Puffing Quality of Experimental Varieties of Proso Millets (*Panicum miliaceum*)

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Cereal Chem. 69(4):359–365

ABSTRACT

Eight experimental varieties of proso millet (*Panicum miliaceum*) were studied to determine varietal differences in puffing quality. The grains were raised to 12, 15, or 18% moisture, equilibrated for 72 hr, and gun puffed at 140 psi. Significant differences in puffing quality were observed on the basis of puffed yields and expansion volumes. Variety 2027, which demonstrated good puffing quality, was selected for further studies of the physical, nutritional, and functional properties of products processed under various puffing conditions. A factorial arrangement of treatments was used. The grains were raised to 12, 15, or 18% moisture, allowed to equilibrate for 72 hr, and gun puffed at 120, 140, or 160 psi. Puffing quality was significantly improved when grains were tempered to 15 or 18% moisture and gun puffed at 140 or 160 psi. The puffed products were more highly expanded, less dense, and higher in protein content, but lower in ash and total dietary fiber, than those tempered to 12% moisture or gun puffed at 120 psi. In vitro nitrogen digestibility of the puffed products was adversely affected by low moisture and the intense heat treatments required to reach high pressures. The puffed products demonstrated a much greater rate of in vitro starch digestibility than unprocessed millet. Nitrogen solubility of the puffed products was greatly reduced under all process conditions.

The millets are a group of variable, small-seeded, annual grasses that are native to many parts of the world. They are resistant to drought and disease and are able to grow in poor soils and hot, dry climates. The millets are of particular value in arid and semiarid regions where unfavorable environmental conditions often lead to failure of wheat, rice, maize, and other cereal crops (Rachie 1975).

This cereal provides a nutritious, staple food source for millions of people in Africa, India, and Asia. It may be ground into a flour and incorporated into fermented or unfermented breads and porridges, or it may be used in the production of alcoholic and nonalcoholic beverages, steamed or boiled foods, and snacks (Vogel and Graham 1979).

In western nations, the millets are of minor economic importance because of the great abundance of wheat, maize, and other cereal crops and the popularity of the products derived from those grains (Rachie 1975). Because of its favorable dryland conditions, Colorado is the largest producer of millet in the United States. Proso millet (*Panicum miliaceum*) is most common, although foxtail millet (*Setaria italica*) and pearl millet (*Pennisetum americanum*) are also grown. Each of these varieties is primarily cultivated for use as livestock feed or in birdseed mixtures (Johnson and Croissant 1985, Croissant and Shanahan 1987). Very little millet is produced for consumption by the American population. Small amounts of lightly pigmented proso millet are decorticated and processed into puffed or hot breakfast cereals (Hinze 1972). Flour ground from proso millet has been successfully used as a partial replacement for wheat flour in breads, cookies, and pasta (Awadalla 1974, Lorenz and Dilsaver 1980). A limited variety of such foods is available through health food stores. Finding new food applications for millet in the American market could serve to enhance Colorado millet production and use of this crop.

Millet, which has structural characteristics similar to those of popcorn and certain varieties of sorghum, is capable of explosive popping that is accompanied by a simultaneous large increase in volume (Hoseney 1986). The popping of millet results in a small, porous, crunchy product with properties similar to those of popcorn. Thus, an ideal food application would be the development of a popped, or puffed, whole-grain snack product.

Limited research on popped millet has been reported in the English literature. Malleshi and Desikachar (1981) studied varietal differences in puffing quality of ragi (*Eleusine coracana*). Of 14 varieties studied, only five demonstrated good puffing quality on the basis of puffing yield and bulk volume.

Muralikrishna et al (1986) studied the effect of popping on the properties of starches isolated from pearl millet, ragi, and foxtail millet. Popping resulted in a complete loss of birefringence. These starches also demonstrated slightly higher solubility and swelling power at pregelatinization temperatures. Lower cold paste, setback viscosity, and relative viscosity were caused by a breakdown of starch granules during popping.

The information available on puffed millet would be greatly enhanced through studies on characteristics that influence product quality, such as puffed yield, expansion volume, bulk density, nutritive content, and functionality. Therefore the objectives of this study were to 1) produce an acceptable puffed millet product that offers potential to increase the economic value of millet through food processing; 2) study the effects of variety, moisture content, and pressure on puffing quality; 3) determine optimal process conditions; and 4) study the physical, nutritional, and functional properties of products processed under various puffing conditions.

MATERIALS AND METHODS

Sample Identification

Proso millet was obtained from the Colorado State University Agronomy Department. Experimental varieties 2001, 2006, 2009, 2022, 2027, 2031, 2036, and 2038 were studied. Variety 2038 was grown during the 1985 season in experimental plots located in Akron, CO. The other varieties were grown during 1987 in experimental plots at the Agricultural Experimental Station farm located in Fort Collins, CO.

Sample Preparation

After initial moisture determinations (method 44-15A, AACC 1983), the samples were raised to 12, 15, or 18% moisture by the addition of a predetermined amount of water to the grains. For each moisture level, duplicate 250-g samples were prepared and sealed in airtight containers. The samples were permitted to equilibrate for 72 hr at room temperature before puffing.

Equipment and Process Conditions

A single-shot, cylindrical gun-puffing vessel was used for expansion puffing of the millets. The vessel had the following physical dimensions: internal diameter, 11 cm; length, 27 cm; internal volume, 700 cm^3. The cylindrical chamber was sealed at one end with a steel plate from which a thick-walled shaft extended to support the weight of the chamber when mounted in a cantilever configuration. The shaft was supported with bearings to permit rotation of the chamber. The vessel was mounted on a tiltable table to allow the chamber to be inclined for locking and discharge. The shaft had an open center extending from the inside of the chamber to the outside, which permitted measurement of the internal pressure during tests. The other end

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of the cylindrical chamber was sealed with a detachable end plate. This plate was held in place during testing by an internal shaft that extended through the chamber, in turn held in place by a locking-and-releasing bolt. When the correct pressure was achieved in the chamber, the locking mechanism was released, thereby transferring the grains to a lower pressure and causing puffing of the grains. Figures 1 and 2 show a diagram and a picture of the vessel, respectively.

Before testing, the chamber was preheated, then charged with 250 g of tempered grain, and immediately sealed. The chamber pressure and temperature were allowed to equilibrate for 2 min or until the pressure of the chamber reached 60 psi, which was a level that could be reached without additional heating. At this point, heating was continued to raise internal pressure. In the initial study, which determined the varietal differences in puffing quality, the internal pressure of the chamber was raised to 140 psi. Additional studies of the physical, nutritional, and functional properties of products processed under various puffing conditions required that the internal pressure of the chamber be raised to 120, 140, or 160 psi. To prevent burning, the volumetric chamber was rotated at a speed of 45–50 rpm. The chamber was heated until the pressure was raised to the desired discharge pressure. Heat was discontinued, and the chamber allowed to equilibrate. At the time of discharge, the chamber was pointed into a vented bin and the detachable end plate was released. The samples were collected and stored in sealed plastic bags at room temperature until evaluation.

Product Evaluation

Puffed yield. Puffed and unpuffed kernels were separated using a U.S.A. standard testing sieve (no. 6, Fischer Scientific Co., Pittsburgh, PA). The puffed yield was calculated as:

$$\text{Puffed yield} = \frac{\text{wt of puffed kernels (g)}}{\text{original sample wt (g)}} \times 100$$

Expansion volume. A 100-ml graduate cylinder was filled with puffed materials and then weighed. The unprocessed kernel volume (in milliliters) of equal weight (in grams) for the given sample was then determined. The average of three measurements was recorded, and expansion volume was calculated as:

$$\text{Expansion vol} = \frac{\text{100 ml of puffed kernels}}{\text{vol of equal wt of unpuffed kernels}}$$

Density. A small beaker was filled to capacity with water and the volume was recorded (in cubic centimeters). The beaker was then filled with an equal volume of unprocessed grain or puffed materials and weighed. The average of three measurements was calculated, and density expressed as density = g/cm^3.

Proximate analysis. Before analysis, all samples were ground in a micromill (The Lab Apparatus, Cleveland, OH) to 2.00-mm mesh. Moisture, protein, crude fat, and ash were determined according to AACC methods 44-15A, 46-13, 30-20, and 08-01, respectively (AACC 1983). Each analysis was done in triplicate. Total dietary fiber was determined according to AACC method 32-05 (AACC 1983). Dietary fiber determinations were performed in duplicate.

In vitro nitrogen digestibility. In vitro nitrogen digestibility was determined using a modification of the method described by Sheffner (1963). On the basis of protein content, samples were measured so as to contain 2 mg of nitrogen per milliliter. The samples were suspended in 40 ml of distilled water and allowed to rehydrate for 60 min at 5°C.

The pH of the rehydrated samples was adjusted to 7 using 0.01, 0.1, and 1*N* HCl and NaOH solutions. The samples were then incubated in a 37°C water bath, and 3 ml of lyophilized, crystallized trypsin (Sigma Chemical Co., St. Louis, MO) at a concentration of 40 mg/ml was added. Changes in pH were measured at 1-min intervals for 10 min. Each analysis was performed in triplicate.

In vitro starch digestibility. In vitro starch digestibility was determined using the method described by Jenkins et al (1987). Two-gram samples were added to 10 ml of pooled fresh human saliva. Distilled water was added to make the final volume of all samples 30 ml. The slurries were thoroughly mixed and quantitatively transferred into 13-cm-long dialysis bags (width, 4.5 cm; pore diameter, 4.8 nm; and molecular weight cutoff, 12,000; Fischer Scientific). The bags were placed into separate beakers containing 800 ml of distilled water at 37°C. The beakers were then placed into a 37°C water bath with continuous agitation. At the time of incubation and at 1, 2, and 3 hr, 2.5 ml of dialysate was pipetted into a 100-ml volumetric flask, diluted to volume with distilled water, and analyzed for total carbohydrate content using the phenol-sulfuric acid method (Dubois et al 1956). Each analysis was performed in triplicate. Products of total starch digestion were expressed as milligrams per milliliter per hour.

Nitrogen solubility. Samples were prepared for determination of nitrogen solubility according to the method of Saunders et al (1974). Unprocessed and puffed samples weighing 0.2 g were measured into centrifuge tubes and suspended in 9 ml of distilled water. The pH of each sample was adjusted to a range between 2 and 10, using solutions of 0.01, 0.1, and 1*N* HCl and NaOH.

The samples were incubated in a water bath with continuous agitation at 25°C for 60 min. Distilled water was then added to make the sample volume 10 ml, and the samples were centrifuged at 6,000 rpm for 15 min using an IEC model CL centrifuge (International Equipment Co., Needham, MA). The samples were then filtered through Whatman no. 2 filter paper, and the supernatant was collected for analysis. The percentage of nitrogen solubilized was determined by the method described by Mitchell (1972).

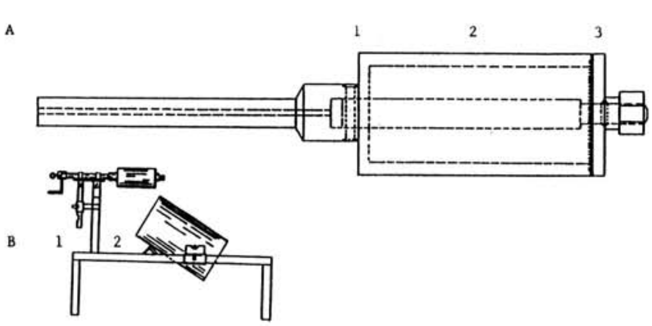

Fig. 1. Diagrams of the single-shot gun-puffing vessel used for expansion puffing of the millet grains. **A,** Locking-and-releasing bolt (1), internal shaft extending through the chamber (2), and detachable end plate (3). **B,** Cylindrical pressure chamber mounted on a tiltable table allowing the chamber to be inclined for locking and discharge (1) and the vented bin used for sample collection (2).

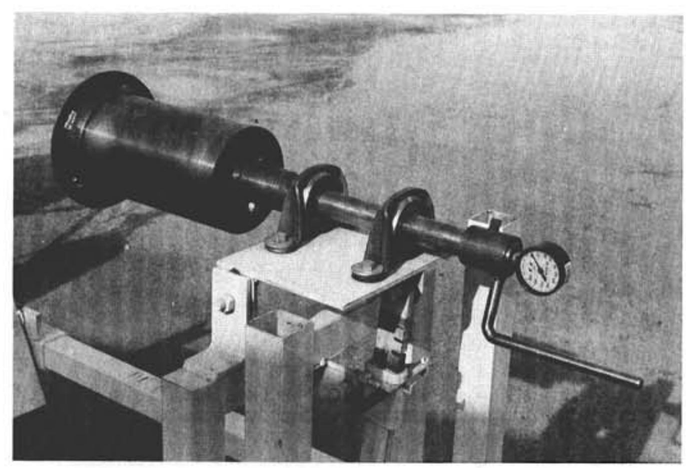

Fig. 2. Gun-puffing vessel used in this study.

Scanning Electron Microscopy

Representative puffed kernels were cut into thin sections with a razor blade and mounted onto Philips aluminum specimen stubs (Philips, Mahwah, NJ) with colloidal graphite. They were then vacuum-coated with gold (200 Å) using a Technics Hummer sputter coater. Samples were viewed with a Philips 505 scanning electron microscope. Polaroid type 55 film was used to photograph the structure of puffed millet.

Statistical Analysis

The data were analyzed using the Statistical Analysis System General Linear Models Procedure (SAS 1987). Means comparisons were performed using Tukey's studentized range test to determine the significance of moisture content and pressure on the following product characteristics: puffed yield, expansion volume, and density.

RESULTS AND DISCUSSION

Varietal Differences in Puffing Quality

Puffed yield. In general, puffed yield for each variety of millet progressively improved as the initial moisture contents of the grains were raised from 12 to 15 or 18% (Table I). However, only differences in puffed yield when moisture was raised from 1 to 15% were statistically significant. A 12% moisture content provided inadequate water for the grain to generate superheated steam as the driving force for optimal puffing of the grains. Unprocessed and puffed kernels of millet variety 2027 are shown in Figure 3.

In a study of the varietal differences in the puffing quality of ragi, Malleshi and Desikachar (1981) reported a puffing yield ranging from 64 to 97% among 14 varieties. In comparison, the puffed yields obtained in this study were considerably lower in all varieties when tempered to 12 and 15% moisture levels. At 18% moisture, the puffed yields for five of eight varieties fell within the range reported by these authors.

Expansion volume. The degree of expansion occurring in a grain depends on the conversion of water to superheated steam and the pressure differential between the vessel and the atmosphere (Fast 1990). The effect of initial moisture content on the expansion volume of each variety of proso millet is shown in Table I. Sequential increases in expansion volume were observed as the moisture contents of the grains were raised from 12 to 15% and then to 18%. In four varieties there is a statistically significant increase from 12 to 15%. Differences in expansion volume when grain moisture is raised from 15 to 18% were not statistically significant. Varieties 2027 and 2031 produced the highest expansion volumes when grain moisture was at 18% at the time of puffing. Like puffed yield, a moisture content of 12% seems inadequate for optimal expansion of most varieties of proso millets. Expansion volumes ranged from 8.27 to 12.16 ml at 12% moisture, from 10.48 to 13.54 ml/g at 15% moisture, and from 9.24 to 14.80 ml/g at 18% moisture. Malleshi and Desikachar (1981) previously reported bulk volumes in ragi at 19% moisture that ranged from 3.9 to 7.7 ml/g. In comparison, the volumes obtained at all moisture levels in this study are much greater.

Density. Like puffed yield and expansion volume, product density may be influenced by process conditions. One such variable is moisture content of the grain before puffing. Densities of the

TABLE I
Effect of Moisture Content on Puffing Quality of Proso Millet[a,b]

Variety	Moisture Content (%)	Puffed Yield[c] (%)	Expansion Volume[d] (ml/g)	Density[d] (g/cm^3)
2001	12	23.12 ± 1.27 a	12.16 ± 0.77 a	0.059 ± 0.001 a
	15	49.89 ± 3.83 b	12.15 ± 0.40 a	0.059 ± 0.002 a
	18	57.53 ± 0.42 b	11.89 ± 1.23 a	0.059 ± 0.010 a
2006	12	28.76 ± 0.14 a	9.20 ± 0.25 a	0.076 ± 0.003 b
	15	52.90 ± 1.20 ab	12.12 ± 0.57 b	0.061 ± 0.004 a
	18	65.80 ± 2.96 b	12.21 ± 0.65 b	0.065 ± 0.002 ab
2009	12	27.48 ± 1.48 a	10.57 ± 0.91 a	0.069 ± 0.006 a
	15	40.09 ± 1.32 ab	10.48 ± 0.24 a	0.069 ± 0.004 a
	18	49.44 ± 1.51 b	11.33 ± 1.04 a	0.068 ± 0.015 a
2022	12	27.33 ± 1.78 a	9.14 ± 0.07 a	0.077 ± 0.002 b
	15	51.13 ± 3.05 ab	12.21 ± 0.25 b	0.064 ± 0.002 ab
	18	67.68 ± 1.04 b	11.63 ± 1.14 b	0.058 ± 0.000 a
2027	12	25.75 ± 1.77 a	8.27 ± 1.00 a	0.082 ± 0.007 b
	15	56.10 ± 2.93 b	13.50 ± 0.56 b	0.055 ± 0.001 a
	18	69.37 ± 4.52 b	14.05 ± 0.87 b	0.053 ± 0.003 a
2031	12	15.84 ± 0.07 a	9.82 ± 0.01 a	0.072 ± 0.007 b
	15	42.96 ± 3.39 b	13.54 ± 0.88 b	0.057 ± 0.006 a
	18	71.01 ± 1.84 c	14.80 ± 0.54 b	0.049 ± 0.001 a
2036	12	17.11 ± 2.62 a	8.76 ± 0.91 a	0.088 ± 0.002 b
	15	32.01 ± 0.91 a	10.65 ± 0.84 ab	0.071 ± 0.007 ab
	18	65.85 ± 2.12 b	12.26 ± 0.36 b	0.060 ± 0.001 a
2038	12	7.77 ± 1.98 a	9.56 ± 0.60 a	0.080 ± 0.001 a
	15	40.24 ± 1.34 b	11.42 ± 0.83 a	0.062 ± 0.002 b
	18	38.07 ± 1.77 b	11.52 ± 1.78 a	0.064 ± 0.009 a

[a]Values are based on averages ± standard deviation using Tukey's studentized range test. Within each variety, mean values in the same column with the same letter are not significantly different. Mean standard deviation = 19.16, 2.49, and 0.16 for puffed yield, expansion volume, and density, respectively.
[b]All products gun puffed at 140 psi.
[c]Average of two replicates in puffing; puffed yield = [(wt of puffed kernels, g)/(original sample wt, g)] × 100.
[d]Average of three replicates in puffing; expansion vol = 100 ml of puffed kernels/vol of equal wt of unpuffed kernels.

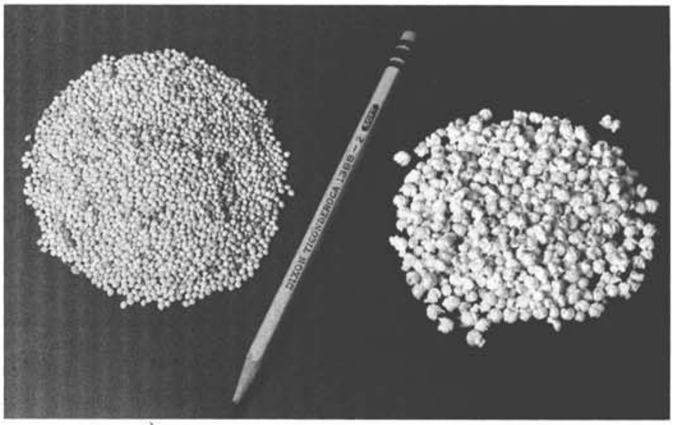

Fig. 3. Unprocessed millets and resulting puffed product (variety 2027).

TABLE II
Effect of Increasing Moisture and Pressure on the Physical Properties Affecting Puffing Quality[a,b]

Pressure (psi)	Moisture (%)	Puffed Yield (%)	Expansion Volume[c] (ml/g)	Density[c] (g/cm^3)
120	12	2.24 ± 0.46 a	8.20 ± 0.19 a	0.078 ± 0.003 b
	15	33.80 ± 2.51 b	9.76 ± 0.28 a	0.065 ± 0.009 ab
	18	51.10 ± 1.04 b	11.10 ± 0.62 b	0.062 ± 0.001 a
140	12	25.76 ± 0.65 a	8.27 ± 1.00 a	0.082 ± 0.006 b
	15	56.10 ± 2.93 b	13.50 ± 0.56 b	0.055 ± 0.009 a
	18	69.38 ± 4.52 b	14.05 ± 0.87 b	0.053 ± 0.003 a
160	12	18.94 ± 2.27 a	7.46 ± 0.32 a	0.101 ± 0.003 b
	15	62.64 ± 0.08 b	12.94 ± 0.27 b	0.056 ± 0.004 a
	18	66.87 ± 0.53 b	13.20 ± 0.05 b	0.057 ± 0.002 a

[a]Experiment used millet variety 2027 and Tukey's studentized range test. Values are averages ± standard deviation. For each puffing pressure, mean values in the same column with the same letter are not significantly different.
[b]Average of two replicates in puffing; puffed yield = [(wt of puffed kernels, g)/(original sample wt, g)] × 100.
[c]Average of three replicates in puffing; expansion vol = 100 ml of puffed kernels/vol of equal wt of unpuffed kernels.

puffed grains were 0.059–0.088, 0.055–0.071, and 0.049–0.077 g/cm^3 at 12, 15, and 18% moisture contents, respectively (Table I). Significant differences in product density were observed in four varieties as grain moisture was raised from 12 to 18%. The density of the puffed grains generally showed a decreasing trend when moisture was raised from 12 to 15 or 18% initial moisture content. When processed, these grains were more highly expanded and thus less dense. Exceptions were noted in varieties 2001 and 2009, where no changes in density occurred as the initial moisture content increased.

Evaluation of puffing quality. On the basis of puffed yield, expansion volume, and density, three varieties, 2027, 2031, and 2036, were judged good in puffing quality. Significant differences in puffed yields and expansion volumes were observed within treatments among these puffed grains.

Variety 2027 was selected for further studies of the physical, nutritional, and functional properties of products processed under various puffing conditions.

Effect of Puffing Conditions on Physical Properties

Puffed yield. In previous studies of the popping performances of several cereals, optimum yields were achieved at moisture levels of 14.4–17.7% in popcorn (Hoseney et al 1983), 14% in paddy rice (Srinivas and Desikachar 1973), and 19% in ragi (Malleshi and Desikachar 1981).

The effect of variations in moisture on puffed yield of proso millet variety 2027 is presented in Table II. The puffed yield of proso millet significantly improved when the moisture content was increased from 12 to 15 or 18% at each pressure level. On the basis of these findings, an 18% moisture content produced an optimum puffed yield in this variety of proso millet. Moisture content, rather than pressure, had the principal influence on puffed yield.

Expansion volume. Like puffed yield, variations in initial moisture content of the grains and gun puffing at constant pressures caused a marked increase in expansion volumes within each treatment (Table II). Significant improvements in expansion volumes of the grains occurred as the moisture content was raised from 12 to 15 or 18%. A moisture content of 12% seemed inadequate for optimal expansion.

A maximum expansion volume of 14.05% was achieved when grains were tempered to 18% moisture and gun puffed at 140 psi. Up to a 30% increase in expansion volume may occur in popcorn containing 13–17% moisture (Hoseney et al 1983). When differences in the kernel sizes of corn, which weigh an average of 350 mg, and of proso millet, which weigh an average of 6.5 mg, are considered, an expansion of approximately 14% in proso millet is quite favorable.

Density. Increases in moisture content of the grain before puffing led to favorable reductions in product density when processed at constant pressures (Table II). Grains tempered to 15 and 18% moisture contents and gun puffed at 140 psi resulted in products that were most highly expanded and, therefore, lowest in density.

Proximate composition. Proximate compositions of proso millet indicate protein contents ranging from 11.3 to 13.7%, crude fat contents from 3.3 to 4.9%, ash contents from 3.0 to 7.6%, and crude fiber contents from 4.2 to 19.2% (Baptist and Perera 1956, Matz 1959, Hinze 1972, Rooney et al 1982, Lorenz and Hwang 1986). Such variations in composition are caused by differences among species and the environmental conditions under which the crop is grown. When compared with other important cereal grains, the protein content of proso millet compares favorably, whereas fat content is somewhat greater.

The proximate compositions of unprocessed millet and products processed under various puffing conditions in this study are shown in Table III. The composition of unprocessed proso millet used in this study is comparable to that previously reported in the literature, although protein content is slightly higher.

In comparison with unprocessed millet, the puffed products were higher in protein but lower in ash and fiber. With processing, protein increased with higher moisture contents and pressures due to loss of ash and fiber. The compositional differences in ash and fiber were most remarkable in grains tempered to 15 or 18% moisture contents and gun puffed at 140 or 160 psi. This is indicative of a more efficient removal of pericarp during processing with greater moisture contents and pressures.

At 12 and 15% moisture, regardless of pressure, lipid content of the puffed materials was greater than that of unprocessed millets. Again, this was attributed to the loss of mineral matter and fiber with processing. A decline in lipid content was noted as pressure was increased from 120 to 140 and then 160 psi at 18% moisture content. This was probably a result of lipid interactions with other components of the grain, such as protein and carbohydrates, that rendered the lipid less available for extraction.

In vitro nitrogen digestibility. Changes in nutrient composition and quality occur when a food is subject to processing. Heating may benefit protein digestibility by rendering the protein more susceptible to hydrolysis because of structural changes (Maga et al 1973). The measurement of the initial rate of proteolysis with trypsin is used as a simple means to determine the digestive acceptability of food protein sources. Heat processing also may be detrimental to protein quality and digestibility.

Figure 4 illustrates the effect of variations in moisture content at 160 psi on the in vitro nitrogen digestibility of unprocessed and puffed proso millet. At 12% moisture, a lower susceptibility to enzymatic hydrolysis was observed, as indicated by the slight decrease in pH. This was attributed to the low level of moisture available within the grain for the conversion to superheated steam that enables expansion puffing. Intense heat treatment was required to expand the grain at this marginal moisture level, which had an adverse effect on digestibility. The in vitro digestibility

TABLE III
Proximate Composition of Unprocessed and Puffed Proso Millet[a]

Process Condition	Ash	Lipid	Nitrogen	Protein[b]	TDF[c]
Unprocessed millet	3.23 ± 0.11	3.88 ± 0.09	2.24 ± 0.06	14.03	17.0 ± 1.2
12% moisture					
120 psi	ND[d]	ND	2.29 ± 0.03	14.29	ND
140 psi	2.50 ± 0.10	4.45 ± 0.20	2.32 ± 0.05	14.51	16.4 ± 0.6
160 psi	2.02 ± 0.10	4.09 ± 0.18	2.38 ± 0.06	14.86	12.2 ± 0.2
15% moisture					
120 psi	2.06 ± 0.12	5.10 ± 0.26	2.43 ± 0.02	15.20	16.1 ± 1.1
140 psi	1.78 ± 0.09	4.62 ± 0.19	2.39 ± 0.06	14.94	12.1 ± 1.0
160 psi	1.58 ± 0.11	4.20 ± 0.20	2.44 ± 0.07	15.27	5.9 ± 0.2
18% moisture					
120 psi	1.80 ± 0.12	3.77 ± 0.18	2.44 ± 0.04	15.22	10.7 ± 1.1
140 psi	1.71 ± 0.09	3.63 ± 0.13	2.35 ± 0.01	14.68	8.4 ± 0.9
160 psi	1.75 ± 0.11	3.37 ± 0.14	2.44 ± 0.01	15.28	6.0 ± 0.4

[a] Millet variety 2027 was used. Values (in percent dry basis) are the average of three replications ± standard deviation.
[b] N × 6.25.
[c] Total dietary fiber.
[d] Not determined.

of the puffed grains progressively shifted toward that of unprocessed millet as moisture content increased from 12 to 15% and then to 18%.

The effect of variations in pressure at 18% moisture content on in vitro nitrogen digestibility of unprocessed and puffed millet is shown in Figure 5. In vitro nitrogen digestibility of the puffed grains decreased when the grains were processed at 140 and 160 psi. These products remained in the puffing vessel for longer periods of time to reach the higher pressures and thus were exposed to more intense heat treatment.

The degree of damage to cereal protein may be influenced by the time and temperature of processing and the moisture content of the product (Geervani 1983). In this study, the major factors that influenced millet protein digestibility were the moisture content and the intensity of heat treatment required for expansion puffing of the grain. Greater initial moisture contents and gun puffing at 120 psi offered the grain some protection from the detrimental effects of intense heat treatments on protein nutriture.

In vitro starch digestibility. The rate of starch digestibility is affected by a number of factors, including the nature of the starch, the starch-protein interactions, the presence of fiber and antinutrients, and the type of processing the starch has undergone. Cooking, or processing such as grinding, often improves the digestibility of the starch source (Dreher et al 1984).

The results of in vitro starch digestibility are shown in Table IV. Low in vitro digestibility was observed in the unprocessed millet, as indicated by the small concentration of total starch-digestion products in the dialysate over a 3-hr period. A high enzymatic susceptibility was noticed in the puffed products, which had undergone varying degrees of heat treatment. These findings are consistent with those described by Muralikrishna et al (1986), in which the digestibility of various millet starches were improved with popping. These authors attributed the change in digestibility to the high degree of starch gelatinization that occurs during popping. Digestibility may have been further enhanced by the coarse, porous structure of the popped grain, which permitted α-amylase entrance to facilitate digestion (Leach and Schoch 1961). Variations in moisture content, intensity of heat treatment, and the presence of fiber did not greatly affect the total concentration of in vitro starch-digestion products.

Nitrogen solubility. Solubility data provide useful information on the potential applications of a protein in food systems. Nitrogen solubility, over a range of pH values, has been used to interpret protein functionality because it relates directly to many important properties, such as use in beverages, emulsification, foaming capacity, and gelation (Kinsella 1975).

The percentages of nitrogen solubilized in unprocessed and puffed millet products at various pH values are shown in Table V. The unprocessed millet protein was more highly soluble than that of the puffed products. The isoelectric point occurred at about pH 4. The nitrogen solubilities of the puffed products were greatly reduced under all process conditions, indicating a loss in protein functionality. Isoelectric points were between pH 4 and 5. In this study, no consistent pattern was observed between the effects of moisture content and the intensity of heat treatment required to reach the desired pressures on nitrogen solubility.

In an earlier study, Lorenz et al (1980) found protein solubility of millet flours to be much lower than the values reported for unprocessed millet in this study. At pH 2, the percentage of nitrogen solubility ranged from 8.38 to 11.03%. The isoelectric point occurred between pH 4.0 and 5.0, where the percentage of nitrogen solubility was lowest at 5.18–9.44%. At pH 10, the percentage of nitrogen solubility was greatest, ranging from 11.59 to 15.95%.

Solubility is affected by a number of factors, including protein concentration, processing, and conditions of solubility determination (Kinsella 1975). Differences in grain composition and the methodologies used in each of these studies most likely contributed to the dissimilarities in nitrogen solubility values. However, the isoelectric points were comparable in both studies.

Scanning Electron Microscopy

Scanning electron micrographs of partially and completely puffed grains are shown in Figure 6. The grains were tempered to 18% moisture content and gun puffed at 140 psi. Figure 6A is the endosperm of a partially puffed millet kernel showing intact and expanded starch granules. Figure 6B shows the tremendous

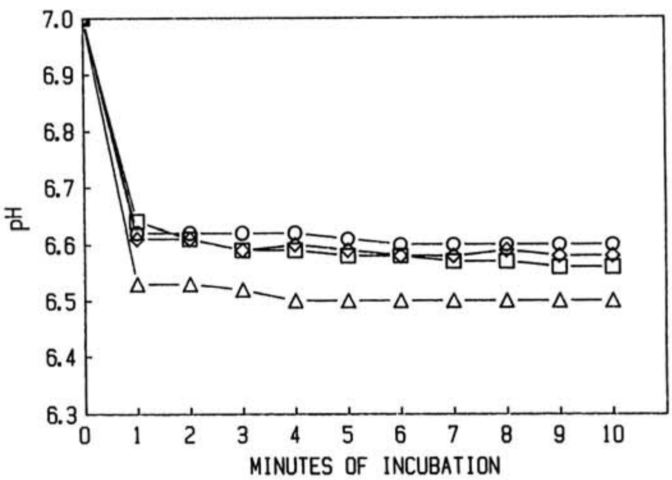

Fig. 5. Effect of variations in pressure at 18% moisture content on in vitro nitrogen digestibility of unprocessed and puffed proso millet. □ = Unprocessed millet, △ = 120 psi, ◇ = 140 psi, and ○ = 160 psi.

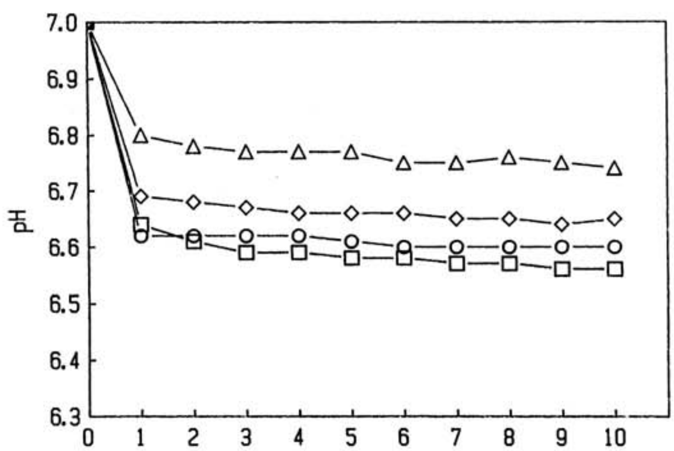

Fig. 4. Effect of variations in moisture content at 160 psi on in vitro nitrogen digestibility of unprocessed and puffed proso millet. □ = Unprocessed millet, △ = 12% moisture, ◇ = 15% moisture, and ○ = 18% moisture.

TABLE IV
Concentration of Total Starch Digestion Products of Unprocessed and Puffed Millet[a]

Treatment	Hours of Incubation 1	2	3
Unprocessed millet	0.17 ± 0.02	0.46 ± 0.06	0.84 ± 0.02
12% moisture			
140 psi	0.89 ± 0.03	1.81 ± 0.08	2.33 ± 0.12
160 psi	0.85 ± 0.06	1.63 ± 0.09	2.22 ± 0.09
15% moisture			
120 psi	0.88 ± 0.03	1.91 ± 0.17	2.49 ± 0.13
140 psi	1.05 ± 0.09	1.57 ± 0.39	2.29 ± 0.06
160 psi	1.01 ± 0.09	1.71 ± 0.09	2.34 ± 0.07
18% moisture			
120 psi	1.17 ± 0.12	1.89 ± 0.14	2.55 ± 0.06
140 psi	1.11 ± 0.10	1.87 ± 0.15	2.41 ± 0.17
160 psi	0.94 ± 0.03	1.77 ± 0.03	2.38 ± 0.06

[a] Millet variety 2027 was used. Products are expressed in milligrams per milliliter per hour and are the average of three replicates (different puffings).

expansion of the translucent endosperm of a completely puffed millet kernel. The hexapolygonal matrix represents individual starch granules that have been gelatinized and expanded by heat during the release of internal steam pressure and dried into a three-dimensional network (Reeve and Walker 1969). This structure is similar to that reported by Muralikrishna et al (1986). Figure 6C is the endosperm of a partially puffed millet kernel showing the characteristic "soap bubble" structure as described by Reeve and Walker (1969). The starch granules were gelatinized but not completely expanded by heat during the release of internal steam pressure. Figure 6D shows this structure under higher magnification.

CONCLUSIONS

Significant differences in puffing quality were observed among varieties of proso millets. Variations in puffing conditions reveal that initial moisture contents of the grains and pressure were

TABLE V
Percent Nitrogen Solubilities of Unprocessed and Puffed Millet at Various pH Values[a]

	pH								
Process Condition	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**
Unprocessed millet	12.25	7.61	6.20	9.70	10.76	11.52	15.93	18.57	25.59
12% moisture									
120 psi	8.90	7.24	3.56	4.30	4.84	5.78	6.94	8.01	8.35
140 psi	6.05	5.58	3.51	4.29	4.78	5.08	5.58	5.88	6.50
160 psi	9.16	8.44	4.73	4.44	4.52	4.86	5.13	6.63	6.80
15% moisture									
120 psi	6.57	4.63	3.31	3.60	3.96	4.54	4.49	4.67	5.92
140 psi	5.79	5.06	3.18	3.39	3.28	3.66	5.09	5.70	6.37
160 psi	9.23	8.37	4.90	6.43	6.52	6.70	7.36	8.30	9.85
18% moisture									
120 psi	9.29	5.62	4.12	4.43	4.86	5.50	5.39	6.30	10.48
140 psi	10.48	4.10	3.13	5.50	5.50	6.14	5.39	6.53	11.48
160 psi	9.65	8.35	5.26	6.21	6.60	6.66	7.24	9.67	10.85

[a] Millet variety 2027 was used. Values are the average of two replicates.

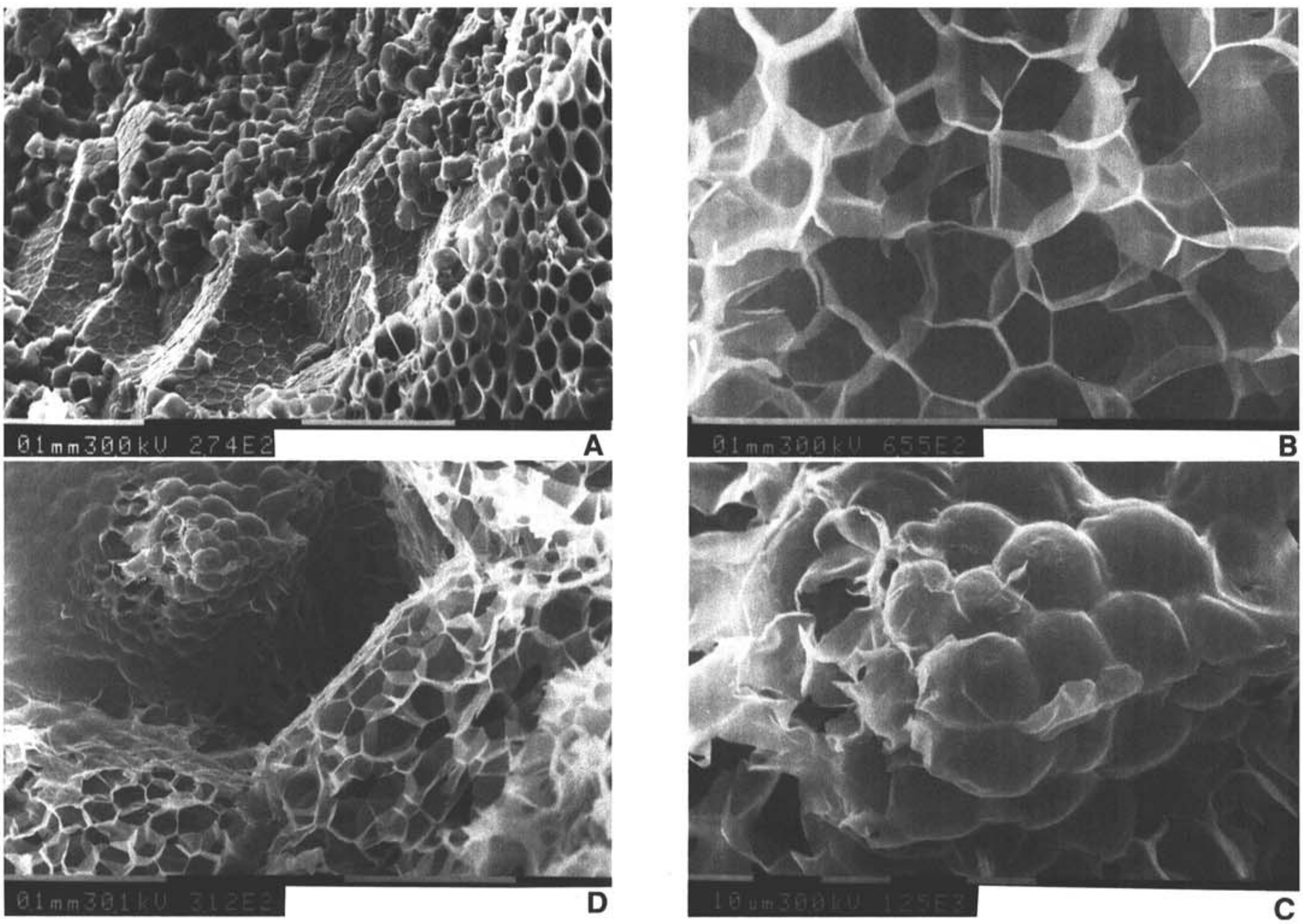

Fig. 6. Scanning electron micrographs. **A,** Endosperm of a partially puffed millet kernel showing intact and expanded starch granules. **B,** Inner portion of the endosperm of a completely puffed millet kernel showing tremendous expansion and retention of the hexapolygonal matrix. **C,** Endosperm of a partially puffed millet kernel showing the characteristic "soap bubble" structure. **D,** Soap bubble structure shown under higher magnification.

important factors in determining puffing quality and optimum process conditions. On the basis of puffed yield and expansion volume, puffing quality significantly improved when grains were tempered to 15 or 18% moisture contents and gun puffed at 140 or 160 psi. The puffed products were higher in protein but lower in ash and total dietary fiber contents than those tempered to 12% moisture content and gun puffed at 120 psi.

In vitro nitrogen digestibility of the puffed products was adversely affected by low moisture content and the intense heat treatment required to reach high pressure. The puffed products demonstrated higher in vitro starch digestibility than unprocessed millet. Nitrogen solubility of the puffed products was greatly reduced under all process conditions.

Some varieties of proso millet demonstrate good puffing quality with favorable physical characteristics. These puffed grains show potential for successful use in human food applications.

ACKNOWLEDGMENT

We thank D. Johnson, Department of Agronomy, Colorado State University, for supplying the millet samples.

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[Received April 22, 1991. Accepted January 15, 1992.]