Low-Input Wet-Milling of Grain Sorghum for Readily Accessible Starch and Animal Feed[1]

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ABSTRACT

An abbreviated, wet-milling process was devised to isolate readily accessible starch from grain sorghum. The process required 1.2 parts fresh water per one part of grain and produced no waste water. Nine grain sorghum samples varying in hardness, color, and protein content were examined. Grain was ground with 1.5 parts recycled process water, and the slurry was poured over a stack of 80-, 200-, and 400-wire mesh screens. The overs on the coarse screen were washed with recycled water, whereas the overs on the fine screens were washed with fresh water. Two soft yellow samples gave 20% starch (0.8% protein) from dry grain; the other samples gave 14–18% (0.7–1.0% protein). The starch from the two soft samples was less bright than commercial corn starch, but the brightness was improved by washing with 0.25*M* sodium hydroxide. The protein on the starch was decreased to 0.5% by high shearing in water at 25°C or by treatment with protease. Approximately 90% of the total process water was recovered, and 75–84% of grain solids were collected in a second stream (animal feed) with 50% moisture content. The animal-feed stream was preserved by ensiling after mixing with one-third part alfalfa meal. After three days at 40% moisture and 25°C, the silage had pH 4.2 and contained 1.1% lactic acid and 0.26% acetic acid (based on dry solids). The high-moisture animal-feed stream was also formulated into a ration for beef cattle.

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Grain sorghum is an important commodity crop for semiarid regions of the world. The major production areas are Argentina, Egypt, Ethiopia, India, Mexico, Nigeria, People's Republic of China, South Africa, Sudan, and the United States (Abdelrahman 1980). The average world production for the last five years was ≈56.8 million metric tons, of which 28% came from the United States (USDA 1993). In parts of Africa, Asia, and Latin America, grain sorghum is a staple food; it furnishes more than 70% of the total calories and most of the protein in the diet (Abdelrahman 1980). Dry milling of grain sorghum gives products that can be interchanged with those from maize (Hahn 1969). Grain sorghum is similar to corn in composition, kernel structure, starch properties, and method of starch isolation (Watson and Hirata 1954, Watson 1984). A waxy cultivar of grain sorghum was known before waxy maize (Hixon and Sprague 1942). Grain sorghum costs less than maize, and because it is dried in the field, its commercial supplies are not heat-damaged (Watson 1984). Although the use of grain sorghum for food is widespread in some countries, nearly all grain sorghum in the United States is used as livestock feed (Hoseney et al 1974).

In 1948, the Corn Products Refining Co. plant at Corpus Christi, TX, produced 50,000 tons per year of starch and 50,000 tons per year of dextrose from grain sorghum (Taylor 1949). Another wet-processing facility for grain sorghum was located in Guadalajara, Mexico. At the present time, the wet-milling of grain sorghum has been discontinued because of the incomplete recovery of starch and its off color (Freeman and Watson 1969, 1971; Watson 1984). Moreover, the yield of oil is low from grain sorghum because of the low proportion of germ in the kernel (9.8% vs. 11.5% for maize) (Rooney and Clark 1968, Watson 1984) and the high wax content in grain sorghum (0.3% dry basis) (Watson and Hirata 1954, Rooney and Clark 1968).

Purification of starch from grain sorghum is more difficult than purification of starch from corn for three reasons. First, grain sorghum contains 65% horny (corneous) endosperm compared to 54% for corn (Wall and Blessin 1970, Watson 1984). Starch granules in the horny endosperm are small, and the protein matrix is thick and heavily cross-linked (Watson and Hirata 1954). Softening the thick protein matrix requires increased levels of sulfurous acid during steeping, which causes starch breakdown during pasting. Small starch granules sediment more slowly than large ones (Stoke's Law), so they are relatively difficult to recover. Second, grain sorghum kernels contain a layer of small, densely proteinaceous, endosperm cells (peripheral endosperm) that lie just under the aleurone layer. During wet processing, those cells tend to be intact when released, and many are small enough to pass through the screens used to remove fibrous particles from the starch milk (Watson and Hirata 1954). Those high-protein cells then contaminate the starch. Third, ≈3–4% of the starch in grain sorghum is located in the middle layer (mesocarp) of the pericarp. The starch in the mesocarp layer occurs as tiny granules that tend to remain with the bran on the screens (Watson 1984).

Any off-color characteristics of sorghum starch negatively affect its value. The color is improved by pearling (Zipf et al 1950) or wet-peeling (Freeman and Watson 1969) the kernels before wet-milling, although a substantial quantity of starch is lost during those processes. The starch color also has been improved by bleaching with sodium chlorite after treating with alkali (Freeman and Watson 1971). Because of the problems associated with exhaustive extraction of starch from grain sorghum, Hahn (1969) suggested a low-cost process might be sought to isolate readily accessible starch. The purpose of this study was to isolate sorghum starch using an abbreviated low-input wet-milling process and to combine all other streams into an animal feed.

MATERIALS AND METHODS

Materials

Nine samples of grain sorghum varying in color and hardness were used; six of them were kindly provided by Pioneer Hi-Bred International Sorghum Research Department, Manhattan, KS; two by Grain Products, Inc., Dodge City, KS; and one by the Department of Animal Sciences and Industry, Kansas State

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University. The Pioneer samples were U.S. no. 1 grade grown in 1992 at Plainview, TX. The two Grain Products samples were commercial U.S. yellow no. 2 grade grown in Kansas during 1992 and 1993. The sample from the Department of Animal Sciences was a Pioneer cultivar (8585) of unknown grade and origin. All grain sorghum samples were type I (no tannins). The samples were stored at ≈5°C before use. Alfalfa meal with 17.0% protein and 7.3% moisture was bought from Key Feeds, Clay Center, KS.

Glucoamylase (from *Rhizopus* mold); glucose oxidase (type II, from *Aspergillus niger*); peroxidase (type I, from horseradish); protease (type II, from *Aspergillus oryzae*); *tris*[hydroxymethyl]aminomethane; and corn starch were purchased from Sigma Chemical Co., St. Louis, MO. *o*-Dianisidine dihydrochloride was purchased from Aldrich Chemical Co., Milwaukee, WI; lactic and acetic acid analysis kits were purchased from Boehringer Mannheim GmbH, Indianapolis, IN. All chemicals were reagent grade unless otherwise specified.

Methods

All analyses were done in duplicate except particle size index, which was done in triplicate. Protein was assayed by Kjeldahl nitrogen (method 46-13, AACC 1983); ash by dry combustion (method 08-01); moisture by oven-drying for 1 hr at 130°C (method 44-15A), and fat by extraction with petroleum ether (method 30-25). Total starch content was determined by a slight modification of method 76-11, and starch color was determined using a tristimulus meter (CR-210, Minolta, Osaka, Japan). Endosperm hardness of grain sorghum was estimated by particle size index after grinding using a slight modification of the method of Kirleis and Crosby (1982). Pasting curves were recorded on a Brabender Viscograph-E (C. Brabender Instruments, Inc., Hackensack, NJ) fitted with a head torque of 700 g·cm (Tipples 1980). A starch slurry at 7.5% solids in water (465 ml) was heated and cooled at 1.5°C/min. Total titratable acidity of silage was determined by method 02-31, and L(+)-lactic and acetic acid were determined by enzymatic methods using analysis kits.

Abbreviated Wet-Milling of Grain Sorghum without Recycling Water

Grain sorghum (100 g, dry basis) and water (150 ml) were ground for 1 min at low speed (18,000 rpm), then for 2 min at high speed (22,000 rpm) in a Waring blender (7010G, Waring Products Division, New Hartford, CT). The blade of the blender was reversed so that impact on the grain came from the blunted edges. The slurry, with a temperature of ≈38°C, was poured onto an 80-wire mesh screen (180-μm opening), and the overs were washed with water (3×, 50 ml). The throughs then were placed on a two-tier stack of sieves, top was a 200-wire mesh (75 μm), and bottom was a 400-mesh nylon bolting cloth (40 μm). The overs were washed with water (1×, 30 ml), and the throughs were centrifuged at 12,000 × *g* for 20 min. The supernatant was decanted from the sediment and kept as process water A (≈190 ml). The upper layer of the sediment or tailings, which contained protein and some B-starch, was scraped off and combined with the overs from the sieving steps. That mixture, together with some additional tailings, formed the animal-feed stream. The bottom sediment layer was slurried with water (30 ml), and the slurry was centrifuged at 12,000 × *g* for 20 min; the process was repeated twice. The supernatants from the washing steps were combined and kept as process water B (≈90 ml); the tailings were added to the animal-feed stream. After being washed with water, the sediment starch was dried in an oven at 40°C overnight, and the starch was weighed and assayed for moisture, protein, and color. The animal-feed stream was centrifuged at 5,500 × *g* for 15 min, and supernatant C (≈20 ml) was combined with supernatant A to give process water A (≈210 ml). The sediment animal-feed stream contained 50% moisture content as determined by the two-stage drying method 44-15A (AACC 1983).

Abbreviated Wet-Milling of Grain Sorghum with Recycled Process Water

One sample of yellow 2-92 grain sorghum (100 g, dry basis) was processed as described above. Process waters A and B were saved. A second 100-g batch of the same grain sorghum was wet-processed as before, except a portion (150 ml) of process water A was used in the grinding step, and the remainder (60 ml) of process water A and process water B (2×, 45 ml) were used in the washing step of the coarse screenings. Fresh water (30 ml) was used to wash the overs on the fine screens, and more fresh water was used to wash the starch (3×, 30 ml). Process water A (≈210 ml) and B (≈90 ml) were saved and used to wet-process a third 100-g batch of grain sorghum. Six iterations of the process were done.

Starch Purification

To remove contaminating protein from sorghum starch, the wet starch isolated from 100 g of grain was mixed with water (30 ml), and the slurry was cooled in an ice bath and stirred vigorously for 30, 45, 60, 90, and 120 sec using a tissue homogenizer (SDT99708, 170W, Tekmar Co., Cincinnati, OH). The sheared slurry was centrifuged at 12,000 × *g* for 20 min, and the supernatant and tailing layers were discarded. The starch was collected and dried in an oven at 40°C, and its moisture and protein contents were determined. Alternatively, a starch slurry (10 g of dry starch in 15 ml of water) was adjusted to pH 7.5 by adding 0.1*M* sodium hydroxide. Protease (100 units) was added

TABLE I
Color, Hardness, and Composition of Grain Sorghum Samples[a]

Sample	Seed Color	PSI[b] (%)	Moisture (%)	Ash (%)	Starch (%)	Protein (%)	Crude Fat (%)
8696Y	Yellow	42	14.0	1.6	79.4	9.4	4.1
8231Y	Yellow	41	14.0	1.5	72.2	10.4	3.3
8557Y	Yellow	41	14.1	1.7	76.6	10.1	4.3
XSW16	Yellow	47	14.0	1.4	77.1	8.6	3.9
Yellow 2-92	Mixed[c]	51	13.6	1.6	77.5	10.5	3.3
Yellow 2-93	Mixed[c]	51	12.3	1.5	77.6	10.6	3.2
8601	Red	45	14.2	1.5	74.9	10.0	3.5
8500	Red	46	13.8	1.5	75.2	10.8	3.7
8585	Red	47	14.5	1.6	76.8	10.3	3.8
LSD (P= 0.05)[d]		3.0	0.18	0.04	2.7	0.36	0.13

[a] Dry weight basis, except PSI and moisture; data represent means of duplicates.
[b] Particle size index.
[c] Yellow grain sorghum samples contain yellow and light red kernels.
[d] Least significant difference. Difference between two means exceeding this value are significant.

to the slurry, and the digestion was allowed to proceed at 37°C for 1 hr and 25°C for 2 hr. The mixture was centrifuged at 12,000 × *g* for 20 min, and the supernatant and tailing layers were discarded. The starch was stirred in 0.02*M* hydrochloric acid (10 ml) for 15 min at ambient temperature to inactivate protease, and the slurry was adjusted to pH 7.0 with 0.01*M* sodium hydroxide and centrifuged. The sedimented starch was washed with fresh water, then collected and dried at 40°C. Moisture and protein contents were determined. Starch (10 g, dry basis) isolated from yellow 2-92 grain sorghum was either mixed with water (15 ml), and 30% hydrogen peroxide (0.3 ml) or 4–6% sodium hypochlorite (2.5 ml) was added. After the mixture was stirred for 1 hr at 25°C, it was centrifuged and the supernatant and tailings were discarded. The starch was washed with fresh water (15 ml) and dried and measured for color. Alternatively, the starch slurry was adjusted to pH 10 by adding 0.25*M* sodium hydroxide. After being stirred for 30 min at 25°C, the mixture was adjusted to pH 7.0 by adding 0.02*M* hydrochloric acid, the starch was isolated and dried and measured for color.

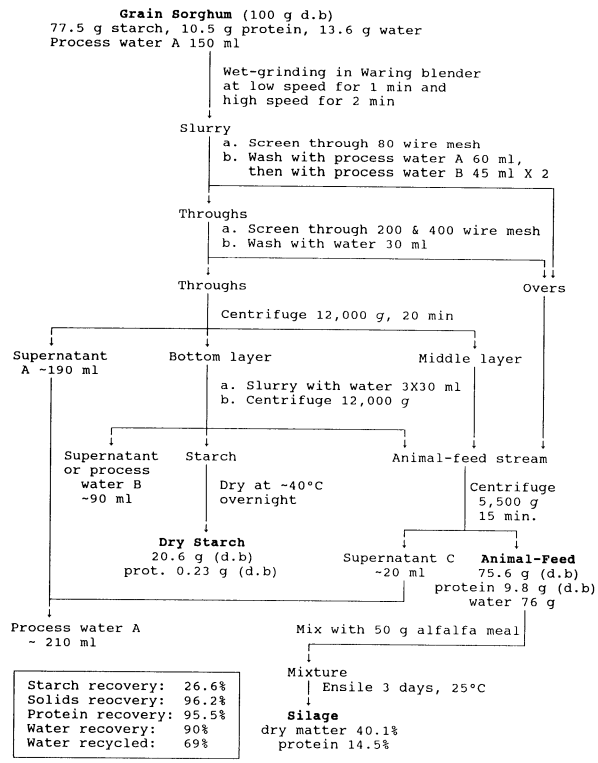

Fig. 1. Abbreviated wet-milling of grain sorghum with recycling of process water.

Ensiling the Animal-Feed Stream

Alfalfa meal (100 g) was mixed with the animal-feed stream (308 g) to give a mixture with 40 ± 1% moisture and 13.6% protein. The mixture was sealed in a glass jar for 20 hr at 25°C to distribute moisture evenly. Portions (35 ± 0.5 g) of the mixture were weighed into ten 50-ml centrifuge tubes, which served as fermentation silos. Each loaded centrifuge tube was plugged with a rubber stopper containing a hole fitted with a short length of plastic tubing. The outside end of the tubing was capped with a rubber policeman, which had a small vertical slit that functioned as a one-way valve. All silos were kept at room temperature, and after a period of time, two silos were opened. Ten grams of silage in each of the duplicate tubes were placed in a volumetric flask (100 ml), brought to volume with water, mixed, and allowed to stand for 1 hr. After the mixture was filtered through a Whatman No. 1 filter, the pH of the filtrate (10 ml) was measured by a pH meter. An aliquot of the filtered sample was used to determine total titratable acidity, L(+)-lactic acid, and acetic acid.

Formulation for Cattle Containing the Animal-Feed Stream

A ration to provide dry matter, energy, and protein to growing cattle was calculated by a least-cost feed formulation program. It was assumed that a growing steer weighing 800 lb. requires 7.8 kg of dry matter, 1.0 kg of protein, and 3.11 Mcal/kg of metabolizable energy to grow 1.8 kg per day with a daily feed consumption of 11 kg (NRC 1984).

Statistical Analysis

Data were evaluated statistically using the one-way analysis of variance procedure with the least significant difference test (SAS 1985).

RESULTS AND DISCUSSION

Color and Composition of Grain Sorghum Samples

Of the nine grain sorghum samples, six were yellow and three were red cultivars (Table I). All samples were sound, clean grain and judged to be U.S. no. 1 or no. 2 grade. With a high particle size index indicating softness (Kirles and Crosby 1982), two samples (yellow 2-92 and 2-93) were relatively soft; three (8696Y, 8231Y, 8557Y) were hard; and the remaining (8500, 8585, 8601, XSW16) were of intermediate hardness. Protein content was 9–11%; crude fat content was 3.2–4.1%. Starch level range was 75–79%, except for one sample at 72%.

TABLE II
Abbreviated Wet-Milling of Grain Sorghum: Yield and Quality of Starch[a]

Sample	Seed Color[b]	Starch Yield (%)	Starch Recovery (%)	Protein Content of Starch[c] (%)	Starch Color[c]		
					L	*a*	*b*
8696Y	Y	16.7	21.0	1.1	91.0	–0.9	2.9
8231Y	Y	17.7	24.5	0.8	91.5	–1.8	3.9
8557Y	Y	14.1	18.4	0.8	91.1	–1.1	3.1
XSW16	Y	16.6	21.5	1.0	91.1	–1.4	3.9
Yellow 2-92	M	20.6	26.6	0.8	92.2	–0.8	4.5
Yellow 2-93	M	20.1	25.9	0.8	92.3	–0.7	4.2
8601	R	16.1	21.5	0.9	89.1	–0.3	3.9
8500	R	15.4	20.5	0.7	88.8	+0.2	4.0
8585	R	17.3	22.5	1.1	89.2	–0.5	3.5
LSD ($P = 0.05$)[d]		3.08	3.97	0.06	1.3	0.1	0.2

[a] Dry weight basis; data represent means of duplicates.
[b] Y = yellow, M = mixed, R = red.
[c] Commercial corn starch sample contained 0.2% protein; color was $L = 94.6$, $a = -2.2$, and $b = 3.8$.
[d] Least significant difference. Difference between two means exceeding this value are significant.

Abbreviated Wet-Milling of Grain Sorghum

Readily accessible starch was isolated from the nine grain sorghum samples by an abbreviated wet-milling process. Figure 1 shows the process using recycled water with the yellow soft sample. The results of wet-milling the nine grain sorghum samples without recycling of water are given in Tables II and III. The starch yield was calculated based on grain mass, while the starch recovery was based on the starch mass in the grain, all on a dry-solid basis. The starch yields were 14–21%, and starch recoveries were 18–27%. The duplicate starch recoveries differed by no more than 4%, with an average difference of 1.8%. The protein content of the starches was 0.7–1.1%, and the colors were somewhat inferior to that of a commercial sample of corn starch (Table II). Total solids recovered in the two product streams were 92–99% (Table III).

The starch recovery in the abbreviated wet-milling process was affected mainly by endosperm texture and by process variables at the grinding step. The grain sorghum was not steeped or presoaked in water, but instead was ground in water. Sorghum grain with soft endosperm, such as yellow 2-92 and 2-93, gave more starch than those with hard endosperm. Grinding time and the ratio of water to grain affected starch recovery (Fig. 2). Three minutes of grinding at a water-to-grain ratio of 1.5:1 gave the highest starch recovery (Fig. 2A,B). Starch recovery apparently declined with excess grinding time, because starch was entrained in the extra fiber released.

The optimum ratio of 1.5:1 (w/w) of water to grain (Fig. 2B) can be explained by two opposing phenomena. Too little water provided insufficient fluid in which to release the starch, whereas excess water increased the collisions between the solids and the grinder blades. The extra collisions increased fines, which entrained starch in the overs on the sieves. In a commercial operation, a Szego mill (General Comminution Inc., Toronto, ON, Canada), for example, could be used to grind sorghum grain with water. As expected from the data on grinding time and the ratio of grain to water, the washing of the overs on the screens also affected starch recovery because of the presence of fines. However, washing was kept to a minimum to conserve water. Fresh water was introduced into the process to wash starch from the fine solids caught on the 200- and 400-mesh screens and to wash and purify the starch. Water left the process only in the two product streams; the process produced no water effluent. Water recovery was 90% in both the single and the water-recycle run (Fig. 1).

When the abbreviated wet-milling process was repeated six times on yellow 2-92 samples using recycled water (as opposed to using all fresh water in cycle 1), starch recovery and quality in cycles 2 through 6 did not decline (Table IV). The mean starch recovery and standard deviation of the six replicate determinations was 26.8 ± 1.2%.

TABLE III
Total Solids Recovered from Abbreviated Wet-Milling of Grain Sorghum Samples[a]

Sample	Starch (g)	Animal-Feed (g)	Solids Recovery (%)
8696Y	16.7	79.6	96.3
8231Y	17.7	74.7	92.4
8557Y	14.1	78.5	92.6
XSW16	16.6	78.5	95.1
Yellow No. 2 92	20.6	75.6	96.2
Yellow No. 2 93	20.1	75.9	96.0
8601	16.1	80.3	96.4
8500	15.4	83.5	98.9
8585	17.3	76.5	93.8
LSD ($P = 0.05$)[b]	3.08	5.23	3.28

[a] Dry solid basis.
[b] Least significant difference. Difference between two means exceeding this value are significant.

Quality of Grain Sorghum Starch Isolated by Abbreviated Wet-Milling

The three red grain sorghum samples (8500, 8585, and 8601) gave slightly red-tinted starches as indicated by their elevated *a* values, whereas the yellow samples gave whiter starches with increased *L* values (Table II). The soft yellow 2-92 and 2-93 samples yielded starch with the highest *L* values, although they contained more than 50% light red kernels, which did increase the *a* values. A commercial sample of corn starch was brighter ($L = 94.6$) than any of the grain sorghum starches ($L = 88.8$–92.3). That difference was readily discerned by eye; the grain sorghum starch appeared slightly dull gray in color compared to the bright light yellow of the corn starch. Bleaching the grain sorghum starch with sodium hypochlorite slightly darkened it, but hydrogen peroxide slightly whitened it. Starch brightness was improved most by treatment with 0.25*M* alkali at 25°C (Table V).

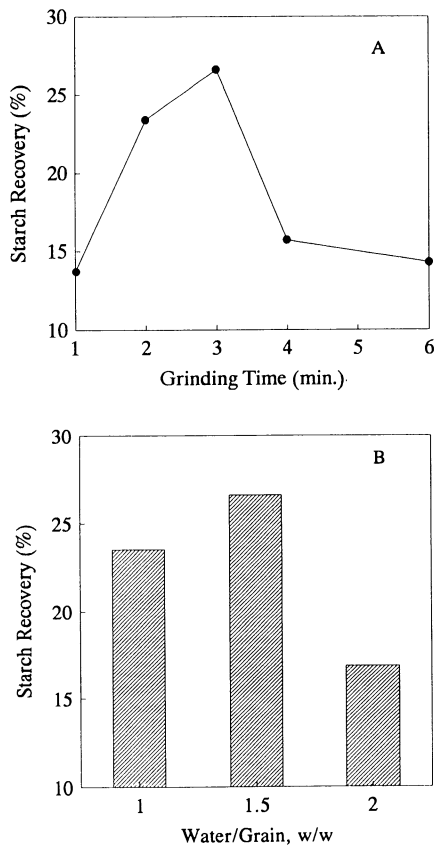

Fig. 2. Grinding time and starch recovery in the abbreviated wet-milling of yellow 2-92 sorghum at a water-to-grain ratio of 1.5:1.0 **(A)**. Starch recovery at other water-to-grain ratios **(B)**.

TABLE IV
Quality of Starch Isolated from Grain Sorghum Sample 2-92 Using the Abbreviated Wet-Milling Process with Recycled Water[a]

Cycle Number	Starch Yield (%)	Starch Recovery (%)	Protein Content of Starch (%)	Starch Color[b]		
				L	*a*	*b*
1	20.6	26.6	0.8	92.2	–0.8	+4.5
2	20.5	26.5	1.0	91.8	–0.7	+3.8
3	22.3	28.8	0.9	92.4	–0.9	+4.9
4	19.9	25.7	1.1	92.6	–0.8	+4.7
5	19.8	25.5	1.1	91.6	–0.9	+4.5
6	21.4	27.6	1.1	91.4	–0.9	+3.7

[a] Yields and protein levels on a dry weight basis.
[b] Color of a commercial sample of corn starch was $L = 94.6$, $a = -2.2$, and $b = 3.8$.

The protein content of the starch was high (0.7–1.1%) compared to that of commercial starches (0.3%). The starch isolated in 20% yield from yellow 2-92 sorghum grain contained 0.8% protein. High shearing this starch in water for 2 min decreased the protein content to 0.5% (Fig. 3). Treatment with 10 units of protease per gram of starch at 25 and 35°C for 1 hr decreased the protein to 0.6 and 0.5%, respectively (Fig. 3). Extending the digestion period for an additional hour removed little additional protein.

TABLE V
Results of Bleaching Sorghum Starch with Hydrogen Peroxide, Sodium Hypochlorite, or Alkali[a]

Treatment	Starch Color		
	L	*a*	*b*
None	91.5	−1.3	4.9
Hydrogen peroxide	91.9	−1.0	3.5
Sodium hypochlorite	91.1	−1.3	4.2
Alkali	92.3	−1.6	3.9
LSD ($P = 0.05$)[b]	0.25	0.1	0.1

[a] Starch was isolated from yellow sorghum sample 2-92.
[b] Least significant difference.

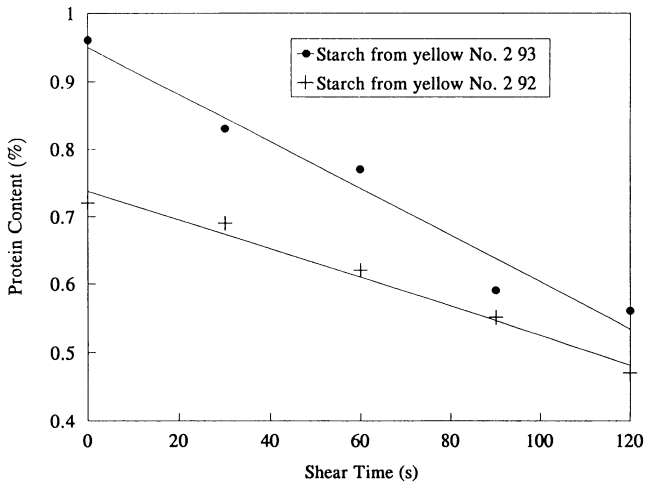

Fig. 3. Reduction of protein contamination in two yellow sorghum starches using high shear in water.

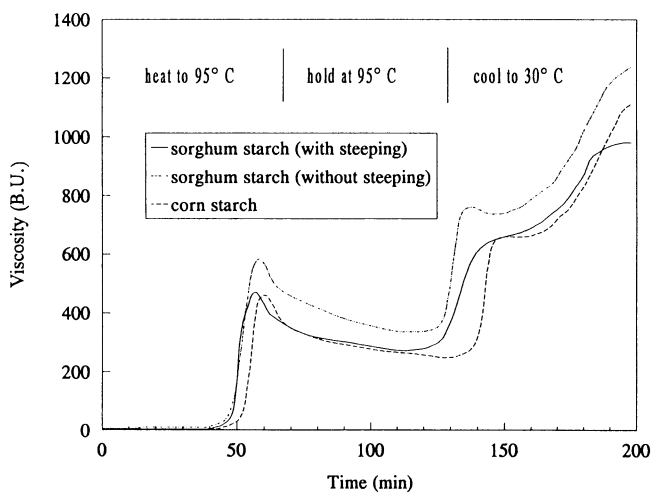

Fig. 4. Pasting curves for corn starch and yellow 2-93 sorghum starch samples at 7.5% dry solids. One sample was steeped in 0.2% SO_2 at 50°C for 24 hr, and the starch isolated according to Watson (1964).

The pasting curve of sorghum starch from yellow 2-93 is compared to that of corn starch in Figure 4. The overall shapes of curves were the same, with the sorghum starch (no steeping) giving somewhat higher consistency. This indicates that the grinding step in the abbreviated process did not damage the starch granules. The hot pastes of the sorghum starches isolated with and without steeping in 0.2% SO_2 at 50°C for 24 hr did not break down excessively, as previously concluded by Subramanian et al (1994).

Animal-Feed Stream

The animal-feed stream from the abbreviated wet-milling process contained 50% water (Fig. 1), so it must be dried, preserved, or fed immediately to cattle. A common method of preserving high-moisture feed is by ensiling. Grain sorghum often is ensiled at 25–40% moisture; therefore, the animal-feed stream was blended with one-third part alfalfa meal and the mixture ensiled. Table VI shows that the pH of the initial mixture was 6.1, but after one day of ensiling, the pH dropped to 4.5. After three days of ensiling, the pH was 4.2 and it declined to 4.0 after six days. Total titratable acidity increased from an initial level of 0.1 meq/g to 1.3 meq/g after six days of ensiling.

The changes in lactic and acetic acid levels in the silage are shown in Figure 5. During the first two days, both lactic and acetic acids levels increased. On the third day, lactic acid was at its maximum level of 1.1 wt% and acetic acid was at 0.26 wt%, which gave a ratio of lactic to acetic acid of 2.8 (molar basis) or 4.2 (weight basis). These results show that the mixture of animal-feed and alfalfa meal at a combined moisture level of 40% gave good silage after three days fermentation at 25°C.

Based on the requirements of dry matter, protein, and metabolizable energy for a growing steer weighing 800 lb. (NRC

TABLE VI
Quality of Silage Made from a Mixture of the Animal-Feed and Alfalfa Meal[a]

Ensiling (days)	pH	Total Titratable Acidity (meq/g)	Lactic Acid (%)	Acetic Acid (%)
0	6.1	0.1	0.03	0.04
1	4.5	1.0	0.68	0.23
2	4.3	1.1	0.89	0.25
3	4.2	1.2	1.06	0.26
4	4.1	1.3	0.89	0.36
5	3.8	1.3	0.78	0.25
6	4.0	1.3	0.78	0.32

[a] Animal-feed stream from the abbreviated wet-milling process was mixed with one-third part dry alfalfa meal; the mixture contained 40% moisture.

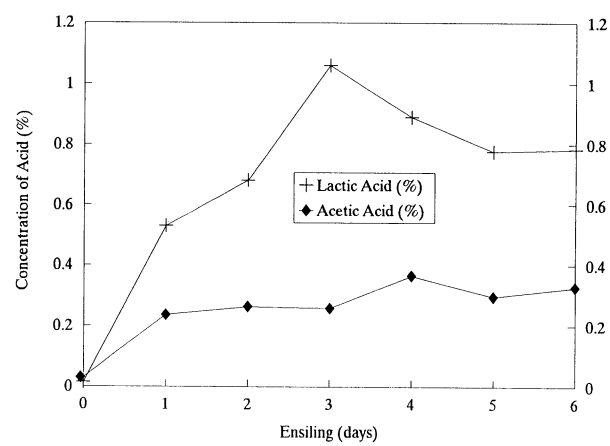

Fig. 5. Lactic and acetic acid levels during ensiling of a 1.0:0.3 mixture of the animal-feed stream with alfalfa meal at 25°C.

1984), a formula containing the animal-feed stream was derived by a least-cost feed formulation program. A mixture of the animal-feed stream (55%), alfalfa meal (35%), and animal fat (10%) was calculated to contain 13.4% protein, 70% dry matter, and 3.11 Mcal/kg of metabolizable energy, which are sufficient to satisfy the requirements of a growing steer.

CONCLUSIONS

An abbreviated wet-milling process, beginning with the wet-grinding of grain sorghum, gives 14–20% starch contaminated with 1% protein. All the remaining grain solids are in the animal-feed stream. The process requires a minimum input of 1.2 parts of fresh water per part of grain and produces no effluent. Decreasing the hardness of sorghum grain increases the yield of starch in the process.

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