zones during cooking.

In the case of triglycerides, no significant variations have been found. For phosphatidylcholine, it is interesting to point out the changes in the BFM, such as the decrease of saturated fatty acids, and the increase of the polyunsaturated fatty acids.

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Effects of Cultivar and Soil pH on Abrasive Milling Rate and Composition of Sorghum Grain

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Four cultivars of grain sorghum, Warner W-840DR, Dekalb C42y+, Funk G-552DR, and NK Savannah 5, which had been grown on acid (pH <4.9) and neutral (pH >6.0) pH soils were studied. Samples weighing 4.5 kg were abrasively milled for short, successive intervals until a cumulative extraction rate (yield of milled grain) of ~50% was reached for each sample. Third-degree polynomials provided an excellent description of the milling process for each cultivar. Milling rates (the rates at which the outer layers of the grain were removed) followed the order Dekalb > Warner > Funk > Savannah. Soil pH affected milling rate for Dekalb and Savannah. For all cultivars, the relative amount of starch in milled grain increased as the outer layers were removed. For all cultivars, the relative contents of protein, fat, fiber, and ash and of tannin for Savannah were reduced in the milled grain as milling proceeded. Soil pH affected starch and ash content in a complex, cultivar-dependent manner.

Grain sorghum (*Sorghum bicolor* (L.) Moench), one of the world's leading cereal crops, fills an important niche due to its drought tolerance (Pedersen and Eggum, 1983). This characteristic has caused expanded sorghum production in semiarid tropical and subtropical regions of the world. Unfortunately, infertility due to acid soil stress often limits yields in these areas. In Georgia where several recent growing seasons have been below average in rainfall, sorghum production increased from 4.7 megabushels in 1970-1972 to 12.1 megabushels in 1980-1982. Supporting this increase in production has been an extensive breeding effort to develop cultivars tolerant to the acidic soils found in the state (Duncan, 1981a,b, 1984; Duncan et al., 1984)).

Although sorghum grain is almost exclusively utilized for animal feed in the United States, there has been considerable research in this country and elsewhere on the factors controlling its functional, nutritional, and toxicological properties as they relate to human food applications (Morad et al., 1984; Choto et al., 1985; Capampang et al., 1984; Chavan et al., 1979). Most of the world sorghum crop

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is consumed directly by humans in developing countries of the semiarid tropics (Khalil et al., 1984), making factors affecting processing and utilization of great importance. Utilization of sorghum as a boiled grain similar to rice is increasing (Ali and Wills, 1983), but it is more commonly reduced to a flour and made into gruel or flat bread before consumption. The whole sorghum grain may be ground into a 100% extraction flour (Pedersen and Eggum, 1983), but it is desirable to first remove the bran layer with its attendant pigments, tannins, and undigestible carbohydrates in order to improve both the organoleptic acceptability and nutritive quality of the grain (Ali and Wills, 1983).

Traditionally, sorghum milling in less developed countries is accomplished by pounding the grain in a mortar and winnowing (Olatunji et al., 1980; Scheuring and Rooney, 1979), but the resulting low productivity and poor product have prompted extensive investigations of mechanical decorticating (Reichert, 1982). These studies have generally concluded that abrasive milling is the method of choice for removing the outer layers of the grain (Reichert and Youngs, 1976). Effects of abrasive milling and cultivar on nutritional quality (Khalil et al., 1984) and on functional properties (Ali and Wills, 1980) of sorghum have been examined, but to our knowledge the milling process has not been fit to mathematical models nor is there information on possible effects of acid soil stress on grain composition.

The purpose of this research was to determine the effects of cultivar and soil pH on milling rate of sorghum, to develop a model for describing abrasive milling of selected sorghum cultivars, and to determine the effects of milling, cultivar, and soil pH on composition.

MATERIALS AND METHODS

Four cultivars of grain sorghum, Warner W-840DR (white-seeded hybrid), DKalb C42y+ (double yellow endosperm hybrid), Funk G-522DR (normal, red-seeded hybrid), and NK Savannah 5 (high-tannin, brown seeded), were studied. Samples of seed grown in Georgia (Duncan, 1982, 1983) on both native acid soils (pH < 4.9) and on parallel companion plots adjusted to pH >6.0 by the addition of lime ($CaCO_3/CaOH$) were obtained following harvest and cleaning and were stored at 10 °C until processed. Samples (4.5 kg) from each of the eight treatments were abrasion-milled as described by Reichert and Youngs (1976), using a PRL minidehuller (Natana Machine Co. Ltd., Saskatchewan) equipped with carborundum stones, operated at 1000 rpm. The mill was stopped at frequent intervals, and the contents were removed and manually sieved on a 20-mesh screen to separate whole grains from the bulk of the polishings. The grain was then passed through an Amalco air blast seed cleaner (Allan Machine Co, Ames, IA) to remove adhering fines. The cleaned grain was weighed at each milling time, and apparent extraction rate ([original weight − weight after milling]/original weight) was calculated. Fifty-gram subsamples were removed for analysis, and the remaining grain was returned to the mill for further polishing. This process was continued until an apparent extraction rate (corrected for removal of analytical samples but not for changes in moisture content) of approximately 50% had been achieved. Moisture content of the whole grain and milling samples was determined by drying in a vacuum oven (AACC, 1983b, Method 44-32). The entire procedure was repeated, although identical milling times were not necessarily used.

Extraction rates were corrected to moisture-free basis (true extraction rate). True extraction rate vs milling time data were fitted to a series of mathematical models in an attempt to find the best expression for relating the two variables and for predicting extraction rate at specific milling times. All mathematical and statistical procedures were carried out on an IBM 4361 computer using the Statistical Analytical System package (SAS, 1985; Freund and Littell, 1981). Models: first-order kinetic, $E = E_0e^{-kt}$; second-order kinetic, $E = E_0/(ktE_0 + 1)$; second-degree polynomial, $E = E_0 + k_1t + k_2t^2$; third-degree polynomial, $E = E_0 + k_1t + k_2t^2 + k_3t^3$. E is extraction rate, t is milling time, E_0 is predicted intercept (extraction rate at $t = 0$), and k's are predicted coefficients. Data were fit to kinetic models by a nonlinear procedure (NLIN) and to polynomials with a least-squares estimation procedure (REG). The models were examined in the same sequence presented above and were evaluated for goodness of fit as indicated by specific tests on parameter estimates (e.g. HO: parm = 0) and by magnitude and pattern of residuals (observed − predicted values). Coefficient of determination (R^2) was defined as model sum of squares/projected total sum of squares for the linear procedure, and as 1 − (regression sum of squares/corrected total sum of squares) for the nonlinear procedure. The model providing the best fit (third-degree polynomial) was tested by a homogeneity of slopes procedure to determine cultivar and pH differences.

Whole grain (100% extraction) and samples representing approximately 90, 80, 70, 60, and 50% extraction were ground to fine flour in a Retsch, Model ZM1 centrifugal grinding mill equipped with a 0.5-mm screen (Retsch GmbH, Haan, West Germany). Analysis for starch was performed with a YSI carbohydrate analyzer, Model 27 (Yellow Springs Instrument Co. Inc., Yellow Springs, OH), according to manufacturers instructions. This instrument utilizes immobilized glucose oxidase and a Pt–Ag/AgCl electrode system to quantify glucose. Starch is estimated following coinjection of gelatinized sample and amyloglucosidase into the instrument's reaction chamber. Protein was calculated as N × 6.25 following micro-Kjeldahl analysis of samples (AACC, 1983b, Method 46-123). Fat was determined by exhaustive extraction with petroleum ether in a Goldfisch apparatus (AACC, 1983a, Method 30-25). Acid detergent fiber was determined by a modification of the method of Goering and Van Soest 1970). Tannin was measured by the method of Price et al. (1978).

RESULTS AND DISCUSSION

Extraction rate vs milling time data for cultivars grown at high and low soil pH are given in Table I. Milling was conducted until extraction rates of 50 had been achieved. This is far more extensive than normally practiced when preparing grain for food (with the exception of rice milled for sake production) but was done to provide a more complete data set for modeling. The observed pattern of the extraction rate vs milling time data and the nature of the process suggested that classical chemical kinetics might provide an appropriate model for describing the data. Beginning with the simplest rate function, the data were initially fit to the first-order kinetic model. Standard errors indicated that first-order kinetics provided a significant model for the data ($R^2 > 0.95$), but examination of residuals indicated a systematic bias. Use of the second-order kinetic rate law improved overall fit somewhat ($R^2 > 0.98$), but the bias, although reduced, was still evident. The second-order model also produced significant differences in E_0 among treatments, an undesirable characteristic since extraction rate is equal to 100 at time 0 by definition. The failure of simple kinetic models (which are based on identical events in a population of particles) to adequately describe the milling process illustrates the complexity of sequential removal of successive, nonidentical layers of the grain kernels. In the absence of sufficient information to construct a mechanistic/kinetic model based on properties of the anatomical components of the grain, empirical modeling using polynomials was investigated. A second-degree polynomial provided marginally improved fit (R^2) of the data compared to kinetic models. Residuals are generally smaller, but a regular, sinusoidal pattern was evident. Finally, a third-degree polynomial model was found to provide the best fit of the data, both in terms of R^2, which averaged 0.997, and in residual patterns. The latter, while retaining a generally sinusoidal shape, were small in magnitude and more diffuse than seen with other models. Therefore, the third-degree polynomial model was used to measure dif-

Table I. Extraction Rate of Sorghum Cultivar × Soil pH Treatment Subjected to Abrasive Milling for Various Times (min)

milling time	extraction rate[a]							
	Savannah		Funk		Warner		Dekalb	
	high pH	low pH	high pH	low pH	high pH	low pH	high pH	low pH
0.0	100[b]	100	100	100	100	100	100	100
1.0	98.3	97.6	97.7	97.4	97.0	97.3	96.7	96.3
2.5	95.6	94.5	94.3	93.9	92.9	93.5	92.7	92.1
3.0								89.8*
5.0	91.4	89.9	89.5	89.3	87.5	88.6	87.8	86.9*
7.5			85.9	85.3	83.3	84.5	83.6	82.2*
8.0								81.7*
10.0	85.7	83.4		81.9	79.5	80.9	80.0	78.2
12.5		80.0	79.7*	78.7				
15.0	81.0	77.0	76.9		74.3	75.7	74.9	72.6
16.0	80.4*							
17.5								69.3
20.0	75.9*	72.5	73.0	72.7	70.1	71.3	70.3	
21.0	76.9*							
22.5		69.6		70.0				
25.0			69.5		66.3	67.8	66.3	63.5
26.5								60.8*
27.5	70.3*	65.6						
28.5	70.9*							
30.0			66.5	65.6	63.2	64.3	62.9	60.4
32.5		61.8						
35.0		60.7*	63.7	62.7	60.4	64.2	60.0	56.4
39.0				59.7*				
40.0	63.6*	57.0	61.2	60.4	58.0	58.8		53.5
41.0	64.8*							
42.5			60.3*					
45.0	59.6*	54.2			54.5	56.9*	56.0	50.8
46.0	60.9*							
47.0								49.9*
49.0				56.0				
50.0		50.2*	57.3*	56.6	52.5	54.8		
52.5		51.5*	57.2*					
53.5		50.4*						
55.0	55.1*				50.6		52.2	
56.0	56.9*							
57.5					50.3*			
59.0				52.5*				
60.0	52.5*		54.2*	53.6*		51.9	50.0	
61.0	54.5*							
62.5			54.4*					
63.0						50.2*		
65.0	49.9*				48.4*	50.5*		
66.0	51.4*							
67.0	50.3*							
69.0				49.5*				
70.0			51.1*	50.7*				
72.5			51.8*					
75.0			49.5*					
77.5			50.3*					
78.0								

[a] Values noted by an asterisk are single determinations; all others are averages of duplicate determinations. [b] The extraction rate at 0 milling time is defined as 100.

ferences among cultivar and soil pH treatments.

The homogeneity of slopes analysis determines constancy of regression coefficients over cultivars and soil pH levels and their interaction by examination of the interaction between the effect and the independent variable time. As noted in the first section of Table II, this test detected no significant difference in intercept due to cultivar, soil pH, or their interaction. Examination of the time components confirmed significant linear, quadratic, and cubic effects over all cultivars and pHs. The significant time by cultivar and time by soil pH interaction terms indicated that cultivar and soil pH were responsible for differences in milling rate (Figure 1).

Milling rate differences among cultivars would be expected due to the differing seed types examined in this study. Savannah and Funk cultivars have thicker seed coats, which resist field-weathering damage more successfully than Warner and Dekalb cultivars (weathering susceptibility order: Dekalb ≫ Warner > Funk > Savannah). The rate at which these cultivars were abrasively milled followed the same trend, although differences were not always significant (Figure 1). Seeds of the Dekalb cultivar produced at both high and low soil pH are more rapidly milled than corresponding Savannah and Funk samples. The effects of soil pH were cultivar dependent. Milling behavior of the two cultivars at the extremes of weathering susceptibility and milling rate, Dekalb and Savannah, were significantly affected by soil pH, while the other cultivars were not. For both susceptible cultivars, samples produced on acid soils milled faster than those produced on neutral soils. This result is especially interesting in light of the fact that while all four cultivars are susceptible to acid soil stress, Dekalb and Savannah are better adapted to general environmental conditions in the region than the others (annual statewide cultivar yield trials in Georgia; Raymer, P. L., University of Georgia,

Table II. Analysis of Covariance and Test of Homogeneity of Slopes

source	degree of freedom	adjusted sums of squares	F
cultivar (Cul)	3	5.095	1.86 NS
pH	1	0.140	0.15 NS
Cul × pH	3	0.605	0.22 NS
time	1	4975.055	5456.78[a]
time 2	1	783.693	859.58[a]
time 3	1	290.781	318.94[a]
time × Cul	3	64.903	23.73[a]
time 2 × Cul	3	40.989	14.99[a]
time 3 × Cul	3	31.350	11.46[a]
time × pH	1	10.396	11.4[a]
time 2 × pH	1	5.347	5.86[a]
time 3 × pH	1	5.526	6.06[a]

[a] Significantly different at $P < 0.01$.

private communication, 1986). In contrast to their similar response to soil pH stress, these cultivars represent extremes in food quality, Dekalb being a full yellow endosperm type; Funk, a red-seeded (phenotypically) heteroyellow; Warner a white-seeded heteroyellow; and Savannah, a brown-seeded, high tannin type. Thus, while acid soil stress reduces yield of grain, it may reduce the time and energy required to mill the resulting seed for some cultivars. Conversely, greater care must be exercised when these susceptible seeds are processed to avoid over-milling.

Results of compositional analyses are presented in Table III. Composition of whole grain was generally similar to that reported by other workers (Neucere and Sumrell, 1980; Pedersen and Eggum, 1983). Protein contents tended to be somewhat lower than usually reported, while the fat content of the Warner cultivar was unusually high. Only Savannah contained detectable tannin. Effects of extraction rate, cultivar, and soil pH on compositional variables were tested by an ANOVA procedure in which nominal extraction rates of 100, 90, 80, 70, 60, and 50 were used. Actual extraction rate values were within 1 unit of nominal values in all cases. This procedure was useful principally for obtaining information on effects of extraction rate. In order to distinguish effects of cultivar and soil pH, an analysis of covariance in which actual extraction rate was the covariate was employed. The differences between cultivar were tested by pooling over the variation in pH. Likewise, soil pH differences were tested by pooling over cultivar variation. Cultivar differences were determined by making pairwise contrasts; soil pH differences were determined within cultivar. Differences within both effects were found by a *t*-test.

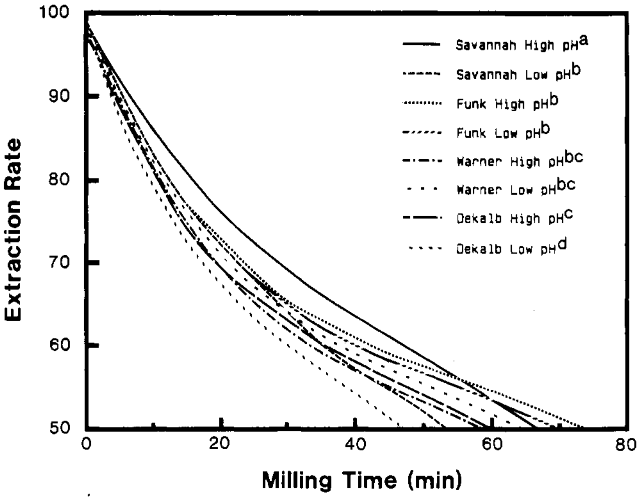

Figure 1. Extraction rate vs milling time relationships (third-order polynomial) for cultivar × soil pH treatments. Regression equations for treatments sharing a common letter are not significantly different ($P < 0.05$).

As would be examined, extraction rate of the sorghum grain had a major effect on composition. Only relative starch content was increased by milling, the major change occurring between 100 and 90% extraction rates. The relative protein content generally declined with extraction rate but was not significantly reduced at 90%. Relative fat and fiber contents declined more rapidly during the first part of the milling procedure and then leveled off somewhat as abrasion continued. Relative ash content declined steadily as more of the grain was removed. Relative tannin content of the Savannah cultivar was

Table III. Sorghum Composition[a] as a Function of Cultivar, Soil pH, and Extraction Rate

cultivar	nominal extractn rate	moisture,[b] % high pH	moisture,[b] % low pH	starch,[c] % high pH	starch,[c] % low pH	protein,[c] % high pH	protein,[c] % low pH	fat,[c] % high pH	fat,[c] % low pH	fiber,[c] % high pH	fiber,[c] % low pH	ash,[c] % high pH	ash,[c] % low pH	tannin,[c] % high pH	tannin,[c] % low pH
Dekalb	100	13.33	12.47	54.7	64.6	10.8	10.5	3.36	2.98	4.12	3.77	1.3	1.5	ND[d]	ND
Dekalb	90	12.34	12.75	70.4	66.7	10.8	10.3	2.50	1.52	1.87	2.72	1.0	1.3	ND	ND
Dekalb	80	12.41	12.78	73.4	71.9	10.3	10.2	2.10	1.49	2.00	1.67	0.8	1.2	ND	ND
Dekalb	70	12.26	12.87	84.1	75.8	10.1	9.7	1.72	1.89	1.42	1.46	0.7	1.0	ND	ND
Dekalb	60	11.73	12.15	91.8	84.7	9.4	9.1	1.23	0.52	1.27	1.43	0.5	0.9	ND	ND
Dekalb	50	11.39	11.51	89.0	87.8	8.9	8.6	0.47	0.54	0.81	1.28	0.2	0.8	ND	ND
Funk	100	13.82	12.05	60.9	62.3	10.8	10.7	3.25	3.01	3.83	3.68	1.5	1.5	ND	ND
Funk	90	13.23	11.57	64.2	69.2	10.7	10.8	2.78	2.68	2.62	2.31	1.4	1.4	ND	ND
Funk	80	12.68	11.83	68.5	72.7	10.4	10.0	2.34	2.21	1.76	1.60	1.2	1.1	ND	ND
Funk	70	12.41	11.38	73.8	78.2	9.6	9.6	2.18	1.64	1.52	2.03	1.0	1.1	ND	ND
Funk	60	11.75	10.98	74.7	80.9	8.8	8.6	1.20	1.33	1.18	1.10	0.8	0.9	ND	ND
Funk	50	11.45	10.75	78.3	86.0	7.6	8.1	0.73	0.99	1.23	1.16	0.6	0.8	ND	ND
Savannah	100	12.54	12.0	60.6	57.5	10.7	10.6	3.75	3.58	5.34	4.74	1.4	1.5	1.3	1.3
Savannah	90	12.17	12.88	68.0	64.6	11.1	10.5	3.53	3.01	3.98	3.35	1.4	1.4	0.7	0.7
Savannah	80	11.78	12.49	74.2	71.8	10.4	10.2	2.85	2.88	2.28	2.34	1.2	1.2	0.1	0.2
Savannah	70	11.41	12.31	76.0	74.1	9.8	9.6	2.57	2.58	1.75	1.54	1.1	1.1	0.02	0.07
Savannah	60	11.16	11.83	81.3	77.2	9.3	9.0	2.36	1.22	1.30	1.15	1.1	1.0	ND	ND
Savannah	50	10.82	11.40	85.0	80.2	8.6	8.7	1.64	1.56	0.78	1.00	0.8	0.8	ND	ND
Warner	100	12.23	13.59	60.1	61.0	9.7	9.9	8.52	9.08	3.45	3.68	1.6	1.5	ND	ND
Warner	90	11.94	13.14	69.6	68.9	9.9	9.5	8.07	8.13	2.06	2.29	1.5	1.3	ND	ND
Warner	80	12.97	12.77	70.1	73.8	9.3	9.1	7.40	7.72	2.16	1.85	1.2	1.1	ND	ND
Warner	70	11.97	12.55	74.1	75.4	8.4	8.4	7.33	7.42	1.81	1.54	1.1	1.0	ND	ND
Warner	60	11.89	11.96	82.4	84.9	7.5	7.9	6.68	6.63	1.25	1.15	0.8	0.9	ND	ND
Warner	50	11.15	11.55	81.2	84.3	7.8	7.1	6.35	6.47	0.98	1.17	0.6	0.7	ND	ND

[a] Values are means of determinations on duplicate samples. [b] Wet basis. [c] Dry basis. [d] Not detectable.

halved by milling to 90% extraction and continued to decline steeply with extraction rate. With the exception of protein, these results are similar to those of Pedersen and Eggum (1983) who found a slight increase in protein as sorghum was milled from 100 to 64% extraction.

Cultivar and soil pH affected composition in a complex manner. Cultivar differences were observed for each component, while soil pH affected only starch and ash content of certain cultivars. Tannin was not included in the overall analysis as it occurred in only one cultivar. However, it appears to be unaffected by soil pH in that instance. It should be remembered that, in this analysis, composition values are pooled across extraction rate so that the results do not necessarily reflect composition at the higher, more practical extraction rates (≥80%).

The results of this study, in agreement with those of others (Ali and Wills, 1983), indicate that both cultivar and production conditions can affect milling rate and composition of sorghum grain. The observed differences in milling rate were not great; however, small variations can be of large importance in the economics of the process. Even at 80 or 90% extraction, required milling times differed by a factor of 1.8, which would factor into a substantial cost differential. The cultivars examined in this work are widely grown in the United States and would likely be among those utilized for human food should sorghum food products be developed by American food processors. Nevertheless, more cultivars and cultural practice treatments must be studied to validate the proposed model for abrasive milling and to verify the effects of cultural practice on milling behavior and composition of the grain. Given the variation in composition and milling rate and the need for functional and nutritional data, it would be premature to attempt to choose the optimal cultivar for food use, even among these four. However, it is important to remember that ultimate utilization largely depends on processing and sensory characteristics. Ali and Wills (1983) reported that consumers of sorghum, where it is a staple, generally prefer indigenous cultivars over improved hybrids for food use due to the poor cooking quality of the latter. Thus, the wider acceptance of sorghum as a food grain in industrialized countries and of improved cultivars in developing countries depend on producing cultivars that are improved with respect to processing, as well as agronomic characteristics.

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