessing of barley, rye, and triticale by abrasion and the effect of fiber removal on concentration of starch in flours from the preprocessed grains. Ethanol concentrations and yields, mass balance and composition of products, and the influence of preprocessing on plant throughput and energy requirements are described.

MATERIALS AND METHODS

Cultivars selected for the study included cereal grains commonly grown in Western Canada and available for processing to ethanol. The grains were: Prima fall rye, CDC Dolly 2-row barley and AC Copia triticale.

A Satake abrasive rice mill, model TM05 (Satake Co., Japan), equipped with a medium coarse-grain stone, was used to evaluate the influence of grain preprocessing on chemical composition, ethanol yield, plant throughput, and energy requirements. Cereal grains, conditioned to 12.5% moisture content, were abraded on the Satake mill for 55 s at stone speed of 1450 rpm. The preprocessed grains (containing mainly endosperm) were separated from fines that were further separated on screens into bran and flour for rye and triticale, and into hulls—bran and flour for barley. The separated flours were combined with preprocessed endosperms.

At each stage of preprocessing samples of grain, preprocessed endosperms, bran and hull-bran fractions were collected, ground, and passed through a 60 mesh screen before chemical analysis and fermentations. All chemical analyses and fermentation experiments were duplicated.

Ground grains or preprocessed flours (Fig. 1) were dispersed in water, ratio of grain or flour to water being 1:3. The alpha-amylase enzyme, Maxaliq (International Bio-Synthetics, Charlotte, NC), was added to the mash in two portions, each at a concentration 0.4% (v/w enzyme to grain/flour). Starch hydrolysis with the first portion of enzyme was carried out at 95°C for 45 min. After lowering the temperature to 80°C, the second portion of enzyme was added and liquefaction was continued for an additional 30 min. Grain or flour mash was then transferred into a jacketed fermenter (Wheaton Scientific, Millville, NJ) containing 0.4% yeast extract (AYE 2200). Saccharification with Allcoholase II (Alltech Inc., Nicholasville, KY) was carried out at 30°C for 30 min at an enzyme concentration of 0.8% (v/w enzyme to grain/flour). Inoculum (10^7 cells/mL mash) of *Saccharomyces cerevisiae* yeast (Alltech Inc., Nicholasville, KY) was added to mash cooled to 27°C. Fermentations were carried out for 72 h.

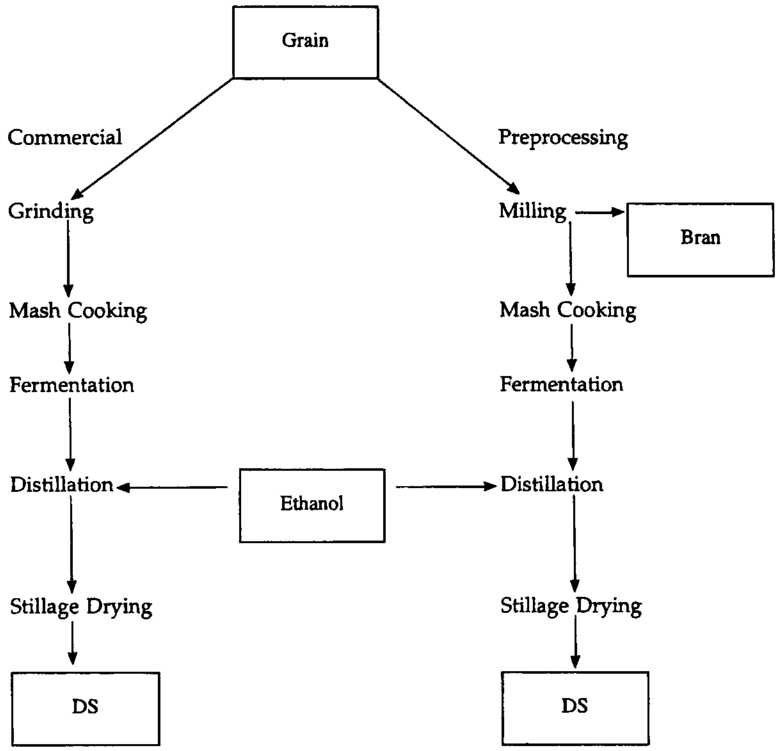

Fig. 1. Ethanol production process.

Ethanol was distilled from beer and the concentration of ethanol in the distillate was measured by an alcohol dehydrogenase assay, Kit # 332-A (Sigma Chemical Co., St. Louis, MO). Stillage was freeze-dried for further analysis.

Samples of grain, preprocessed flours, bran or hull-bran fractions, and dried stillage (DS) were analyzed by standard AACC *(4)* procedures for moisture (Method 44-15A), crude protein (Method 46-13) and crude fat (Method 30-25). Protein contents of samples were calculated using the nitrogen-to-protein conversion factor of 5.7 *(5)*. Starch in grains, flours, and dried stillage was measured as glucose after hydrolysis with alpha-amylase and amyloglucosidase, following the procedure of Budke *(6)*. Total dietary fiber (TDF) was quantitated by the enzymatic gravimetric method of Prosky et al. *(7)*.

Economic evaluation of ethanol production from the preprocessed cereal grains and energy requirements for the process were carried out using a computer program developed for a small-scale ethanol plant. Data to create the computer program included equipment energy requirements, commercial and experimental process conditions, e.g., temperature, time of treatment, amounts of grain and water, and so on.

Table 1
The Influence of Grain Class and Grain Preprocessing on Ethanol Concentration in the Beer

Grain class and product	Protein	Starch	Ethanol concentration		Fermentation efficiency
	--- % as is ---		% w/v	% v/v	%
<u>Grain</u>					
Fall rye	8.8 ± 0.1	56.1 ± 0.6	9.5 ± 0.6	12.1 ± 0.7	91.6 ± 0.7
Triticale	11.4 ± 0.2	55.6 ± 0.4	9.5 ± 1.0	12.0 ± 1.1	90.8 ± 1.1
2-row barley	10.2 ± 0.3	51.7 ± 0.5	8.8 ± 0.8	11.1 ± 0.9	89.2 ± 0.8
<u>Flour</u>					
Fall rye	8.2 ± 0.2	60.1 ± 0.2	10.2 ± 0.8	12.9 ± 0.8	93.6 ± 0.8
Triticale	11.4 ± 0.1	61.1 ± 0.4	10.4 ± 0.8	13.2 ± 0.9	94.6 ± 0.9
2-row barley	9.9 ± 0.2	61.6 ± 0.5	10.5 ± 0.8	13.3 ± 0.9	92.3 ± 0.9

*Ratio of grain/flour to water 1:3.

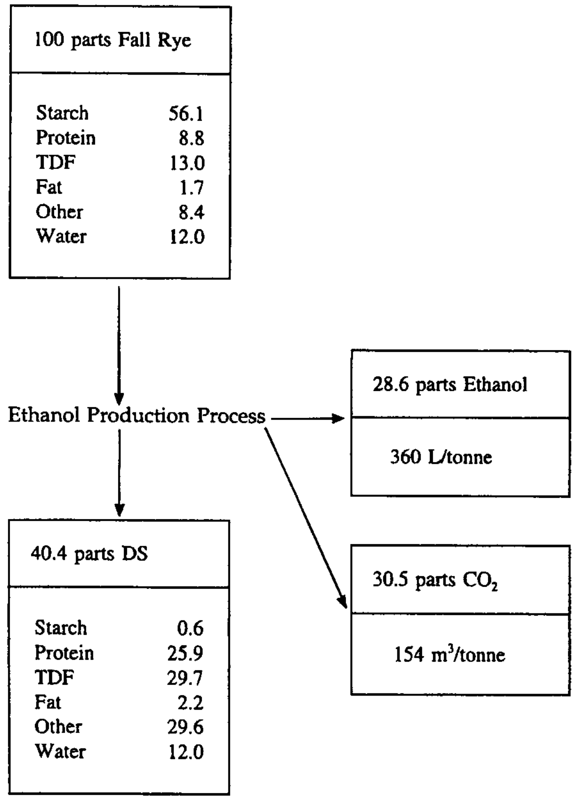

Fig. 2. Mass balance, ethanol yield, and dried stillage composition for Prima fall rye after commercial processing.

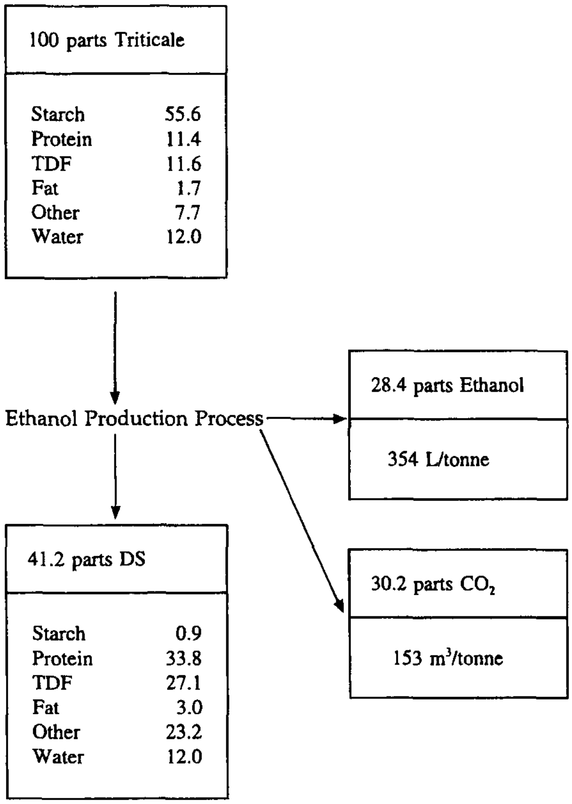

Fig. 3. Mass balance, ethanol yield, and dried stillage composition for AC Copia triticale after commercial processing.

RESULTS AND DISCUSSION

Fall rye contained the lowest protein and the highest starch contents (Table 1). Triticale was the highest in protein among the three grains, but was comparable to rye in starch content. Thus both grains should yield similar volumes of ethanol. Although intermediate in protein, barley was about 5% lower in starch than rye. As concentration of ethanol in the beer depended directly on the starch content in the feedstock, rye, and triticale yielded beers that were almost 1% higher in ethanol than barley.

Preprocessing of grain reduced protein and increased starch contents in the flours (Table 1). The increased concentrations of starch, from 51–56% in grains to 60–62% in the flours, increased concentrations of ethanol in the beer from an average 9.2% (w/v) to 10.3% (w/v), respectively. This represents an 11.9% increase in ethanol concentration in the beer that will significantly reduce distillation cost. The greatest increase in ethanol concentration, because of preprocessing, was observed for barley.

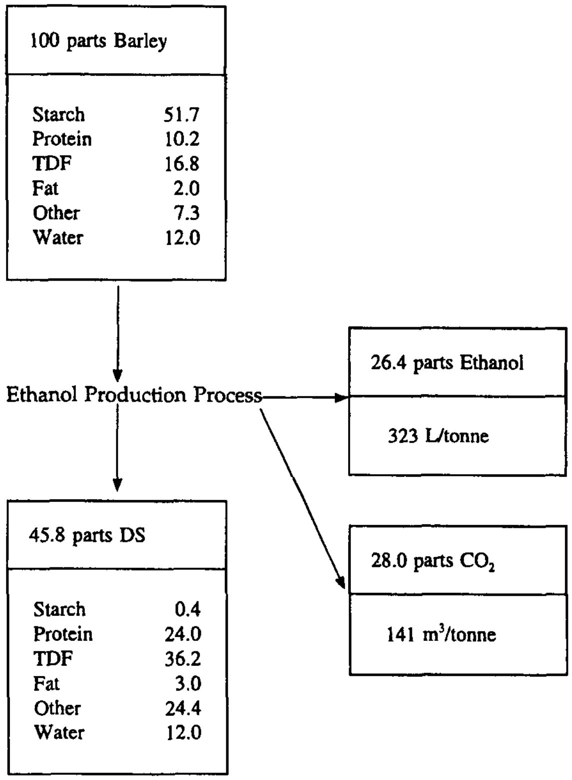

Fig. 4. Mass balance, ethanol yield, and dried stillage composition for CDC Dolly 2-row barley after commercial processing.

The fermentation efficiencies, calculated as the ratio between experimental and theoretical ethanol yields, ranged from 89.2–91.6% for grain to 92.3–94.6% for preprocessed grain samples (Table 1).

The volumes of ethanol produced from cereal grains corresponded to their starch contents. Fall rye and triticale, which were similar in starch contents, yielded 360 L/tonne and 354 L/tonne, respectively (Figs. 2 and 3). Barley, low in starch but high in TDF and protein as compared to rye and triticale, produced 323 L of ethanol per tonne of grain (Fig. 4). Ethanol represented only 26.4–28.6% of total product yields (Figs. 2–4). Carbon dioxide, which is not utilized in small ethanol plants, accounted for 28.0–30.5% of total products. Dry stillage (DS) represented 40.4–45.8% of total products from ethanol production. More stillage was produced from barley than from rye or triticale. And the stillage from barley contained the lowest level of protein and the highest level of fiber.

In addition to protein (24.0–33.8%), TDF (27.1–36.2%), and fat (2.2–3.0%), DS contained 23.2–29.6% of other constituents, including pentosans, beta-glucans, ash, phytate, and fermentation by-products such as

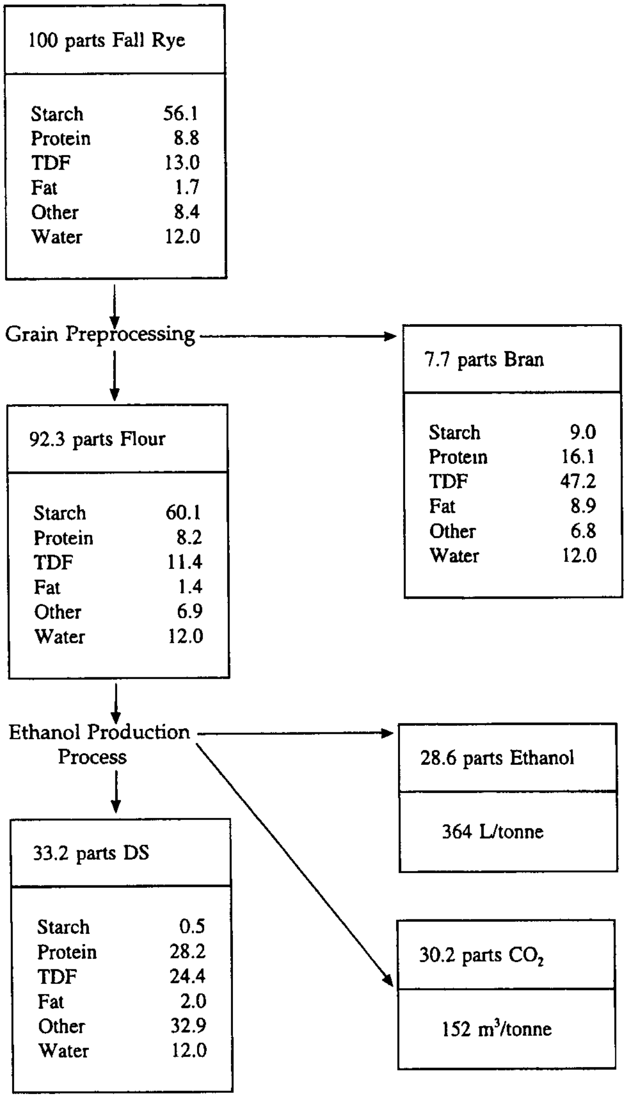

Fig. 5. Mass balance, ethanol yield, and product compositions for preprocessed Prima fall rye.

glycerol and organic acids (Figs. 2–4). The residual starch was below 1%. No free glucose was determined in stillage.

Preprocessing of grain removed from 7.7–21.7% of grain weight into bran fractions (Figs. 5–7). TDF was the major component of bran. However, bran contained 9.0 to 23.8% starch that represented a 2.0–9.7% loss of the total grain starch into bran. The most starch was lost during preprocessing of soft-kerneled triticale, followed by barley and rye. The starch lost to bran, although not available for conversion to ethanol, would

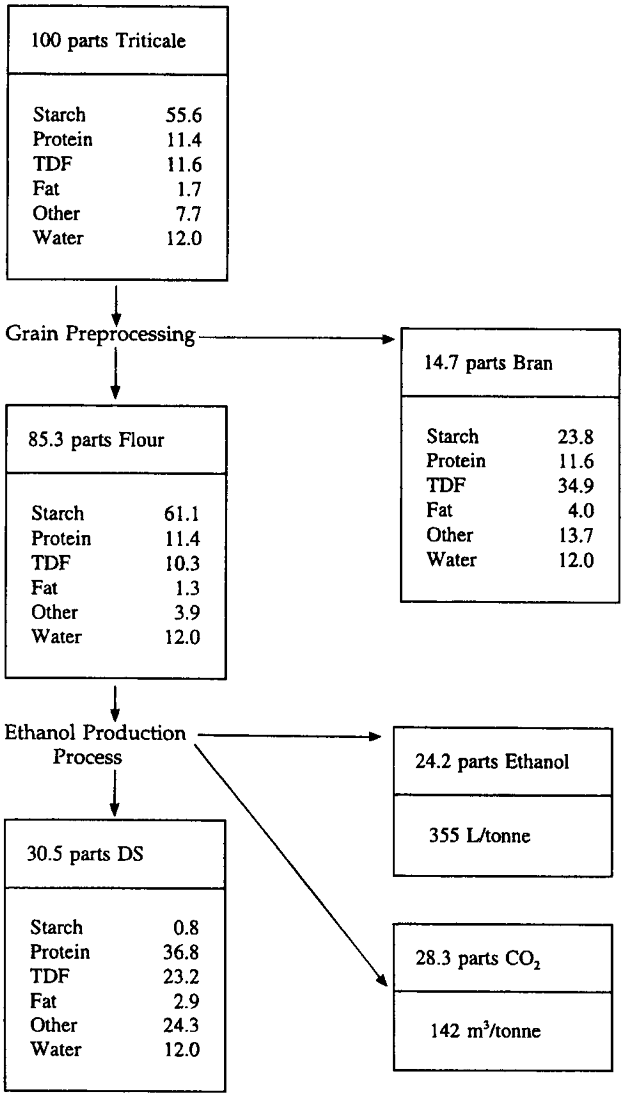

Fig. 6. Mass balance, ethanol yield, and product compositions for preprocessed AC Copia triticale.

increase bran quality as animal feed in an integrated fuel ethanol-feedlot operation.

The flours represented 78.3–92.7% of grain weights and contained 60.1–61.6% starch (Figs. 5–7). Preprocessing of rye and triticale increased starch concentration in the flour by 4–5%, which corresponded to low or intermediate removal of grain dry matter to bran fractions. Removal of hull and bran from barley, which represented 21.7% of grain, increased starch concentration in the flour by 10%. Increased starch concentrations in flours as compared to grain yielded greater concentrations of ethanol in the beer (Table 1).

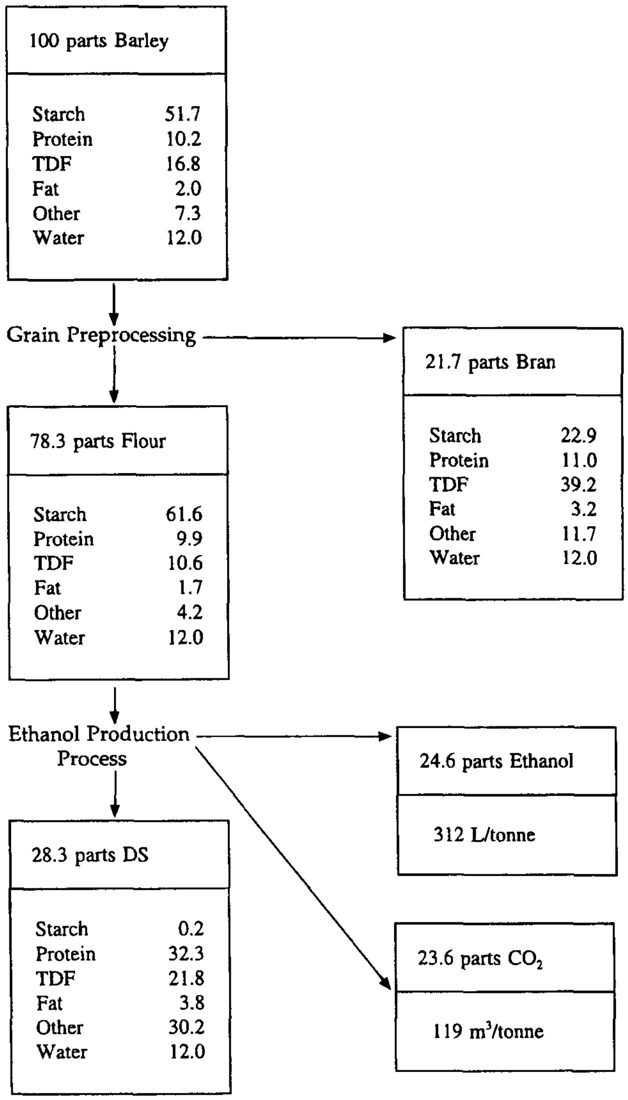

Fig. 7. Mass balance, ethanol yield, and product compositions for preprocessed Dolly 2-row barley.

Protein concentrations in the preprocessed flours were only slightly lower as compared to grains, but TDF contents were substantially reduced (Figs. 5–7). Reduction of TDF in flours, which became the feedstocks for ethanol fermentation, reduced TDF in DS with corresponding increases in protein contents, as compared to DS from grains (Figs. 2–4). No residual glucose and lower residual starch in DS from flours, as compared to DS from grains, indicate that preprocessed rye, triticale, and barley flours can be successfully fermented to ethanol.

Table 2
Effect of Preprocessing on Product Yields and Energy Required During Fermentation, Based on a 10 Million L Ethanol Plant Processing Prima Fall Rye

	Prima fall rye	
	Whole grain	Preprocessed
Material balance:		
Grain processed (tonnes)	27,778	30,095
Flour (tonnes)	--	27,778
Bran (tonnes)	--	2317
DS (tonnes)	11,112	9179
Ethanol (million L)	10.00	10.80
Ethanol production increase (%)	--	8.0
Energy balance:		
Gas:		
Cooking (MJ/L)	2.06	1.97
Distillation (MJ/L)	7.70	7.58
Drying (MJ/L)	19.60	18.83
Total gas (MJ/L)	29.36	28.35
Gas use decrease (%)	--	3.5
Electricity:		
Preprocessing (MJ/L)	--	0.09
Grinding (MJ/L)	0.16	0.15
Ethanol production	2.54	2.32
Total electricity (MJ/L)	2.70	2.56
Electricity use decrease (%)	--	5.2

The results from the experimental laboratory fermentations were used to evaluate the benefits of preprocessing of cereal grains for a theoretical 10 million L/y ethanol plant. On a constant throughput basis for the fermenters, preprocessing increased ethanol production capacity of this theoretical plant by 8–23%, depending on the preprocessed cereal grain (Tables 2–4). The best results were obtained with barley.

Preprocessing of grain to remove bran, or hull and bran in barley, and thus reducing nonfermentable constituents in feedstocks for the fermentation process, reduced material weights for distillation and drying to DS. Both units of operation showed decreased energy requirements per one L of ethanol (Tables 2–4). Combined use of natural gas was reduced by 3.5–11.4%. Reduction in power consumption ranged from 5.2 to 15.6%.

Table 3
Effect of Preprocessing on Product Yields and Energy Required During Fermentation, Based on a 10 Million L Ethanol Plant Processing AC Copia Triticale

	AC Copia triticale	
	Whole grain	Preprocessed
Mass balance:		
Grain processed (tonnes)	28,248	33,116
Flour (tonnes)	--	28,248
Bran (tonnes)	--	4868
DS (tonnes)	11,638	8616
Ethanol (million L)	10.00	11.16
Ethanol production increase (%)	--	11.6
Energy balance:		
Gas:		
Cooking (MJ/L)	2.03	1.93
Distillation (MJ/L)	7.67	7.54
Drying (MJ/L)	19.40	18.60
Total gas (MJ/L)	29.10	28.08
Gas use decrease (%)	--	3.5
Electricity:		
Preprocessing (MJ/L)	--	0.09
Grinding (MJ/L)	0.16	0.16
Ethanol production (MJ/L)	2.58	2.20
Total electricity (MJ/L)	2.74	2.44
Electicity use decrease (%)	--	10.9

CONCLUSIONS

1. Preprocessing of grain reduced fiber and increased starch contents in feedstock for ethanol production, yielding beers with increased concentrations of ethanol. Preprocessing was especially beneficial for barley where removal of 22% grain weight increased starch content by 10%.
2. Grain preprocessing would increase the capacity of an ethanol plant, since more starch is processed in the same weight of feedstock. The increase in plant capacity would be in the range 8–23%, depending on grain, with the highest value being for barley flour.
3. Grain preprocessing reduced energy requirements in ethanol production. Total gas use would be reduced by 3.5–11.4%, whereas power consumption would be reduced by 5.2–15.6%.

Table 4
Effect of Preprocessing on Product Yields and Energy Required During Fermentation, Based on a 10 Million L Ethanol Plant Processing CDC Dolly 2-row Barley

	CDC Dolly 2-row barley	
	Whole grain	Preprocessed
Mass balance:		
Grain processed (tonnes)	30,950	39,527
Flour (tonnes)	--	30,950
Bran (tonnes)	--	8577
DS (tonnes)	14,175	8759
Ethanol (million L)	10.00	12.33
Ethanol production increase (%)	--	23.3
Energy balance:		
Gas:		
Cooking (MJ/L)	2.20	1.91
Distillation (MJ/L)	7.92	7.49
Drying (MJ/L)	21.00	18.20
Total gas (MJ/L)	31.12	27.60
Gas use decrease (%)	--	11.4
Electricity:		
Preprocessing (MJ/L)	--	0.10
Grinding (MJ/L)	0.18	0.15
Ethanol production (MJ/L)	2.83	2.29
Total electricity (MJ/L)	3.01	2.54
Electricity use decrease (%)	--	15.6

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