Extrusion Cooking of Pearl Millet for Production of Millet-Cowpea Weaning Foods[1]

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ABSTRACT

Pearl millet was decorticated to yield 91%, milled into flour, and extruded at different moisture contents (12.5, 13.6, 15.0, and 16.3%). Porridges were prepared from extruded millet, press-dried cowpea, and sorghum malt. Although decortication of millet removed some pericarp and peripheral endosperm, the proximate compositions of millet and some of the essential amino acid content remained constant, whereas the in vitro protein digestibility increased. Increased radial expansion, water solubility, and cold paste viscosity was observed in extrudates prepared from decorticated millet under low moisture conditions. A lower degree of molecular dispersion in water at 85°C was observed in extrudates prepared under low-moisture extrusion conditions than were found in those prepared under high-moisture conditions. Porridges prepared from extruded millet and press-dried cowpea had high nutritional quality with acceptable properties for weaning foods (e.g., an intermediate consistency, smooth texture, and pleasant color and flavor). Treatment with sorghum malt allowed the preparation of more fluid products.

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Pearl millet (*Pennisetum americanum*) is an important staple food in India and Africa, where millets and sorghum are used interchangeably in similar traditional food systems (Serna-Saldivar et al 1991). The nutritional value of pearl millet is greatly enhanced when mixed with legumes because of better balanced essential amino acid profiles (Serna-Saldivar et al 1991). The use of pearl millet and cowpea (*Vigna unguiculata*) blends to produce weaning foods is an option for some African countries where these crops are produced (Guiro et al 1987). Low-fiber materials, which are desirable for weaning food preparation, are ideal for extrusion puffing (Guy and Horne 1988). Thin porridges with acceptable sensory characteristics can be prepared from extruded sorghum flours with no additional cooking (Gomez et al 1988).

Extrusion cooking is a continuous process with high production capacity, versatility, and low cost per product unit (Colonna et al 1984). Feed moisture is one of the most critical processing variables for extrusion cooking because it contributes to thermomechanical liquefaction and gelatinization of starch (Gomez and Aguilera 1984, Linko 1989). Cereal and tuber starches undergo several physicochemical changes during extrusion cooking (Mercier and Feillet 1975, Mercier 1977, Colonna et al 1984, Gomez and Aguilera 1984, Launay and Koné 1984, Diosady et al 1985). The extent of molecular degradation of starch is a function of extrusion parameters: temperature, moisture, feed rate, screw speed (Davidson et al 1984), and feed composition (Faubion and Hoseney 1982, Colonna and Mercier 1983).

Recent progress in starch characterization permits more detailed analysis of the physicochemical changes occurring during extrusion. The objectives of this article were to characterize extrudates obtained from decorticated pearl millet and processed under different extrusion moisture levels and to compare functional properties of weaning foods prepared from ground extruded millet blended with cowpeas.

MATERIALS AND METHODS

A 1:1 mixture of yellow and blue pearl millet grown in Nebraska (10.3% moisture, 1.484 g/cm^3 density, and 81.7 kg/hl test weight) and Kansas (11.3% moisture, 1.493 g/cm^3 density, and 78.8 kg/hl test weight) in 1988 was used to evaluate the effects of feed moisture level during extrusion.

Decortication of Millet

Millet (5 kg) was processed to yield 91% decorticated kernels using an IDRC abrasive mill (International Development Research Centre, Ottawa, Canada) equipped with eight 24-cm-diameter disks (Reichert 1982). Decorticated kernels were cleaned and ground into flours as reported by Almeida-Dominguez et al (1993). Flours were stored in polyethylene bags at −18°C.

Extrusion Cooking of Millet

A Wenger TX-52 twin-screw extruder (Wenger Manufacturing Co., Sabetha, KS) equipped with a 25.5:1 (nine heads) L/D extruder barrel, a final conical bore head, a die with two 4.7-mm-round (185/1,000 in.) holes, and a corn snack screw con-

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figuration was used to process all samples. The feeder, conditioner, and main twin-screws were operated at 33, 180, and 350 rpm, respectively. Material flow rate was held at 178 kg/hr. Temperatures of zones 1–4 of the extrusion barrel were set at 200, 225, 240, and 240°C, respectively.

Flour from decorticated millet was extruded at moisture contents of 12.5, 13.6, 15.0, and 16.3%. Extrudates were collected after the process reached steady state. The extrudates were cooled on trays at room temperature and stored in polyethylene bags at −18°C.

Weaning Food Formulation

Press-dried cowpea and sorghum malt were prepared according to the procedure described by Almeida-Dominguez et al (1993). Extruded millet, cowpea flakes, and sorghum malt were ground in a Udy cyclone mill (Udy Co., Fort Collins, CO) equipped with a 1-mm hole screen. Two weaning foods were formulated using (percent dry basis): a paste from extruded millet (66.5%), cowpea (28.5%), and sugar (5%); and a liquid from extruded millet (63%), cowpea (27%), sorghum malt (5%), and sugar (5%). Weaning food blends were mixed with tap water (26°C) to a concentration of 20% solids.

Analytical Methods

The proximate composition and enzyme-susceptible starch ratio were determined according to standard AACC methods (1983) and Khan et al (1980), respectively. Amino acids were determined after acid hydrolysis with 6*N* HCl (Spackman et al 1958) and after alkaline hydrolysis with 4.2*N* NaOH (LaRue 1985). Hydrolysates were analyzed with a Beckman 121*M* amino acid analyzer equipped with a Beckman W-1 resin ion exchange. In vitro protein digestibility was determined with a multienzyme assay (AOAC 1984). The protein efficiency ratio calculated from both essential amino acid composition and enzymatic digestibility of sample protein (C-PER) was calculated (AOAC 1984).

Wet ashing was performed by digestion of samples with nitric acid and perchloric acids (Sandel 1950). Ca and Fe were determined with a Perkin Elmer 603 A/A spectrophotometer (Perkin Elmer, Norwalk, CT). Inorganic phosphorus was measured colorimetrically after reaction with molybdate (Fiske and Subbarow 1925).

Water solubilities, the average of apparent molecular weights of starch, and amylose and amylopectin concentration and ratio from extruded millet were determined by high-performance size-exclusion chromatography (HPSEC). Extruded millet flour (0.50 g) was brought to 100 ml with distilled water. The suspension (10 ml) was cooked in water at 85, 100, or 120°C for 10 min. The cooked suspension was equilibrated at 55°C, sonicated for 18 sec, centrifuged for 10 min at 3,400 × *g*, and the supernatant filtered through a 5.0-μm nylon filter. Peak identities were confirmed by comparing elution profiles of starch with purified samples of amylose and amylopectin. The amount of starch passing through the column and the average apparent molecular weight of amylose and amylopectin were determined according to Jackson et al (1988).

The radial expansion ratio was calculated as the ratio of the extrudate diameter to the extruder die diameter. The bulk density (test weight) of extrudates was determined with a Winchester bushel meter. Water absorption (WAI, grams of gel per gram of dry matter) and solubility (WSI, grams of dry soluble per 100 g of dry matter) indices were determined by shaking flour (1 g) in distilled water (15 ml) for 30 min at 30°C (Anderson et al 1969).

Viscosity of raw and extruded millet flours was determined with a Rapid Visco-Analyzer 3C (Newport Scientific Pty. Ltd., Sydney, Australia) as reported by Almeida-Dominguez et al (1993).

Color (L, a, b) was determined with a Hunterlab tristimulus colorimeter model D25-M-9 (Standard tile: $L = +91.77$, $a = -1.07$, and $b = +1.36$).

Sensory Evaluation

A group of 13 African mothers evaluated a paste (20% solids) and a liquid (20% solids) prepared from extruded millet, press-dried cowpea, and sugar without and with sorghum malt in a home trial. A commercial weaning food was used for comparison. Each mother evaluated a 30- to 40-g sample. Thick and thin porridges were evaluated for mouthfeel, color, flavor, and general acceptability.

Statistical Analysis

One-way analysis of variance and simple regression with a completely randomized experimental design were used to determine the effects of extrusion moisture level on extrudate properties and the effects of food formulation on product properties (SAS 1988).

RESULTS AND DISCUSSION

Effects of Decortication

Starch, protein, fat, and ash contents were not significantly affected by decortication (Table I). The in vitro protein

TABLE I
Proximate Composition (%) of Millet, Cowpea, Sorghum Malt, and Weaning Foods[a]

Product	Starch	Protein	Fat	Ash
Whole millet	70.8	15.7	5.2	1.8
91% yield	72.6	15.5	4.8	1.7
Press-dried cowpeas	62.2	26.0	2.0	1.8
Sorghum malt	71.9	10.5	2.8	1.5
Millet-cowpea, 70:30	72.9	7.9	3.2	1.6
Soy-wheat-oat	41.0	37.2	6.4	8.2
LSD[b]	2.9	0.4	0.7	0.1

[a]Values are means of three observations and expressed on a dry basis.
[b]$P = 0.05$.

TABLE II
Protein Quality (g/100 g of Protein) and Mineral Composition (mg/100 g) of Millet, Cowpea, Sorghum Malt, and Weaning Foods[a]

Product	Protein Digestibility (%)	Lys	Trp	His	Thr	C-PER[b]	Ca	Fe	P
Raw whole millet	71.7	3.1	1.7	2.4	4.1	1.09	4.6	6.5	187
91% yield	73.8	3.1	1.7	2.5	4.2	1.10	4.5	6.2	186
Extruded whole millet	78.8	2.8	...	2.2	3.6	1.09	4.7	6.9	189
91% yield	79.8	2.9	...	2.4	4.2	1.08	4.5	6.4	186
Press-dried cowpeas	89.6	7.9	1.1	3.7	4.3	1.72	12.1	10.0	281
Sorghum malt	78.7	3.0	1.1	2.5	3.7	1.00	3.0	3.7	220
Millet-cowpea, 70:30	85.0	4.6	1.5	2.8	4.0	2.50	4.9	7.1	209
Soy-wheat-oat	89.4	6.5	1.4	2.8	4.2	2.50	772.4	67.8	492
LSD[c]	2.0	0.2	0.1	0.2	0.2	...	0.1	0.2	3.0

[a]Values are means of two observations.
[b]A value of 0.229 g of Cys/100 g of dry sample from FAO (1973) was used for calculations.
[c]$P = 0.05$.

digestibility of whole millet increased after decortication; whereas C-PER values remained constant because some essential amino acids were retained (Table II). Calcium, iron, and phosphorus contents remained constant after decortication (Table II).

Effects of Extrusion

Functional properties of extrudates such as radial expansion, bulk density, water solubility and absorption indices, and paste viscosity are a result of thermal and mechanical stresses applied during extrusion. Radial expansion and bulk density values of millets extruded at 13.6 and 15.0% moisture were similar (Fig. 1A); however, expansion decreased and bulk density increased when millets were extruded at 16.3 and 12.5% moisture. Presumably, at 16.5% moisture, a soft, viscous, homogeneous extrudate texture developed, which resulted in a densely packed structure with thick cell walls attributed to lower mechanical energy input. At 12.5% extrusion moisture content, some areas of the starch granule contained less water than the minimum required for a high degree of puffing. Harper (1986) indicated that extrudates processed at higher extrusion moisture contents expanded immediately after the die did but collapsed and solidified before they cooled, creating a very hard texture. Hayter et al (1986) observed that an increase in the extrusion moisture content of corn grits resulted in increased bulk density. On the other hand, more starch conversion occurred during very low moisture conditions, resulting in a densely packed structure with uniform distribution of small, thin-walled air cells (Harper 1986). Hence, extrudates prepared from low- and high-moisture conditions had quite different structures but similar bulk densities.

The WSI of extrudates decreased slightly as the extrusion moisture content increased from 12.5 to 16.3% (Fig. 1B). Low-moisture extrusion products apparently contained more starch aggregates or microgels suspended in water at 30°C, resulting in a higher WSI. Millet extrudates processed at an extrusion moisture content above 13.6% had similar WAI. Colonna et al (1989) indicated that starch granules damaged during extrusion absorb water and swell at room temperature and that the water absorption index decreases with the onset of dextrinization.

The amyloglucosidase hydrolysis (or enzyme-susceptible starch rate) of extrudates increased as the extrusion moisture conditions decreased (Fig. 1B). Starch was extensively damaged (>90%) during low-moisture extrusion. The increased enzyme digestibility was probably caused by the composite operation of hydrating, heating, and shearing during extrusion. This would disrupt the starch granule structure and cause mechanical damage and/or gelatinization in the starch fraction.

Pasting viscosities of millet extrudates indicated that starch was extensively gelatinized during extrusion, because the flour was readily hydrated and formed a viscous slurry at 35°C (Fig. 2). All extrudates had higher viscosities at 95°C than they did at 35 and 65°C. The lower viscosity of extrudate processed at 35°C and 16.3% moisture indicated a different, more rigid, less dispersible extrudate structure. This is consistent with a higher bulk density, as noted earlier. Hence, millet extrudates probably contained some partially gelatinized or ungelatinized starch that was further gelatinized during analysis (heating in excess water) and contributed to the sample viscosity.

The molecular dispersion of starch was affected by extrusion moisture content (during processing) and the temperature of water during extraction (during analysis) (Fig. 3). Uncooked millet had 6.7% molecular dispersion of starch in water at 85°C. Jackson et al (1989) observed relatively low starch dispersion at 85°C, which is 10–15°C above the starch gelatinization temperature. Increased starch dispersion occurred at 100 and 120°C.

The molecular dispersion of starch from extrudates at 85°C increased from 10.1% (low-moisture extrudates) to 19.0% (high-

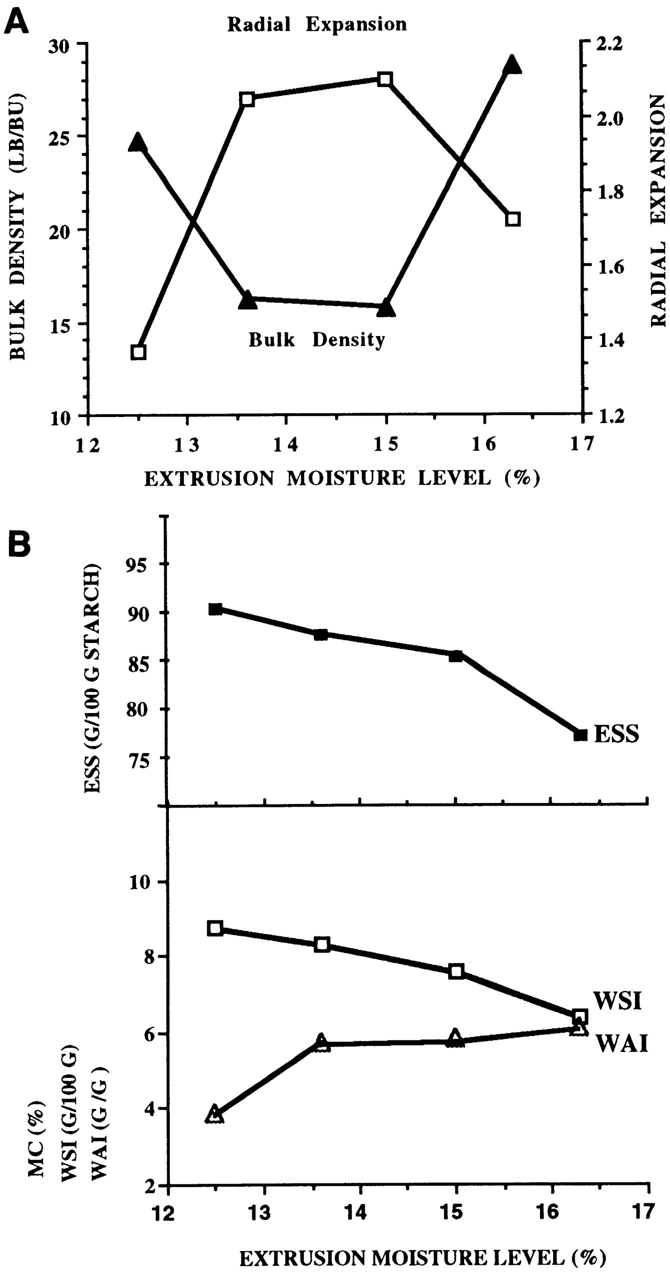

Fig. 1. A, Bulk density and radial expansion ratio of millet extrudates processed at different moisture levels. LSD = 0.7 and 0.1, respectively ($P = 0.05$). **B,** Water solubility (WSI) and absorption (WAI) indices and enzyme susceptible starch (ESS) of millet flours extruded at various moisture levels. LSD = 0.3, 0.3, and 1.2, respectively ($P = 0.05$).

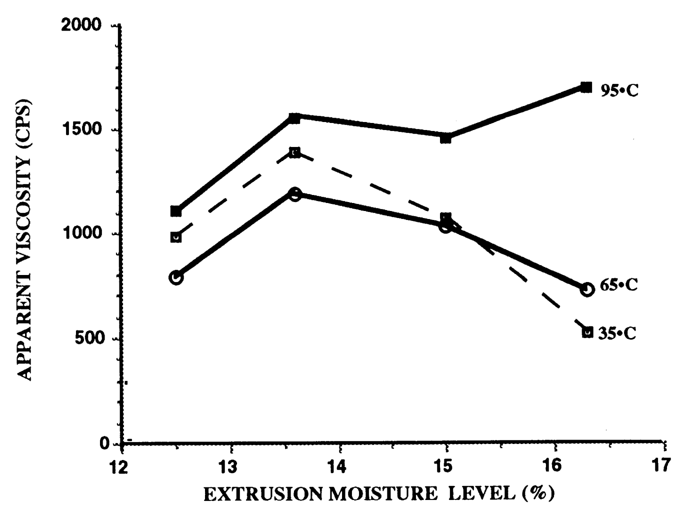

Fig. 2. Viscosity of slurries (15% solids) at 35, 65, and 95°C from millet flours extruded at different moisture levels. LSD = 91, 42, and 78, respectively ($P = 0.05$). Viscosities at 35, 65, and 95°C of raw millet were 25, 50, and 1,950 cP, respectively.

moisture extrudates) as the extrusion moisture content increased (Fig. 3). Although the starch fraction was highly modified during extrusion under limited moisture conditions, the extrudates had reduced molecular dispersion in water at 85°C. The low starch dispersion revealed extensive reorientation of polymers or retrogradation during processing.

The molecular dispersion of starch in water at 100°C was higher for millet flour than it was for extrudates (Fig. 3). The starch in extrudates gelatinized during processing and reoriented and/or retrograded after extrusion, which decreased molecular dispersion of starch at 100°C. Koné and Launay (1987) indicated that all extrudates exhibit a slow reassociation of macromolecules in the semidry state during storage. These progressive reassociations reduced the molecular dispersion of the extrudates.

The dispersion of starch at 120°C was greater than that observed at 85 and 100°C but was similar for uncooked and extruded samples (Fig. 3). Apparently, treatment at autoclaving temperature and pressure caused the molecular dispersion of more than half of the starch.

Similar amylopectin-amylose ratios for raw and extruded millets were observed when starch was extracted in water at 100 and 120°C (Table III). Uncooked flour and the extrudates prepared at extrusion moisture content of 12.5% contained less amylopectin and more amylose when compared with other samples extracted at 85°C. The average molecular weights of amylopectin from extrudates extracted at 85°C were lower than those from uncooked millet or extrudates extracted at 100° and 120°C (Table III). Apparently, extrusion altered or debranched the structure of amylopectin. The average molecular weight of amylose was affected by extraction temperature. Higher molecular weight amylose was extracted at 100°C than at 85 or 120°C. There may be pools of different molecular weight amyloses: a lower molecular weight amylose extracted at 85°C, a high molecular weight of amylose extracted at 100°C, and another low molecular weight amylose dispersed during autoclaving. Although fragmentation of starch is a well-accepted consequence of the extrusion process, the degree of fragmentation is a function of the chemical nature of the extrudate, the design and configuration of the extruder, extruder operating conditions, and the analytical method to quantify. The HPSEC method used in this study detected some lower molecular weight amylopectin when the sample was extracted at 85°C. These data are consistent with the data reported by Rodis et al (1993), suggesting that some cleavages might occur in internal regions of amylopectin during extrusion without formation of glucose or maltodextrins. Sugars (glucose and maltose) (1.86 $\pm$ 0.09%) were detected in similar amounts in uncooked and extruded samples.

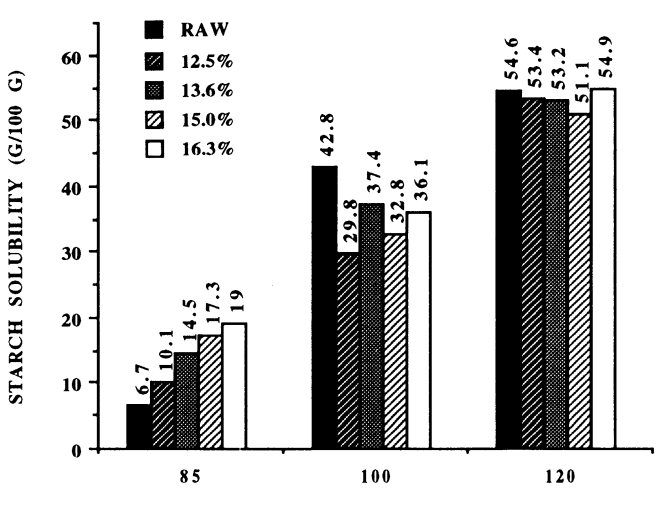

Fig. 3. Starch solubility of decorticated (91%) millet flours extruded at 12.5, 13.6, 15.0, and 16.3% moisture levels determined with high-performance size-exclusion chromatography at 85, 100, and 120°C. LSD = 4.8, 4.9, and 3.8, respectively ($P = 0.05$).

Use of Millet Extrudates in Weaning Foods

Extrudates with high starch dispersion, cold viscosity, and water solubility and absorption indices produced from decorticated millet at 15% moisture were used for weaning foods formulation. The foods prepared from extruded millet; millet and cowpea; and the commercial blend of soy, wheat, and oat (control) had similar color, susceptibility to glucoamylase hydrolysis, water solubilities, and absorption indices (Table IV).

The addition of press-dried cowpea, sugar, and sorghum malt to extruded millet flour decreased the viscosity of weaning food (Fig. 4). The diastatic action of the sorghum malt caused a significant decrease in the paste viscosity. Addition of 5% sorghum malt reduced the viscosity of composite pastes by 80–90%, yielding drinkable weaning foods.

African panelists liked the smooth viscous texture of both the millet-cowpea blend and the commercial soy-wheat-oat weaning foods (Table V). The liquid characteristics of the millet-cowpea blend treated with sorghum malt was preferred by panelists. They commented that the slurries could be easily fed with a bottle. The color of the millet-cowpea blend was similar to that of the commercial soy-wheat-oat food. Panelists commented that white

TABLE III
Apparent Molecular Weight of Amylopectin and Amylose and Ratio of Amylopectin to Amylose (AMP:AMY) of Decorticated (91% Yield), Extruded Millet

Product	Amylopectin ($\times 10^6$)	Amylose ($\times 10^5$)	AMP:AMY
Extraction at 85°C			
Raw	6.0	3.4	68:32
Extruded at			
16.3% moisture	4.4	3.5	75:25
15.0% moisture	4.1	4.0	78:22
13.6% moisture	4.0	5.0	77:23
12.5% moisture	4.1	4.6	71:29
LSD[a]	0.4	0.5	4:2
Extraction at 100°C			
Raw	6.4	5.8	75:25
Extruded at			
16.3% moisture	5.4	5.4	74:26
15.0% moisture	5.2	5.8	72:28
13.6% moisture	5.3	5.9	75:25
12.5% moisture	4.8	6.0	72:28
LSD[a]	0.3	0.4	3:2
Extraction at 120°C			
Raw	6.3	3.6	78:22
Extruded at			
16.3% moisture	6.3	3.9	75:25
15.0% moisture	6.2	4.3	78:22
13.6% moisture	5.7	3.5	79:21
12.5% moisture	5.9	3.7	78:22
LSD[a]	0.4	0.4	3:3

[a] $P = 0.05$.

TABLE IV
Enzyme Susceptible Starch (ESS), Water Solubility (WSI), and Absorption Indices (WAI) and Color of Experimental and Commercial Weaning Foods

Product	ESS (g/100 g of starch)	WSI[a] (g/100 g)	WAI[a] (g/g)	Color[b] *L*	*a*	*b*
Extruded millet	87.6	18.2	4.8	68.1	−0.9	8.6
Millet-cowpea, 70:30	86.7	16.2	5.1	76.2	−0.6	12.0
Soy-wheat-oat	85.9	18.8	4.9	75.5	−0.3	19.1
LSD[c]	3.2	0.4	0.3	0.3	0.1	0.4

[a] Values are means of three observations.
[b] Values are means of three observations obtained with a Hunterlab colorimeter using a white tile of $L = +91.77$, $a = -1.07$, and $b = +1.36$. Samples were ground with a Udy mill before color measurements.
[c] $P = 0.05$.

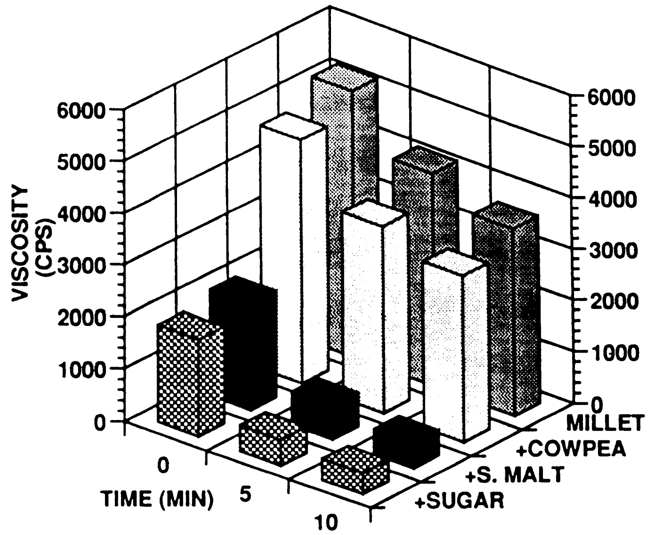

Fig. 4. Viscosity of slurries (20% solids) of extruded millet and press-dried cowpea, sorghum malt and sugar, added sequentially, during 10-min stirring at 30°C. LSD at 0 min = 585, 5 min = 143, and 10 min = 44 ($P = 0.05$).

TABLE V
Organoleptic Evaluation of Experimental and Commercial Weaning Foods by African Mothers[a]

Weaning Food	Mouth-feel	Color	Flavor	General Accept-ability
Millet-cowpea-sugar	7.4	7.2	7.7	7.8
Soy-wheat-oat/sugar	8.0	8.3	8.2	8.4
Millet-cowpea-sorghum malt-sugar	8.6	7.4	8.2	8.2
Soy-wheat-oat/sorghum malt-sugar	8.6	8.1	8.1	8.0
LSD[b]	1.1—	1.1—	1.2—	1.1—

[a] A group of 13 untrained African mothers familiar with millet and cowpea consumption used a nine-point Hedonic preference scale where 1 = dislike extremely and 9 = like extremely.
[b] $P = 0.05$; — = nonsignificant effects.

and yellow colors were highly desirable for baby foods.

The nutritional value of millet was improved by the addition of cowpea (Table II). Experimental blends had >17% protein and >66% starch (Table I). The commercial blend had a higher protein content than did the experimental blend, but protein digestibility and C-PER were similar (Table II).

CONCLUSIONS

Extrusion of decorticated millet (91% yield) at intermediate moisture content (13–15%) produced expanded extrudates with low bulk density, high water solubility, and molecular dispersion of starch. Extrusion moisture of decorticated millet at 15% moisture produced the highest radial expansion, water solubility, and molecular dispersion of starch. This extrudate, when ground, could be mixed with water to produce a viscous slurry. A composite of extruded millet flour (70%) and press-dried cowpea (30%) had high nutritional quality, low moisture, and the ability to form smooth pastes in cold water. The composite paste can be liquefied by the addition of sorghum malt (5%) to allow bottle feeding.

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