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CHEMICAL COMPOSITION OF GRAIN AMARANTH CULTIVARS AND EFFECTS OF PROCESSING ON THEIR NUTRITIONAL QUALITY

RICARDO BRESSANI
Instituto de Nutrición de Centro Americal y Panamá
Apartado Postal Guatemala, Guatemala

ALFREDO SÁNCHEZ-MARROQUÍN
Miami 40, Col. Napoles
Mexico D.F. 03810, Mexico

ENRIQUE MORALES
Instituto de Investigación Nutricional
Apartado Postal 18—0191
Lima—18, Peru

ABSTRACT

Research was conducted to examine different aspects of amaranth processing and utilization in Guatemala, Mexico, and Peru. The trials included assays to determine proximate analysis of grain from different species grown at a number of locations. In addition, analyses of processed products were conducted to determine the effects of processing on food value. Feeding tests with rats and young children as test subjects were conducted. Processing methods included the production of toasted flour, flakes, extruded products, and "popped" amaranth. The value of amaranth as an ingredient in products containing wheat, maize, or oats was also investigated. Special emphasis was placed on determination of protein quality and quantity. In one study, leucine was identified as the limiting amino acid.

INTRODUCTION

A number of attractive features of grain amaranth have gained the attention of researchers in various parts of the world. Grain amaranth has a unique protein content, the fat fraction is higher than in many cereal grains, and there is an interesting starch structure within the carbohydrate fraction. In addition, there appear to be many ways grain amaranth can be used alone or in combination with other grains in nutritious food products.

The relatively high protein content of grain amaranth, as compared with that of cereal grains, has attracted considerable attention. The essential amino acid pattern (Becker et al., 1981; Bressani, 1989) is of particular interest because it is quite similar to the FAO/WHO reference pattern (FAO/WHO, 1973) for amino acids in human nutrition. Furthermore, this amino acid pattern shows a relatively high level of lysine, an essential amino acid notoriously deficient in common cereal grains (Howe, Jansen, and Filfillan, 1965).

A second nutrient of interest in amaranth grain is fat. As with protein content, oils are also found in higher concentrations in grain amaranth than in most cereal grains (Becker et al., 1981).

Much has been written about the unresolved problems regarding agricultural production of grain amaranth. However, if amaranth is to be adopted into consumption systems, it is also important to know how processing methods affect nutritional value. Furthermore, it is important to learn how to process the grain successfully by identifying its functional properties. The goal is to identify processing methods that improve or develop those functional properties without reducing the potential nutritional contribution from adding grain amaranth to the food product.

This paper presents a review highlighting recently completed research in Mexico, Guatemala, and Peru on the nutritional and functional characteristics of grain amaranth. This is the first time results from research projects on chemical composition and processing techniques for grain amaranth have been compiled and compared. Special emphasis is placed on protein quality.

The processes examined include wet and dry thermal processing, milling, and germination. Atmospheric and pressure cooking are discussed as examples of wet thermal processes. Studies of popping, roasting, and extrusion cooking were conducted to learn more about dry thermal processing. Some of the processed products were tested for nutritive value in human studies using children. Some processing techniques were used for a number of applications. These aspects are also reviewed.

THE CHEMICAL COMPOSITION OF GRAIN AMARANTH: EFFECTS OF SPECIES, CULTIVAR, AND AGRONOMIC VARIABLES

Information on the variability in chemical composition of amaranth grain is available, although to a limited extent (Becker et al., 1981; Teutonico and Knorr, 1985). Large differences in protein content have been reported. The reasons for these differences have not been adequately explained, though they appear to result from interactions among genetic makeup, environmental factors, and cultural practices (Bressani, 1989).

Studies were conducted (Imeri et al., 1987a) using 25 lines of *A. caudatus*, all of which were cultivated at one location in Guatemala using the same cultural practices. Significant differences were observed, as follows:

- Yield (5.1–11.5 g/30 m^2)
- Seed weight (0.496–0.933 mg/seed)
- Fat (6.4–11.4%)
- Protein content (11.1–13.9%)
- Methionine content (168 ± 29 mg/g N)
- Threonine content (276 ± 44 mg/g N)
- Cystine content (74 ± 12 mg/g N)
- Leucine content (381 ± 18 mg/g N)
- Lysine content (370 ± 41 mg/g N)

The variability in protein content among the selections was relatively small in this group of samples. This may be because there was not a great deal of genetic variability among the amaranth lines used in this trial. The protein quality [net protein ratio (NPR)] of the cooked samples showed a variation ranging from 3.28 to 3.79, with an average of 3.54. The casein used as a control was 3.58. True digestibility of the protein averaged 80%. The study indicated that there was a positive significant correlation between protein content and yield.

A second study was conducted (Bressani et al., 1987a) at the same location to see whether different rates of nitrogen fertilizer affected grain quality. Four lines were fertilized at rates of 0, 30, 60, and 90 kg N/ha. The study included selections of grain amaranth from the species *A. cruentus*, *A. hypochondriacus*, and *A. caudatus*. The amount of nitrogen applied during the growing season did not influence yield. No differences were noted in the protein content of *A. hypochondriacus* or *A. cruentus*; however, the protein content of *A. caudatus* increased from 12.35% (with no fertilizer added) to 14.50% (with 90 kg/ha added N).

In studies conducted in Mexico, the proximate composition of seven selected lines of *A. cruentus* and *A. hypochondriacus* was reported (Sánchez-Marroquín, 1984). The two lines of *A. cruentus* averaged 16.9% protein content and 4.5% fat. The five lines of *A. hypochondriacus* averaged 16.2% protein and 6.1% fat. The mineral and fatty acid content of the seven selected lines was also analyzed. In this study, the composition of all seven lines was significantly different from values for Ca, Mg, and K previously reported by Becker et al. (1981).

A similar study was reported by Bressani et al. (1987c). Fourteen grain amaranth lines were observed, including three selections of *A. caudatus*, three of *A. cruentus*, seven of *A. hypochondriacus*, and one of *A. hybridus*. Protein content varied from 12.5% to 16.0%. Fat content ranged from 7.7% to 12.8%. Mineral content in this group of samples confirmed values obtained by others (Becker et al., 1981) but differed from the values reported by Sánchez-Marroquín (1984) for Ca, Mg, and K. The average values of fatty acids in these 14 lines (Bressani, 1987c) are presented in Table 1. Palmitic acid (C16:0) varied from 16.83% to 23.83% of the oil. The C18:0 fatty acids (stearic) varied from 1.86% to 4.11%, while the C18:1 (oleic) varied from 20.29% to 35.46%. The C18:2 (linoleic acid) content varied from 38.25% to 57.86%, a high variability. These fatty acid levels are similar to those reported by Sánchez-Marroquín (1984) and other investigators (Imeri et al., 1987a).

Table 2 summarizes the protein and fat content (on a moisture-free basis) of four selected lines grown in Mexico and Guatemala. The samples from Mexico contained more protein than samples from the same lines grown in Guatemala. However, the reverse was true for fat content. These data suggest an important environmental effect on chemical composition.

The variability of fatty acid composition deserves additional comment because of the nutritional implications. All of the lines analyzed by Bressani et al. (1987c) were grown in the same trial. Therefore, it is assumed that the differences occurred as a result of the genetic makeup of the selections.

Table 1. Fatty Acid Content of Amaranth Species Grown in One Location in Guatemala

	Fatty acid (%)			
Species	C16:0	C18:0	C18:1	C18:2
Caudatus	18.63	2.33	27.47	48.57
Hybridus	19.01	2.92	22.23	53.29
Cruentus	19.86	3.62	31.91	43.43
Hypochondriacus	21.30	-2.90	23.49	51.45

Source. Bressani et al. (1987c).

Table 2. Protein and Fat Content of Amaranth Species from Two Localities (moisture-free basis)

Line	Country of production	Protein (%)	Fat (%)
RRC-1011	MEX[a]	18.9	4.9
	GUAT[b]	14.7	12.8
RRC-1023	MEX[a]	17.5	5.8
	GUAT[b]	15.3	10.6
RRC-674	MEX[a]	16.8	4.8
	GUAT[b]	15.1	8.2
RRC-1008	MEX[a]	16.6	6.6
	GUAT[b]	15.6	7.7

[a]MEX: Mexico; source: Sánchez-Marroquín (1984).
[b]GUAT: Guatemala; source: Bressani et al. (1987c).

Table 3 shows a comparison of the fatty acid content of four varieties of grain amaranth grown at two different locations. The differences may have been the result of environmental factors, although genetic variability may have had an effect as well. The oleic acid (C18:1) content of *A. cruentus* was higher at both locations than that of *A. hypochondriacus*. On the other hand, the linoleic acid content of the *A. hypochondriacus* lines was, on average, higher than that of the observed lines of *A. cruentus*.

The nutritional significance of the fat quality in amaranth is very important and should receive additional study. In studies by García, Alfaro, and Bressani

Table 3. Fatty Acid Content of Species of Amaranth Grain Produced in Two Countries

		Fatty acid content (%)			
Line no.	Country of production	Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoleic C18:2
RRC-1011	MEX[a]	17.65	4.58	32.61	42.85
A. cruentus	GUAT[b]	16.83	2.75	35.46	43.13
RRC-1023	MEX[a]	21.50	10.22	28.01	38.38
A. hypoch.	GUAT[b]	21.33	3.11	26.37	48.25
RRC-674	MEX[a]	20.80	1.39	22.70	54.83
A. hypoch.	GUAT[b]	21.56	2.91	22.96	52.56
RRC-1008	MEX[a]	26.52	1.14	18.43	53.49
A. hypoch.	GUAT[b]	23.83	3.34	22.94	48.84

[a]MEX: Mexico; source: Sánchez-Marroquín (1984).
[b]GUAT: Guatemala; source: Bressani et al. (1987c).

(1987a, 1987b), the following ranges were noted for the digestibility of the fat fraction of observed lines of three species of amaranth:

- *A. caudatus*, 93.8–94.1%
- *A. cruentus*, 91.1–91.7%
- *A. hypochondriacus*, 92.0–93.2%

In comparison, the digestibility for cottonseed oil is 98.8%.

EFFECTS OF PROCESSING

The effects of processing on the nutritional value of grain amaranth are as important as those of chemical composition. The conditions under which the amaranth grain is processed for consumption need to be well controlled. Its functional properties need to be maintained or improved without causing losses in nutritive value. There have been few studies on the various processes for converting amaranth grain into edible form. A review and a comparison of some of the results are presented here.

Wet Cooking at Ambient Atmospheric Pressure

Various cooking studies have been conducted with each of the three commonly grown grain amaranth species. The preparation of amaranth porridge made by boiling the grain at ambient atmospheric pressure merits attention since it represents a process commonly used at home. The results of a study on amaranth porridge made from *A. caudatus* (Imeri et al., 1987b) are shown in Table 4.

Before the analyses were conducted, the product was air-dried. Seven different cooking times were observed. The boiling temperature and the water-to-grain ratio remained constant for each treatment. No significant change in true protein digestibility was observed as cooking time increased from 0 to 60 min. On the other hand, protein quality as NPR reached its peak at 10 min, and then began to decrease with additional cooking. As cooking time increased, the percentage of damaged starch continued to increase; at 60 min cooking time, 100% of the starch was damaged. However, even at 60 min cooking time, there was no reduction in the amount of available lysine.

It is not possible to explain fully the decrease in NPR when the grain is cooked for more than 10 min. It may be due to decreased availability of one or more amino acids other than lysine. It was also found that NPR was not correlated with lysine, leucine, threonine, or total sulfur amino acids. NPR depends on amino acid balance and the most limiting amino acid.

The increase in protein quality after only 10 min of cooking is of special interest. The trials indicate that this is the optimum cooking time. This represents a

Table 4. Effect of Cooking on the Chemical and Nutritional Characteristics of Grain Amaranth *A. caudatus*

Conditions:	Water/grain ratio:	3/1		
	Temperature:	96°C		
	Time:	0 to 40 min		
Cooking time (min)	**True protein digestibility (%)**	**NPR**	**Damaged starch (%)**	**Available lysine (g/g N)**
0	82.0	2.31	0	0.38
10	79.0	3.59	31	0.39
20	81.0	3.38	48	0.34
30	80.0	3.28	54	0.40
40	81.0	3.19	56	0.36
50	79.0	3.30	56	0.44
60	79.0	3.44	100	0.42

Source. Imeri et al. (1987b).

significant saving in energy, particularly in areas of the world where energy sources are most limited. In comparison, the cooking time (atmospheric pressure) for recently harvested common beans ranges from 180 to 240 min.

High-Pressure Wet Cooking

Results of a similar study on light- and dark-colored amaranth grain cooked under pressure are shown in Table 5. In this study, only seed from two lines of *A. cruentus* was used (Bressani, 1986). Four cooking times, ranging from 0 to 60 min, were used. All other conditions were constant. A 3:1 ratio of water to grain was used, and all samples were cooked at 15 psi. Before the analyses were conducted, the samples were air-dried.

The changes in protein quality can be seen by comparing the scores for NPR with those for casein. It should be noted that the experiments on the two different grain color samples were conducted at different times; therefore, the individual comparisons with casein were made each time. Three important observations can be made:

- The protein in light-colored grain is superior in quality to that in dark-colored grain.
- The optimum cooking time for light-colored grain is 20 min, and that for dark-colored grain is 40 min.
- For both colors of seeds, the cooking process causes an increase in protein quality as compared with raw grain.

Table 5. Effect of Pressure Cooking on the Nutritional Quality of Cream- and Dark-Colored *A. cruentus*

	Conditions:	Water/grain ratio:	3/1	
		Pressure:	15 psi	
		Time:	0–60 min	
	Cream color		Dark color	
Processing time (min)	Average weight gain (g)	RNPR (%)[a]	Average weight gain (g)	RNPR (%)[a]
Raw	36	66.2	19	60.0
20	69	82.2	35	73.9
40	78	71.9	52	82.9
60	67	76.5	40	71.1

Source. Bressani (1986).

[a]RNPR: relative net protein ratio: % casein.

NPR casein: cream color expt 4.17
dark color expt 3.98

Drum Drying

In the two studies that have been discussed so far, the cooked grain was air-dried at 60°C before being ground into a flour for nutritional and chemical evaluation of the processing method. A number of studies were conducted to determine whether drum drying of precooked grain would change nutritive value as compared with the air-dried product. Comparisons were made by measuring weight gain in rats. Some grains were cooked using the wet processing methods previously described; with the other samples, the grain slurry was preheated.

In one of the studies, reported by Bressani et al. (1987b), grain was cooked by boiling for 30 min and was then dried in drums set at a constant 2 rpm. Steam was applied at 60 lb of pressure to give a surface temperature of 132°C. Results from the feeding studies are shown in Table 6.

The four amaranth cultivars used for this trial represent three species (*A. cruentus, A. hypochondriacus,* and *A. caudatus*). In all samples, the protein quality of the cooked grain was higher than that of the raw grain. As expected, the cooked grain caused an increase in weight gain in the test animals.

It is interesting to note that there was little variability in weight gain among grain samples cooked or dried by different methods (see Table 6). However, there were great differences in weight gain among the rats that were fed different sources of raw grain. It is possible that raw grain from different amaranth lines has differing levels of the substances that inhibit growth. Likewise, with the exception of *A. cruentus* from the United States, the increase in protein quality from raw to cooked is proportionally less (1.13 times) than the increase in body weight gain (1.40 times).

Table 6. Effect of Drum Drying on the Protein Quality of Four Selections of Amaranth Grain

Conditions: Moist grain (2500 g grain—hot water) 30 min
Drums: 2 rpm
Vapor pressure: 60 lb/in², 132°C

Amaranth species	Raw		Drum dried	
	Average weight gain (g)	PER	Average weight gain (g)	PER
A. cruentus (US)	68 ± 12.4	1.96 ± 0.30	110 ± 14.5	2.40 ± 0.19
A. hypochondriacus (US)	91 ± 12.5	2.44 ± 0.16	114 ± 16.8	2.60 ± 0.22
A. caudatus (Peru)	70 ± 13.7	2.19 ± 0.25	108 ± 0.24	2.56 ± 0.24
A. cruentus (Guatemala)	88 ± 15.4	2.46 ± 0.24	106 ± 16.7	2.66 ± 0.21

Adapted from Bressani et al. (1987a).

In another study, drum cooking and drying was examined in more detail, using grain with 15%, 20%, and 25% moisture, passed through the drums at three speeds (3, 5, and 7 rpm), with vapor in the drums at 60 psi. Protein digestibility and quality did not significantly differ as a result of processing conditions; this was true for all three species that were tested (*A. caudatus, A. cruentus,* and *A. hypochondriacus*). However, protein quality values were improved as a result of cooking. As in the other studies, weight gains were better for the cooked grains than for the raw grains.

Extrusion

Extrusion cooking was attempted with grain amaranth. The appeal of this method is that it is of relatively low cost. The extruded product has a better nutritional value as compared with raw amaranth and does not require additional cooking by the end-product user.

These studies were conducted using a Brady Extruder Cooker. Whole amaranth grain was fed into the machine at a rate of 34 rpm. It was not necessary to add moisture because of the relatively high oil content in amaranth grain. Because of a short supply of amaranth grain, the extruder was filled with soybeans and heated to a temperature of 154–163°C. When the desired temperature was reached, the soybeans were discarded. The amaranth grain was fed into the extruder, and all the product obtained for 3 min was discarded. The rest of the product was used for evaluation.

Some representative results are shown in Table 7 from the studies of Mendoza and Bressani (1987). The extruded product was monitored for protein and fat. Samples with the desired levels of the two components were used. The extruded product from lines of both *A. cruentus* and *A. caudatus* had a significantly higher

Table 7. Effect of Extrusion Cooking on Selected Physical and Nutritional Characteristics of Amaranth Grain

	Conditions: Brady extruder Cone opening: <1.5 mm Temperature: 154–163°C No water added Feeding rate: 34 rpm	
Sample	**Raw**	**Extruded**
A. cruentus (GUA-17)		
Ave. wt. gain, g	29 ± 4.5	65 ± 3.2
NPR	2.19 ± 0.34	3.59 ± 0.41
Available lysine g/g N	0.39	0.35
T° max viscosity, °C	58	44
Water abs. index	0.96	3.31
Damaged starch, %	8.4	70.5
A. caudatus (CAC-38)		
Ave. wt. gain, g	21 ± 3.7	53 ± 3.1
NPR	2.35 ± 0.38	3.30 ± 0.30
Available lysine g/g N	0.38	0.36
T° max viscosity, °C	47.5	25
Water abs. index	1.41	2.45
Damaged starch, %	0	81.1
Casein		
Ave. wt. gain, g	58 ± 3.2	
NPR	3.16 ± 0.34	

Source, Mendoza and Bressani (1987).

NPR than the raw seed. The weight gain and NPR of rats fed extruded samples of grain amaranth were similar to those for the samples in the casein control.

The extrusion process did not significantly affect available lysine levels. However, the gelatinization temperature was decreased. Increases were noted in the water absorption index and the amount of damaged starch.

It should be noted that the small size of the amaranth seed makes it necessary to close the cone opening of the extruder to less than 1.5 mm. Nevertheless, the process proved to be quite convenient.

It is important to note also that the nutritional quality of extruded amaranth is often equal to or greater than that of casein. At this time, there is no explanation for this finding.

Popping

Popping is the most common method of processing amaranth for human consumption. There is concern that high temperatures during this process reduce protein quality in the finished product.

Studies were conducted to determine the optimum temperatures for minimizing the destruction of protein quality. The goal was to learn how to maximize protein quality for this cooking method.

Observations of different variables in the popping process were conducted on lines of *A. cruentus* by Sánchez-Marroquín et al. (1985b) and on lines of *A. caudatus* by Bressani et al. (1987b). The *A. cruentus* was popped by placing the grain on a hot surface at 170°C. The *A. caudatus* was actually puffed under pressure using a "popping gun" at a temperature of 175–190°C. A comparison of the findings from these two studies is presented in Table 8. In both studies, the protein quality of popped amaranth was better than that of raw grain. According to the data of Sánchez-Marroquín et al. (1985b), protein digestibility increased.

Because of the ease of processing and the pleasant end product, popping is a very attractive technology for processing grain amaranth. However, it is important that more information be developed to determine the optimal temperature for popping, as well as the optimal amount of time the raw grain is exposed to the heat. Processing at high temperatures for relatively long periods of time usually reduces the nutritive value of foodstuffs because of losses in lysine. At present, no data are available for comparing the nutrient content of the finished products from an identical sample of amaranth, half of which is popped by hot air and half on a hot surface.

Toasting

Raw amaranth grain is sometimes processed by toasting the raw grain at high temperatures before it is milled into flour. This process provides increased protein quality and digestibility as compared with the raw product. However, the improvement is less than that observed when amaranth is popped (Bressani et al., 1987b; Sánchez-Marroquín et al., 1985b). A comparison of results from the two studies is shown in Table 9.

Some data are available to show that lysine is partially inactivated by roasting. In one study, the addition of 0.3% lysine-HCl to light-colored roasted amaranth flour increased protein quality from an NPR value of 2.20 to 2.78. The same was

Table 8. Effect of Popping on the Protein Quality of Amaranth Grain

Species	Process	Protein quality, % casein	Protein digest., %	Ref.
A. cruentus	Raw	68.0	80	Sánchez-Marroquín
	Popped (170°)	84.0	92	et al. (1985b)
A. caudatus	Raw	47.4	76.0	Bressani et al.
	Popped	87.4	78.7	(1987b)

Table 9. Effect of Roasting on the Protein Quality of Amaranth Grain

Species	Process	Protein quality, % casein	Protein digest., %	Lysine, g/16 g N	Ref.
A. cruentus	Raw	68.0	80	5.18	Sánchez-Marroquín
	Roasted (90°)	72.0	90	5.10	et al. (1985b)
A. caudatus	Raw	47.4	76.0	5.3	Bressani et al.
	Roasted (150°C, 60–90 sec)	61.4	62.2	4.3	(1987b)

true for roasted dark-colored seed, in which added lysine caused an increase in NPR from 1.46 to 1.94 (Bressani, 1986).

Germination for the Production of Amaranth "Sprouts"

Germinated or sprouted seeds of alfalfa and other legumes or grains are sometimes consumed. It has been noted that sprouted seeds have an increased amount of total sugars, as well as of the vitamin B complex and vitamin C.

In studies conducted by Colmenares de Ruiz and Bressani (1990), amaranth sprouts were grown for 24 to 72 h. Some protein hydrolysis usually takes place during germination, as shown in Table 10. Therefore, it was of interest to learn whether such a process would affect protein quality.

A summary of the NPRs of raw and cooked sprouts, and the resultant weight gains when the sprouts were fed to test animals, are shown in Table 11. Some improvement in protein quality was noted in the raw amaranth sprouts. However, it was noted that when sprouts were cooked at atmospheric pressure, their protein quality decreased significantly at all observed stages of growth.

Table 10. Effect of Germination of Changes in Nutrients of *A. cruentus* (INCAP-7 US)

Germination time (h)	Protein (%)	Ether extract (%)	Reducing sugar (%)	Total soluble sugars (%)	Vitamins, mg/100 g Thiamin	Riboflavin	Ascorbic acid
0	16.3	7.1	0	4.0	0.08	0.21	4.62
24	15.8	5.5	0	9.5	0.09	0.36	5.28
48	17.1	4.6	3.3	28.0	0.11	0.45	8.92
72	16.9	4.0	8.3	59.0	0.12	0.60	12.16

Source. Colmenares and Bressani (1990). Similar changes were measured with *A. caudatus* and *A. hypochondriacus*.

Table 11. Effect of Germination on the Protein Quality of Raw and Processed *A. cruentus* (INCAP-7 US)

	Raw		Cooked	
Germination time (h)	Ave. weight gain (g)	NPR	Ave. weight gain (g)	NPR
0	8	2.0	45	3.6
24	10	2.3	5	1.5
48	12	2.1	9	1.7
72	19	2.7	4	1.4
Casein	65	3.8	—	—

Source. Colmenares and Bressani (1990).

It appears that sprouting amaranth is not a way to retain or improve its protein quality. However, amaranth sprouts do provide a source of thiamine and riboflavin (two of the B vitamins) and vitamin C. In certain situations, sprouted amaranth could be a source of those nutrients.

Dry Milling

In a number of studies, the effect of dry milling of grain amaranth on flour fraction yield and chemical composition has been reported (Sánchez-Marroquín et al., 1985a, 1985b, 1985c, 1986). In one study, Sánchez-Marroquín (1984) tested the efficiency of various mills for milling amaranth RRC1011 (*A. cruentus*). In all cases, two fractions were obtained: a flour fraction low in protein content and a fraction high in protein content. The results are shown in Table 12.

The flour yield and protein content are determined by the mesh used to obtain the two fractions after the milling has been completed. The type of mill does not affect either measure. However, differences in efficiency were noted when different mills and sieve sizes in different combinations were used. Using the Raymond separator, the 80-mesh screen yielded 32.0% flour with 29.0% protein; the 60-mesh screen yielded 68.0% flour with 9.90% protein.

The results of the tested mills were of special interest. The Brabender mill, with a 60-mesh screen, yielded 26.0% flour and 13.2% protein. The Strong-Scott pearler, which also had a 60-mesh screen, yielded 22.0% flour and 36.0% protein. When a two-part process was used, combining a Simpector mill followed by a Raymond mill (with 50- to 60-mesh screen), there was a yield of 34.4% flour and 36.0% protein.

Fractions from the Strong-Scott pearler, as well as those from the Simptor-Raymond combination, were analyzed for their chemical composition. Results from those trials, conducted by Sánchez-Marroquín (1984), are shown in Table 13.

Table 12. Some Characteristics of Amaranth RRC1011 Milling

Mills	Mesh	Yield (%)	Protein (%) (N × 6.25)
Christy	50	31.6	11.07
	90	32.8	13.30
Kek	90	36.0	11.80
	120	40.1	14.70
Brabender	60	26.0	13.20
	30	74.0	15.10
Christy + Alpine	80	3.0	36.00
	45	96.1	13.03
Kek + Alpine	80	32.0	29.00
	45	96.1	13.03
Raymond separator	80	32.0	29.00
	60	68.0	9.90
Strong-Scott pearler	60	22.0	36.00
	30	75.8	12.40
Simpactor + Raymond	40	75.5	12.50
	50–60	34.4	36.00

Source. Sánchez-Marroquín (1984).

Fractions 1 and 1R represent the testa and embryo of the grain; fractions 2 and 2R represent the perisperm. In both cases, fractions 1 and 1R contained significantly more protein than fractions 2 and 2R.

Other milling combinations and classifications were tested with similar results (Sánchez-Marroquín and Maya, 1985; Sánchez-Marroquín et al., 1985b, 1985c, 1986). The flours tested were used for infant food products. The following milling

Table 13. Proximate Analysis of Amaranth Seed Fractions *A. cruentus* RRC1011 (%)

	Pearler		Raymond fractions	
Nutrient	Testa + embryo fraction R1	Perisperm fraction R2	Fraction R1	Fraction R2
Moisture	8.5	9.3	9.0	10.3
Protein	36.0	9.4	29.0[a]	8.1
Fat	19.1	5.2	11.1	2.1
Ash	6.0	1.7	4.0	1.1
Raw fiber	9.5	4.6	6.9	1.4
Carbohydrates	20.9	69.8	40.0	76.4

Adapted from Sánchez-Marroquín (1984).

[a]36.0–38.0% protein under appropriate moisture conditions (20%) and 50–60 mesh.

conditions were judged to be most effective according to Sánchez-Marroquín and Maya (1985):

- Seed pearling with five passes in a pearler, which yielded approximately 22% flour and 36% protein
- A combination of the Miag mill and Raymond air separator, which yielded approximately 32% flour and 30–36% protein

The viscosity characteristics of the fractions differed among samples. The viscosity of both differed from that of whole wheat flour. Gelatinization characteristics were similar among the products tested. Much additional research is needed to select the type of mill and milling system required to produce acceptable yields of product with the desired chemical composition.

A COMPARATIVE ANALYSIS OF PROCESSES

To allow some comparisons among processing methods, information was gathered from a number of sources on the performance of a single variety of *A. caudatus* processed by roasting, flaking, popping, and water cooking. Results for the following grain characteristics are presented in Table 14:

- Average weight gain
- Protein digestibility
- NPR

Table 14. Effect of Different Processes on Chemical and Nutritional Characteristics of *A. caudatus*

Conditions:	Roasting:	Dried grain—temp. 150°C; 60–90 sec
	Flaking:	Grain 26% moisture—drum at 200°C; 1–3 sec
	Popping:	Dried grain—temp. 175–195°C; 15–25 sec
	Cooking:	Grain/water ratio—1/3; 96°C; 15 min

Process	Ave. weight gain (g)	Protein dig. (% Ap)	RNPR (%)[a]	Available lysine (g/16 g N)	Damaged starch (%)	Dietetic fiber (%)
Raw	7 ± 5.3	76.0 ± 2.8	47.4	5.3	0	7.0
Roasting	17 ± 6.7	62.2 ± 1.9	61.4	4.3	97.0	20.7
Flaking	26 ± 7.6	79.5 ± 3.5	76.2	6.5	68.0	14.3
Popping	37 ± 6.3	78.7 ± 2.4	87.4	5.7	63.5	13.4
Wet cooking	42 ± 8.2	—	84.18	—	—	—
Casein	52 ± 7.9	92.9 ± 1.2	100.0	—	—	—

Source. Bressani et al. (1987b).

[a]Percentage of casein (NPR casein 3.65 ± 0.23).

- Available lysine
- Damaged starch
- Dietary fiber

All processes provided products that increased weight gain, NPR, and dietary fiber as compared with raw grain. In addition, the compared processes all damaged the starch. Among the observed processed samples, the roasted seed gave the lowest protein digestibility and available lysine. It also had the most damaged starch and dietetic fiber. The extruded and wet-cooked samples exhibited the best protein quality. Casein was used for the comparison. The trends are shown in Table 15.

The evaluations were conducted using biological assays of true metabolizable energy in chicks as the experimental animal (Lopez and Bressani, 1987). Light-colored grain contained slightly higher levels of metabolizable energy than dark-colored grain. All of the test processes increased the metabolizable energy as compared with raw grain. Extrusion cooking, however, induced the greater increase in the light-colored seed as compared with the dark seed. A possible explanation is that seeds not properly processed "escaped" from the extruder because of their small size and hard seed coat.

One trend is constant. Cooking, whether by wet or dry methods, increases protein quality and digestibility as compared with raw grain. There is no single, simple explanation for this.

Many studies—including those by Bressani et al. (1987a, 1987b), Mendoza and Bressani (1987), and García et al. (1987a)—have shown that there is a significant increase in food intake of cooked versus raw amaranth grain. This suggests that the raw grain may present any of the following problems:

- Lack of palatability
- Lack of availability of amino acids
- Presence of antiphysiological or antinutritive substances

Table 15. Effect of Various Processing Methods on the True Metabolizable Energy of *A. cruentus* from Guatemala

Process	Conditions	Light-colored grain (kcal/g)		Dark-colored grain (kcal/g)	
		Average	Range	Average	Range
Raw	None	2.91	2.00–3.70	2.79	2.02–3.46
Atmospheric cooking	20 min, 96°C	3.44	3.30–3.60	3.22	3.06–3.37
Drum drying	2 rpm, 132°C	3.67	3.20–4.05	3.52	3.39–3.68
Extrusion cooking	165°C, feed rate 34 rpm	4.22	3.99–4.43	3.36	2.91–3.90

Source. Lopez and Bressani (1987). No moisture added in Brady extruder. Cone opening less than 1.5 mm. Chicks as experimental animals.

Table 16. Effect of Heat Processing of Amaranth Grain on Diet Intake

Species	Process	Food intake, g/rat/14 days	Ref.
A. caudatus	Raw	101	Bressani et al. (1987b)
	Cooked, atm. pressure	177	
A. cruentus	Raw	164 ± 5.8	Mendoza and Bressani (1987)
	Extrusion cooked	220 ± 7.1	
A. caudatus	Raw	123 ± 5.0	Mendoza and Bressani (1987)
	Extrusion cooked	179 ± 7.4	
A. cruentus	Raw	377 ± 35.0	Bressani et al. (1987a)
	Cooked, drum drying	464 ± 34.5	
A. hypoch.	Raw	361 ± 31.7	Bressani et al. (1987a)
	Cooked, drum drying	458 ± 46.9	
A. caudatus	Raw	332 ± 30.8	Bressani et al. (1987a)
	Cooked, drum drying	437 ± 43.9	
A. caudatus	Defatted raw	313	García et al. (1987a)
	Defatted processed	447	
A. cruentus	Defatted raw	339	García et al. (1987a)
	Defatted processed	447	
A. hypoch.	Defatted raw	343	García et al. (1987a)
	Defatted processed	391	

A summary of total amounts of food intake identified by different research groups is shown in Table 16. The data indicate that there is an increase in intake when the diet includes processed grain amaranth. All of these issues require additional research efforts.

THE NUTRITIONAL CONTRIBUTION OF GRAIN AMARANTH WHEN ADDED TO OTHER FOOD PRODUCTS

There is a great deal of interest in the value of amaranth when mixed with other grains, especially maize and wheat. Trials were conducted at the Institute of Nutrition of Central America and Panama (INCAP) to gather additional information on this question.

Two graphs of previously unpublished information are presented in Figure 1, showing the potential for increasing protein quality by adding amaranth to other cereal grains. When extruded amaranth flour was mixed with raw wheat flour, the NPR continued to increase as more amaranth was added. When amaranth was mixed with maize, the NPR reached its maximum value at a mixture of 45%

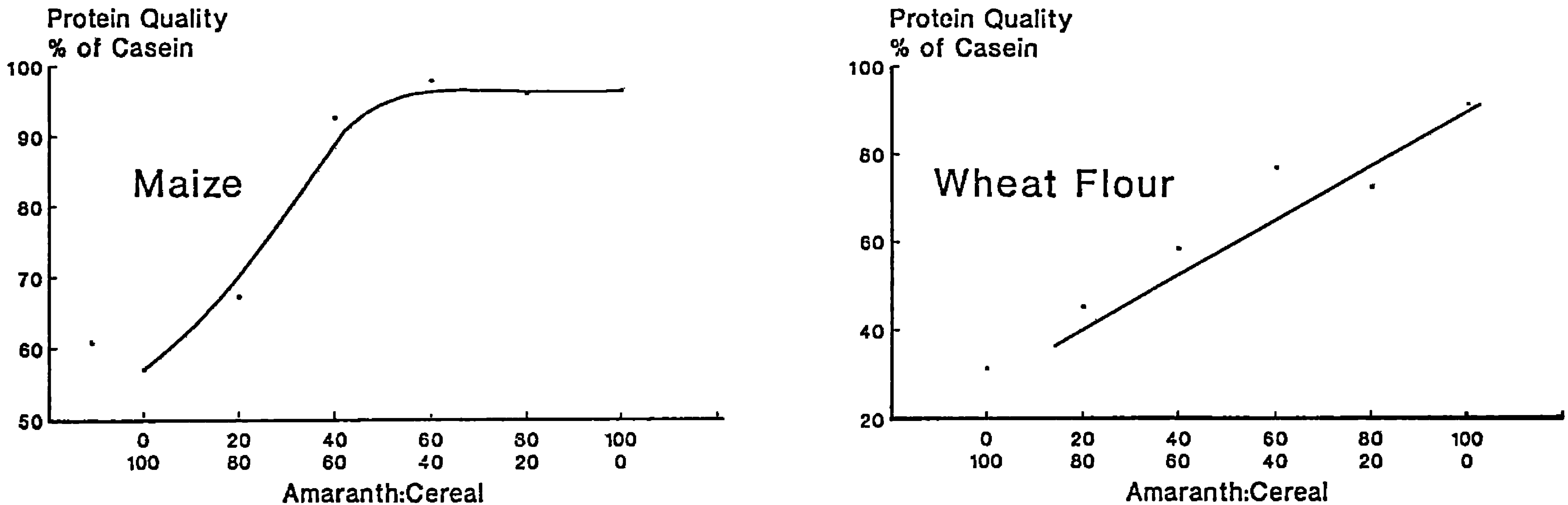

Figure 1. Protein complementation between maize/amaranth and wheat flour/amaranth. From Bressani (1989).

cooked amaranth flour and 55% cooked maize flour. The value of a 45/55 amaranth and maize mixture was equal to that obtained with 100% extrusion-cooked amaranth flour.

Experiments were conducted to gain additional information on the value of maize and amaranth mixtures. It was decided to use a mixture of 25% amaranth and 75% maize in all experiments. Both amaranth and maize flours were cooked in all experiments. The grain amaranth was roasted, popped, and extruded under the conditions reported previously. Comparisons were made with 100% amaranth flour and 100% maize flour.

The results of the INCAP studies are shown in Table 17. Multiple-point biological assays of protein quality were used. When fed alone to young growing rats, the extruded product showed the highest protein quality, with an NPR of 4.21. It contained 5.2 g/16 g N of available lysine. The roasted amaranth grain had an NPR value of 3.91, with an available lysine of 4.4 g. The popped seed gave a protein value of 3.51, with 4.3 g/16 g N available lysine.

The NPR values correlated well with available lysine. However, it should be pointed out that in previous trials, popped amaranth provided superior protein quality as compared with roasted samples. Because different results were obtained in this trial, it is possible that the process used for popping was not well standardized. There may be an interaction between variety and processing method.

The protein quality of the 25:75 toasted amaranth grain/maize mixture was 3.58–3.63, as compared with 2.91–3.12 for the popped amaranth and 3.28–3.30 for the extruded sample.

As expected, the highest protein quality for 100% amaranth products was found in flour processed by extrusion. Furthermore, the mixture of 25% amaranth and 75% maize provided superior protein quality when compared with

Table 17. Protein Quality of Processed Amaranth Fed Alone and Mixed with Maize

Process used	Available lysine, g/16 g N	Amaranth fed alone	Amaranth with maize[a] (25/75)	Amaranth with maize[b] (25/75)	Maize fed alone	Casein
Roasted	4.4	3.91	3.58	3.63	—	—
Popped	4.3	3.51	3.12	2.91	—	—
Extruded	5.2	4.21	3.30	3.28	—	—
Maize Ch.	3.2	—	—	—	2.63	—
Maize Ja.	3.2	—	—	—	3.06	—
Casein	—	—	—	—	—	4.60

Source. Bressani (unpublished data).
[a]Maize Ch.
[b]Maize Ja.

100% maize flour in all cases but one. These results are similar to those of previous studies.

Sánchez-Marroquín and Maya (1985) have reported on the enrichment of industrial lime-treated maize flour with whole grain amaranth and its milling fractions. The amaranth used for these studies was from an accession of *A. cruentus* of the Mexican morphological group. It was selected because it is the most commonly grown amaranth and has been shown to have acceptable qualities for food-processing purposes.

Whole flour and milling fractions of raw amaranth seeds were mixed with industrialized maize flour (MINSA) to prepare tortillas and arepas, both of which are basic nutritional foods in several Latin American countries. Three different maize:amaranth ratios were used:

- 90% maize:10% amaranth
- 80% maize:20% amaranth
- 50% maize:50% amaranth

The three maize:amaranth mixtures provided a good protein and fat content, as well as amino acid profile. In addition, the mixture provided adequate physical characteristics for making tortillas; the addition of amaranth flour to the maize flour did not have a detrimental effect in this regard.

The addition of amaranth flour to tortillas provided an improvement in the tortillas' mineral and fatty acid content for every mixture prepared. Therefore, the enrichment of tortillas with whole amaranth flour is recommended for use in programs aimed at improving nutritional status.

Moreover, commercial maize flour and amaranth whole flour mixtures in the proportions 80:20 and 50:50 were found suitable for the preparation of arepas. Protein and fat content was substantially improved, with no change in organoleptic characteristics.

The protein-rich (1R) and starchy (2R) fractions of amaranth flour obtained by air classification also provided acceptable products when mixed with other grains. Gruels were prepared using two different fractions: a 50:50 blend of 1R fraction amaranth flour:maize flour, and a 50:50 blend of 2R fraction amaranth flour:maize flour. The gruels were prepared using 1:8 and 1:12 water dilutions. The organoleptic characteristics of the finished products were improved by including fractionated flours.

Flakes and extrudates were also used, yielding blended maize and amaranth products with a 13.3–15% protein content, 1.7–3.7% fat, and 65.2–74.1% carbohydrates. In addition, extrudates were used to prepare snacks of better nutritional quality than existing similar commercial products.

In another study by Sánchez-Marroquín et al. (1985a), distinct selected lines of *A. cruentus* from different places of origin were used to prepare baking products in mixtures with wheat flour. A number of mixtures were made using whole amaranth flour, fractionated amaranth flour, and white wheat flour. The mixtures were at levels of 10% to 50% amaranth and were compared with breads made with 100% wheat flour. The mixtures of white wheat flour plus flour from whole amaranth were prepared using amaranth flour made from raw, toasted, and popped amaranth grain.

These experiments provided baseline data on the properties of blends of amaranth flour and wheat flour. Tests were conducted using the amylograph, alveograph, and farinograph. As expected, amaranth flour and amaranth-wheat mixes have characteristics far different from those of 100% wheat flours. The data generated in these studies can provide the information needed by producers of baked goods to better utilize the distinctive physical qualities of amaranth for baking applications.

The six amaranth lines selected for the study exhibited different properties. These differences are probably the result of genetic differences, as well as differences in the way the plants were grown, harvested, and handled after harvest.

Enriched cookies and "bolillos" (French bread) with NPR values of 3.63 and 4.35, respectively, slightly higher than values of casein (3.0 and 4.0), are especially recommended as amaranth-enriched baked goods. These results further emphasize the potential value of amaranth as an ingredient for enriching commonly consumed products. Mixtures of amaranth flour and wheat flour could be especially useful for improving the diet of a population's marginal sectors.

Another potential use for amaranth is in the production of infant foods (Del Valle et al., 1987; Sánchez-Marroquín et al., 1986). Amaranth flour (*A. cruentus*) was blended with wheat and oats in a number of formulations. The amaranth flour was in the form of whole amaranth, air-classified fractions, or extruded flour.

Proximal chemical analyses—including mineral content, fatty acid composition of lipid fractions, amino acid content, and protein efficiency ratio (PER) and NPR values—were obtained for each form of amaranth flour, wheat flour, and oat flour. In addition, analyses were done of products made from amaranth flour blended in 50:50 and 60:40 mixtures with both oats and wheat.

The 50:50 and 60:40 blends of whole amaranth flour and wheat flour or oat flour were found to be highly suitable for use in infant formulas. In addition, the protein-rich air-classified fractions of amaranth flour were found to be especially nutritious for use in this type of high-value product.

NUTRITIONAL VALUE OF GRAIN AMARANTH TO CHILDREN

Although there have been a number of studies evaluating the use of grain amaranth for experimental and domestic animals, very few studies have been conducted with human subjects. Morales et al. (1988) conducted studies on nitrogen balance at the Institute of Nutrition Research in Lima, Peru.

The test subjects were nine young children, aged 10.1 to 25.4 months. All the children had been severely malnourished but were well on their way to recovery at the time of the studies. The experimental diet fed to the children included sufficient amaranth products to provide 50% of the diet's total energy. The other 50% was provided in equal amounts by corn syrup solids and sucrose. The protein in the amaranth-supplemented diet provided 6.4–6.7% of the total energy requirements.

The amaranth in the diet was all from the variety CAC-064 (*A. caudatus* L.), which was grown at the Centro de Investigación en Cultivos Andinos (CICA) of San Antonio Abad National University, Cusco, Peru. The amaranth was processed into three forms—toasted flour, popped grain, and flakes—and comparisons were made of the value of these processed forms in the children's diet.

- The toasted flour was obtained by treating the raw grain at a temperature of 150°C for 60–90 sec, and then grinding it into flour.
  - –Protein content: 12.81%
  - –Energy content: 389 kcal/100 g
  - –Protein quality as percentage of casein: 60.8%
- The popped grain was obtained by heating the grain in covered clay pots at 175–195°C for 15 to 25 sec.
  - –Protein content: 13.43%
  - –Energy content: 399 kcal/100 g
  - –Protein quality as percentage of casein: 87.4%
- For the flakes, whole grain amaranth that had been soaked in water for 10 min was passed between two rotating cylinders heated to 200°C for a period of 1–3 sec.
  - –Protein content: 12.20%
  - –Energy content: 386 kcal/100 g
  - –Protein quality as percentage of casein: 76.2%

There were no differences in nitrogen absorbed as a result of the processing method, as is noted in Table 18. The toasted amaranth was absorbed at a rate of 69.6%, the popped at a rate of 69.0%, and the flaked at a rate of 69.2%. The casein control provided a nitrogen absorption rate of 83.8%.

The nitrogen retention rates, however, did indicate significant differences as a result of the processing method. Nitrogen was retained at a rate of 30.3% of total N intake for the toasted flour, 28.8% for the popped, and 24.7% for the flaked. The rates for toasted and flaked differed significantly. The nitrogen retention rate for casein was 36.6% of total N intake. Therefore, it was calculated that the relative protein quality values were 82.5% for toasted, 78.7% for popped, and 67.5% for flaked amaranth grain.

Another study (Graham, Lembcke, and Morales, 1990) refers to the postprandial plasma-free amino acids of five small children on the ninth day of consuming

Table 18. Nitrogen Balance of Nine Children Consuming Grain Amaranth as Toasted Flour, Popped Grain, and Flakes

Nitrogen, % of intake	Amaranth		
	Toasted	Popped	Flakes
Absorbed	69.6 ± 2.7	69.0 ± 5.6	69.2 ± 2.7
Retained	30.3 ± 4.6[a]	28.8 ± 8.6	24.7 ± 5.7[b]

Adapted from Morales et al. (1988). Values are means ± *SD*, $N = 4$. Values in same row with different superscript letters are significantly different from each other, $p < .05$, paired *t* test.

toasted, flaked, and popped grain amaranth. On the basis of the decrease in a number of amino acids between fasting and 4 h postprandial, the authors conclude that leucine was the first limiting amino acid in the amaranth protein.

Because one of the main values of adding amaranth to the diet is the high amounts of lysine, it is important to assess carefully the effect of processing method on the lysine content of the finished product. Lysine is the most likely amino acid to be inactivated by dry heat processing. The relative amounts of lysine were measured by looking at the plasma lysine levels from fasting to 4 h postprandial. Those levels dropped 7.3% for toasted grain, 5.9% for the flakes, and 5.6% for the popped samples. These decreases in plasma lysine agree well with the relative protein quality values established with rats of 60.8%, 76.2%, and 87.4% (Morales et al., 1988). The same is true for leucine.

Morales et al. (1988) also evaluated mixtures of wet-milled whole-kernel maize meal and toasted milled amaranth flour in weight ratios of 80:20 and 70:30. These blends were fed to children using the same methods as the previous study. The results, as presented in Table 19, were as follows:

- 80:20 blend
  –Nitrogen absorbed as percentage of intake: 70.4%
  –Nitrogen retention: 28%

Table 19. Nitrogen Balance of Seven Children Consuming Maize/Amaranth Diets and Casein

Nitrogen, % of intake	80% maize; 20% amaranth	70% maize; 30% amaranth	Casein control
Absorbed	70.4 ± 4.1[a]	72.1 ± 5.3[a]	83.8 ± 1.9[b]
Retained	28.0 ± 5.2[a]	29.0 ± 2.8[a]	36.6 ± 3.1[b]

Adapted from Morales et al. (1988). Values are means ± *SD*, $N = 7$. Values in same row with different superscript letters are significantly different from each other, $p < .01$, paired *t* test.

- 70:30 blend
  - –Nitrogen absorbed as percentage of intake: 72.1%
  - –Nitrogen retention: 29.0%
- Casein control
  - –Nitrogen absorbed as percentage of intake: 83.8%
  - –Nitrogen retention: 36.6%

The authors conclude that as little as 12.7% by weight (20% of protein) of amaranth flour added to maize meal should be able to satisfy protein and lipid needs of young children if the mixture provides around 90% of the diet energy.

Graham, Lembcke, and Morales (1990) also studied the plasma-free amino acid from diets of 80:20 and 70:30 maize:amaranth. Since maize contains a high leucine level, this amino acid was not limiting. However, lysine and isoleucine were limiting. Both showed a decrease in plasma levels at 4 h postprandial.

Lysine and isoleucine are both found in low quantities in maize protein, although lysine is especially low. The potential improvement in protein quality that occurs when maize and amaranth are mixed was noted earlier in this paper.

Graham et al. (1989) conducted other studies of children who were fed maize and mixtures of maize and amaranth. However, in these studies, there were no gains as a result of maize and amaranth mixes. The authors claim that this lack of improvement may be due to overprocessing of the amaranth grain.

However, it is interesting to compare the nitrogen balance results of another study conducted by Morales and Graham (1987) with results of rat studies shown in Figure 1. The children in the Morales and Graham study were fed the following diets:

- 100% maize
- 80% maize and 20% amaranth
- 70% maize and 30% amaranth
- 50% maize and 50% amaranth

Nitrogen balance results and biological values calculated from the nitrogen balance data are shown in Table 20. Biological value was 75% on the 100% maize diet and increased as amaranth replaced maize up to the 70% maize, 30% amaranth diet.

The same kind of study, but with young growing rats fed similar maize/amaranth mixtures, provided the responses shown in Figure 1, with the PER values shown in Table 20. The results show that as amaranth replaced maize, there was an improvement in protein quality, as indicated by the PER values. Those values increased from 1.62 on the 100% maize diet to 2.63 on the 70% maize and 30% amaranth diet.

These results show a similar type of response in both children and young growing rats. This demonstrates that amaranth protein can efficiently supplement

Table 20. Nitrogen Balance in Children and PER of Rats Fed Mixtures of Processed Amaranth with Maize

Nitrogen balance measure[a]	Maize 100%; amaranth 0%	Maize 80%; amaranth 20%	Maize 70%; amaranth 30%	Maize 50%; amaranth 50%
NA, % intake	94	84	86	84
NR, % intake	70	76	80	74
BV, %	75	90	93	87
PER	1.62	1.90	2.63	2.72

Source. Graham et al. (1989); Morales et al. (1988); Morales and Graham (1987); Bressani (from Fig. 1).
[a]NA = nitrogen absorbed in children; NR = nitrogen retained in children; BV = biological value in children; PER = protein efficiency ratio in rats.

maize protein, representing an important application in countries where maize is the main staple cereal grain.

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