

$$Z_{21} = A_3 + A_4 T \quad (6)$$

T is the temperature in kelvin.

The objective function relating experimental and calculated data is minimized by a sequential search procedure developed by Nelder and Mead (1965) from the simplex method introduced by Spendley et al. (1962).

Registry No. Methanol, 67-56-1; 1-hexanol, 111-27-3; maltodextrin, 9050-36-6; β -cyclodextrin, 7585-39-9; water, 7732-18-5; dextrin, 9004-53-9; 1-propanol, 71-23-8; 1-butanol, 71-36-3; ethanol, 64-17-5; 1-pentanol, 71-41-0.

LITERATURE CITED

- Beebe, A. H., Jr.; Coulter, K. E.; Linsday, R. A.; Baker, E. M. *Ind. Eng. Chem.* **1942**, *34*, 1501.
 Butler, J. A. V.; Thomson, D. W.; Mac Lennan, W. H. *J. Chem. Soc.* **1933**, 674.
 Carey, J. F.; Bertelsen, L. W. *Ind. Eng. Chem.* **1932**, *24*, 882.
 Derr, E. L.; Deal, C. H. *Inst. Chem. Eng. Symp. Ser.* **1969**, *32*, 3.
 Duhem, P.; Vidal, J. *Fluid Phase Equilib.* **1978**, *2*, 231.
 Fredenslund, A.; Gmehling, J.; Rasmussen, P. "Vapor-Liquid Equilibria using UNIFAC"; Elsevier: New York, 1977.
 Fredenslund, A.; Jones, R. L.; Prausnitz, J. M. *AIChE J.* **1975**, *21*, 1086.
 Green, S. J.; Vener, R. E. *Ind. Eng. Chem.* **1955**, *47* (1), 103.
 Jones, C. A.; Schoenberg, E. M. *Ind. Eng. Chem.* **1943**, *35*, 666.

- Kojima, K.; Tochigi, K. "Prediction of Vapor-Liquid Equilibria by the ASOG Method"; Elsevier: Amsterdam; Kodansha Ltd.: Tokyo, 1979.
 Lebert, A.; Richon, D. *J. Food Sci.* **1984**, in press.
 Le Maguer, M. "Water Activity: Influence on Food Quality"; Academic Press: New York, 1981.
 Leroi, J. C.; Masson, J. C.; Renon, H.; Fabries, J. F.; Sannier, H. *Ind. Eng. Chem. Process Des. Dev.* **1977**, *16*, 139.
 Mac Glashan, M. L.; Williamson, A. G. *J. Chem. Eng. Data* **1976**, *21* (2), 196.
 Nelder, J. A.; Mead, R. *Comput. J.* **1965**, *7*, 308.
 Othmer, D. F.; Benenati, R. F. *Ind. Eng. Chem.* **1945**, *37* (3), 299.
 Prausnitz, J. M. "Molecular Thermodynamics of Fluid Phase Equilibria, Prentice-Hall: Engelwood Cliffs and New York, 1969.
 Ramalho, R. S.; Tiller, F. M.; James, W. J.; Bunch, D. W. *Ind. Eng. Chem.* **1961**, *53* (11), 896.
 Renon, H.; Prausnitz, J. M. *AIChE J.* **1968**, *14* (1), 135.
 Richon, D.; Antoine, P.; Renon, H. *Ind. Eng. Chem. Process Des. Dev.* **1980**, *19*, 144.
 Richon, D.; Renon, H. *J. Chem. Eng. Data* **1980**, *25*, 59.
 Spendley, W.; Hext, G. R.; Himsworth, F. R. *Technometrics* **1962**, *4*, 441.
 Verhoeve, L.; De Schepper, H. *J. Appl. Chem. Biotechnol.* **1973**, *23*, 607.

Received for review March 1, 1984. Accepted June 18, 1984.

Relationship between Physical and Chemical Characters and Cooking Quality in Lentil

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The cooking quality (shear force) of 101 samples of three cultivars of lentil grown at several locations in 1980 and 1981 was related to their protein, hardness, phosphorus (P), Ca^{2+} , Mg^{2+} , Na^+ , K^+ , $(\text{Na}^+ + \text{K}^+)/\text{P}$, and $(\text{Ca}^{2+} + \text{Mg}^{2+})/\text{P}$ contents. The major significant correlation obtained was between cooking quality and $(\text{Ca}^{2+} + \text{Mg}^{2+})/\text{P}$ ratio, suggesting some role of these mineral elements in the cooking quality of the lentil. The cooking quality of 10 samples of lentil, having extreme values for shear force, was not related to seed size, hardness, or amylose content. The good-cooking lentil had significantly higher hydration coefficients (water uptake) than the poor-cooking lentil. However, the rate of water uptake was similar in both the good- and poor-cooking lentil samples. Scanning electron microscopy showed similar starch granules in both good- and poor-cooking lentil; nor were there any consistent differences in the differential scanning calorimetry properties of the starches. However, viscoamylograms of the lentil meals showed consistently higher peak and set-back viscosities for the good-cooking lentil samples.

The lentil is now a well-established crop in Western Canada. Saskatchewan is the major producer, the 1983 production area was 36 000 ha out of the total Canadian production of 46 000 ha. Lentil cultivars grown in Saskatchewan are Laird and Chilean (Chilean type), which are yellow cotyledon, large and medium seeded, respectively, and Eston (Persian type), which is a yellow cotyledon and small seeded lentil (Slinkard and Bhatta, 1979; Slinkard, 1981).

Cooking quality is the foremost quality criterion in lentil. In our previous studies (Bhatta et al., 1983, 1984), it was reported that location and season of growth (environments) had a major influence on the cooking quality of lentil. The intracultivar variability in cooking quality was 94-97% in Laird and Chilean grown in 1980 and 35-92% in Laird, Chilean, and Eston lentil grown in 1981. How environ-

ments exert such a large influence on the cooking quality of lentil is not known. A number of factors has been reported to affect cooking quality in legumes. An earlier study (Mattson et al., 1950) reported that cooking quality in pea was affected by the seed coat, the phytic acid and pectin contents of the seed, and the ratio between the monovalent (Na^+ , K^+) and divalent (Ca^{2+} , Mg^{2+}) ions. Later, Muller (1967) reported a relationship between cooking quality and phytic acid, Ca^{2+} , Mg^{2+} , and free pectin in a number of pulses. Other factors thought to influence cooking quality in pulses were thickness of the seed coat pallsade layer and the lignin and α -cellulose contents of the seed. Cell contents such as starch and protein had no detectable effect on the cooking quality of pulses. However, more recently Youssef et al. (1982) observed differences in amylograph peak viscosity and differential scanning calorimetry properties of starch isolated from hard and soft cooking faba bean. In another study (Wassimi et al., 1978), externally applied major and trace elements improved the cooking quality of lentil grown in a pot experiment, though no direct relationship was found

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between phytic acid and cooking quality.

Undoubtedly, many factors are involved in the cooking quality of legumes. However, few studies have been conducted on factor(s) affecting cooking quality of lentil. The present study was conducted to determine the relationship between physical and chemical characters and cooking quality in a large number of lentil samples grown on farmers' fields.

EXPERIMENTAL SECTION

Lentil Samples. One hundred and one samples of Laird, Chilean, and Eston lentil (*Lens culinaris* Medik.) were obtained from cooperating farmers in 1980 and 1981. They were field grown at 30 locations in Saskatchewan, 6 in Manitoba, and 1 in Alberta in the 1980 growing season (52 samples) and at 18 locations in Saskatchewan and 6 in Manitoba in the 1981 growing season (49 samples). On arrival in the laboratory, the samples were manually cleaned and sized by passing through a Dockage tester fitted with 14, 13, and 10 mm opening screens for Laird, Chilean, and Eston lentil, respectively, and stored in airtight plastic jars at room temperature. Subsamples of lentil were ground in a Udy cyclotec mill having a 1.0-mm screen and the ground samples (meals) stored at 5 °C.

Determination of Cooking Quality. The cooking quality of lentil was determined in quadruplicate by a procedure described previously (Bhatty et al., 1983, 1984). The optimum cooking time was 60 min for Laird and Chilean and 30 min for Eston lentil. At these times, at least 50% of the samples were considered cooked as they had shear force values smaller than 4.0 kg/g.

Physical Measurements. One-gram seed lots of each cultivar were counted manually in triplicate to obtain number of seed per gram (seed size). Seed hardness was determined with a Brabender microhardness tester at an arbitrary setting of 30. Hardness was indicated by shorter and, conversely, softness by a longer grind time. Hydration coefficient was calculated by measuring water uptake by 10 g of lentil soaked in 25 mL of distilled water for 8 h at room temperature (Hulse et al., 1977). The rate for water uptake was determined by immersing 10 g of lentil in 50 mL of boiling water. After appropriate times (0, 5, 10, 20, 40, and 60 min for Laird and Chilean and 0, 5, 10, 20, 25, and 30 min for Eston), the lentil sample was removed from the boiling water and blotted dry, its weight recorded, and the sample returned to the water. The seed to water ratio was kept constant. The log time (X) and weight gain (Y) were used to calculate the rate (slope) from the regression equation $Y = a + bx$. The least significant difference between two rates of water uptake within each cultivar was calculated by the t test (Steele and Torrie, 1980).

Chemical Analyses. Moisture and protein contents ($N \times 6.25$) of the samples were determined by the official methods (AOAC, 1980). Starch was prepared from selected samples as described previously (Bhatty and Slinkard, 1979). Amylose content of the starch was determined colorimetrically (Williams et al., 1970), with potato amylose (type III; Sigma) as a reference standard. For mineral analysis the ground lentils were wet ashed with 5 volumes of concentrated sulfuric acid. P, Ca²⁺, and Mg²⁺ were determined by atomic absorption spectroscopy and Na⁺ and K⁺ by flame photometry.

Scanning Electron Microscopy (SEM). Lentil starch was sprinkled on taped aluminum stubs that were then coated under vacuum with a gold palladium alloy and scanned with a Cambridge stereoscan MKII SEM operated at 10 kV.

Differential Scanning Calorimetry (DSC). DSC of lentil starch was determined with a Perkin-Elmer differ-

Table I. Percentage of Lentils Cooked in 15–60 Minutes for Laird, Chilean, and Eston Grown in 1980 and 1981

year	Laird ^a			Chilean ^a			Eston ^b		
	30	45	60	30	45	60	15	30	45
1980	0	23	55	0	29	58			
1981	9	41	95	6	53	88	0	64	100
1982		65						100	

^aOptimum cooking time 60 min. ^bOptimum cooking time 30 min.

ential scanning calorimeter (Model 2C). Temperature and power calibrations were established with indium of thermometric quality. Approximately 4 mg of starch of known moisture content was weighed into stainless steel pans, and water was added to a total weight of about 70 mg. The starch was heated from 30 to 130 °C at a scan rate of 5 °C/min. Peak areas and interpolation of temperature data were determined with the Perkin-Elmer data station. The thermograph was used to measure onset temperature (T_o), temperature at peak height (T_p), end temperature (T_e), and heat of transition (ΔH), which was calculated by using the standard equation. The volume fraction of water (v_1) was calculated by taking the average density of water as 1.00 mg/mL and that of starch as 1.5 mg/mL.

Viscoamylograph. The pasting and gelling properties of lentil meals were determined with a Brabender viscoamylograph. The slurry concentration was 12% (pH 5.5), and the temperature rise during the run was 1.5 °C/min. The viscoamylogram was used to determine pasting temperature (A), peak viscosity (B), viscosity at 95% (C), viscosity at the end of a 30-min holding period (D), and viscosity after cooling to 51 °C (E).

RESULTS AND DISCUSSION

The wide variations observed in the cooking quality of the three lentil cultivars grown at several locations in 1980 to 1982 are summarized in Table I. The lentil grown in 1980 had the poorest cooking quality when only 55–58% of the Laird and Chilean lentil samples were cooked in the optimum time of 60 min compared to 88–95% for the same two cultivars grown in 1981 and cooked for identical times. In addition, Table I shows results of the cooking quality tests for 130 individual plant progeny rows of Laird and 125 individual plant progeny rows of Eston lentil grown at one location (Saskatoon) in 1982. For these samples, the optimum cooking time (when 50% or more of the samples was cooked) was reached in 45 min in Laird (65% cooked) compared to 60 min for the same cultivar grown in the two previous years. Similarly, a large variability in cooking quality was observed in Eston lentil grown in 1981 (64% cooked) and in 1982 (100% cooked) in an optimum time of 30 min. Thus, a large intracultivar variability was apparent in the cooking quality of different lentil cultivars grown over a 3-year period. Environmental influences on the cooking quality of a few pea samples have been reported previously (Chernick and Chernick, 1963; Halstead and Gfeller, 1964). As far as is known, the extent of environmental variability in cooking quality in this many lentil samples has not been reported previously in the literature.

The 101 samples of the three lentil cultivars, grown in 1980 and 1981, were analyzed for protein, seed hardness, cooking quality, and mineral composition. The data in Table II show the range, mean, and coefficient of variability of the 12 parameters investigated. There were cultivar and year differences among some of the means, particularly for protein, hardness, and cooking quality. The ranges for the total number of samples grown in 1980 and 1981 were protein 59%, hardness 100%, shear force

175%, P 125%, Ca²⁺ 300%, Mg²⁺ 300%, K⁺ 64%, and 121-133% for (Na⁺ + K⁺)/P and (Ca²⁺ + Mg²⁺)/P ratios. These differences were due largely to location and season of growth as shown by the protein content of the lentil. The mean protein contents of Laird or Chilean lentil grown in 1980 or 1981 or those of Laird, Chilean, and Eston lentil grown in 1981 were generally similar, but the interyear variability in protein content was 13%. Similar conclusions may be drawn from the rest of the data given in Table II, although the seasonal differences were smaller in most other cases. The largest CV in mineral elements for the 1980 and 1981 samples was obtained for Ca²⁺ (28.6%) followed by P (15.6%) and Mg²⁺ (10.0%); the content and CV of Na⁺ were ignored because of its low concentration and the possibility of contamination from external sources. The protein content of lentil is of nutritional significance. The range in protein content was large (59%); the data showed a typical Gaussian distribution, except in 1981, when there were no lentil samples containing 23-24% protein. The mean protein content in 1980 and 1981 was 23.6% and 26.7%, respectively. About 17% of the lentil samples approached the mean protein content in 1980 and 24% in 1981.

Simple correlation coefficients were calculated between cooking quality and protein, hardness, P, Ca²⁺, Mg²⁺, Na⁺, K⁺, Na⁺ + K⁺, Ca²⁺ + Mg²⁺, and the (Na⁺ + K⁺)/P, and (Ca²⁺ + Mg²⁺)/P ratios (Table III). Although many correlations were statistically significant, the more meaningful correlations (+0.66-0.69**) were obtained between the cooking quality and (Ca²⁺ + Mg²⁺)/P ratios, particularly in 1980. The correlation for the total number of samples was +0.62**. The (Ca²⁺ + Mg²⁺)/P ratio will depend on the availability and uptake of soil P by the lentil plants, which require relatively large amounts of phosphate fertilizer. This ratio was larger by 12.8% in Laird and 7.9% in Chilean lentil grown in 1980 than in the same lentil grown in 1981. A larger ratio indicates that less P was present in lentil in 1980 when the cooking quality of the samples was the poorest (Table I). This was confirmed by the lower P content of the lentil grown in 1980 (0.42%) compared to those grown in the 1981 (0.47%) season. The implications of the significance of this correlation are not clear but may relate to some role that P, particularly phytic acid P, play in determining the cooking quality of lentil. A major portion of total P (53-82%) in 50 bean cultivars was present as phytic acid (Lolas and Markakis, 1975); lentil seeds may contain a similar proportion. Phytic acid (*myo*-inositol hexaphosphoric acid) has a preponderance of negative charge and a large potential for binding positively charged cations such as Ca²⁺ and Mg²⁺. Excess levels of phytic acid in lentil seeds, derived from soil P, may reduce the availability of Ca²⁺ and Mg²⁺ for the formation, in conjunction with pectin, of the relatively insoluble Ca²⁺- and Mg²⁺-pectates. Under these conditions, the more soluble Na⁺- and K⁺-pectates may predominate and facilitate the dissolution of the lentil cell wall during the cooking process. Indeed, in our previous studies (Bhatty et al., 1983, 1984) scanning electron microscopy had clearly shown that in undercooked lentil seeds (shear force >4.0 kg/g) the cell wall was undissolved and clearly visible unlike in cooked lentil seeds (shear force <4.0 kg/g) where a complete dissolution of the cell wall had taken place with a concomitant loss of cellular structure. Thus, though more definitive evidence is needed from experiments conducted under controlled environmental conditions, it is conceivable that variability in P levels in the samples (and hence phytic acid) partially contributed to variability in cooking quality. Phytic acid has been re-

Table II. Range, Mean, and Coefficient of Variability (Percent) of Protein, Hardness, Shear Force (Cooking Quality), and Mineral Elements of 101 Samples of Lentils Grown in 1980 and 1981

cultivar	year	param-eter	protein, %	hardness, s	shear force, kg/g	P, %	Ca ²⁺ , %	Mg ²⁺ , %	Na ⁺ , %	K ⁺ , %	Na ⁺ + K ⁺ , %	Ca ²⁺ + Mg ²⁺ , %	(Na ⁺ + K ⁺)/P	(Ca ²⁺ + Mg ²⁺)/P
Laird	1980 (22)	range	20.5-26.2	43.6-58.8	3.2-6.3	0.28-0.51	0.04-0.09	0.09-0.12	0.02-0.11	0.93-1.44	0.95-1.46	0.14-0.20	2.58-4.04	0.33-0.57
		mean	23.7	50.5	4.3	0.41	0.07	0.11	0.04	1.16	1.20	0.18	3.00	0.44
		CV	6.8	17.0	17.0	17.07	14.29	9.09	75.00	9.48	9.17	11.11	12.00	13.64
1981 (22)	range	21.2-29.2	43.2-58.5	2.4-4.6	0.39-0.63	0.05-0.16	0.09-0.13	0.02-0.18	1.10-1.41	1.12-1.45	0.16-0.25	2.14-3.03	0.28-0.57	
	mean	26.3	50.5	3.6	0.49	0.08	0.11	0.04	1.20	1.24	0.19	2.56	0.39	
	CV	7.8	7.4	17.5	14.29	25.00	9.09	100.00	5.83	7.26	10.53	9.38	17.95	
Chilean	1980 (30)	range	19.5-26.9	37.7-53.7	3.4-6.6	0.31-0.59	0.05-0.11	0.09-0.14	0.02-0.07	0.94-1.42	0.94-1.49	0.14-0.25	2.13-3.38	0.29-0.62
		mean	23.6	44.7	4.3	0.44	0.07	0.10	0.03	1.15	1.18	0.18	2.76	0.41
		CV	8.2	10.7	15.7	18.18	28.57	10.00	33.33	9.57	9.32	16.67	11.96	17.07
1981 (17)	range	24.9-30.4	36.1-49.1	3.1-4.8	0.38-0.55	0.05-0.08	0.08-0.12	0.02-0.10	0.88-1.32	0.90-1.40	0.15-0.19	1.73-3.13	0.31-0.47	
	mean	26.9	44.5	3.8	0.45	0.07	0.10	0.04	1.14	1.18	0.17	2.66	0.38	
	CV	7.0	7.7	11.3	11.11	14.29	10.00	50.00	8.77	9.32	5.88	13.91	13.16	
Eston	1981 (10)	range	21.8-31.0	46.4-72.5	3.7-5.0	0.36-0.54	0.05-0.07	0.09-0.11	0.02-0.07	1.00-1.21	1.02-1.24	0.16-0.18	2.06-2.76	0.30-0.49
		mean	27.1	60.2	4.2	0.46	0.07	0.10	0.04	1.09	1.13	0.17	2.46	0.37
		CV	9.4	14.0	9.2	10.87	14.29	10.00	50.00	6.42	6.19	5.88	8.54	16.22
1980 (52)	range	19.5-26.9	37.7-58.8	3.2-6.6	0.28-0.59	0.04-0.11	0.09-0.14	0.02-0.11	0.93-1.44	0.95-1.49	0.14-0.25	2.13-4.04	0.29-0.62	
	mean	23.6	47.1	4.3	0.42	0.07	0.10	0.04	1.15	1.19	0.18	2.86	0.42	
	CV	7.6	11.5	16.3	19.05	28.57	10.00	50.00	9.57	9.24	11.11	12.59	14.29	
total	1981 (49)	range	21.2-31.0	36.1-72.5	2.4-5.0	0.36-0.63	0.05-0.16	0.08-0.13	0.02-0.18	0.88-1.41	0.90-2.45	0.15-0.25	1.73-3.32	0.28-0.57
		mean	26.7	50.4	3.8	0.47	0.07	0.11	0.04	1.16	1.20	0.18	2.57	0.38
		CV	7.8	14.8	15.0	12.77	28.57	9.09	75.00	7.76	8.33	11.11	11.28	15.79
1980 and 1981 (101)	1981 (101)	range	19.5-31.0	36.1-72.5	2.4-6.6	0.28-0.63	0.04-0.16	0.08-0.14	0.02-0.18	0.88-1.44	0.90-1.49	0.14-0.25	1.73-4.04	0.28-0.62
		mean	25.1	48.7	4.0	0.45	0.07	0.10	0.04	1.19	1.19	0.18	2.72	0.40
		CV	9.9	13.7	16.8	15.56	28.57	10.00	75.00	8.62	9.24	11.11	13.24	15.00

Table III. Simple Correlations between Shear Force (Cooking Quality) and Protein, Hardness, and Mineral Elements in 101 Samples of Lentils Grown in 1980 and 1981

component	1980			1981				1980 and 1981 (101) ^c
	Laird (22) ^a	Chilean (30) ^a	total (52) ^a	Laird (22) ^a	Chilean (17) ^a	Eston (10) ^a	total (49) ^a	
protein	0.23	0.52	0.40	0.34	-0.12	0.41	0.26*	0.01
hardness	-0.19	0.10	0.02	0.14	0.19	-0.07	0.25*	0.03
phosphorus	-0.48* ^b	-0.38*	-0.42**	-0.42	-0.43*	-0.18	-0.41**	-0.49**
calcium	0.02	0.28	0.17	0.36	0.28	-0.21	0.11	0.13
magnesium	0.01	-0.06	-0.02	0.30	0.14	0.23	0.08	-0.03
sodium	0.19	0.22	0.21	-0.36	-0.01	-0.50	-0.27	-0.04
potassium	-0.57**	-0.44**	-0.49**	-0.43*	0.33	-0.12	-0.28*	-0.40**
sodium + potassium	-0.50**	-0.39*	-0.43	-0.52**	-0.29	-0.24	-0.34**	-0.38**
calcium + magnesium	0.02	0.17	0.11	0.52**	0.35	-0.03	0.15	0.09
(sodium + potassium)/phosphorus	0.43*	0.33*	0.38**	0.27	0.54*	0.14	0.24*	0.43**
(calcium + magnesium)/phosphorus	0.69**	0.66**	0.67**	0.61**	0.55*	0.27	0.44**	0.62**
significant values for <i>r</i> at								
0.05	0.36	0.31	0.23	0.36	0.41	0.55	0.23	0.16
0.01	0.49	0.42	0.32	0.49	0.56	0.72	0.32	0.23

^a Number of samples. ^b *, significant; **, highly significant.

Table IV. Relationship between Shear Force (Cooking Quality) and Some Physical Characteristics of Laird, Chilean, and Eston Lentil Grown in 1980 and 1981

character	Laird 1980		Chilean 1980		Laird 1981		Chilean 1981		Eston 1981	
	3.5 ^a	6.3 ^a	3.4 ^a	5.2 ^a	2.4 ^a	4.6 ^a	3.1 ^a	4.8 ^a	3.7 ^a	4.9 ^a
seed size, seeds/g	13.3	13.3	18.0	17.7	13.0	14.0	18.0	16.0	26.7	26.7
hardness, s	54.5	48.2	50.2	38.3	54.1	54.2	36.1	46.9	52.3	62.4
hydration coefficient, ^b %	195	187			198	188			191	185
rate of water uptake ^c	4.11	4.02	3.54	3.61	4.34	3.83	3.54	3.81	6.29	5.49

^a Shear force (kg/g). ^b The least significant difference at 0.05 was 1.7% for Laird 1980, 2.1% for Laird 1981 and 1.5% for Eston 1981. ^c The least significant difference at 0.05 was 2.3 within each cultivar pair.

ported to influence the cooking quality of pea (Mattson et al., 1950), *Phaseolus* bean (Kon and Sanshuck, 1981), and pigeon pea (Fasidi, 1981). More recently, Chong et al. (1983) reported positive correlations between cooking quality and P/Mg²⁺, K⁺/P, and Mg²⁺/K⁺ ratios in pea. However, Wassimi et al. (1978) reported no correlation between phytic acid and cooking quality in lentil. This discrepancy may be due to incomplete complexing of the divalent ions by phytic acid. Crean and Haisman (1963) reported that in pea only 44% of the Ca²⁺ and Mg²⁺ formed insoluble phytates; the rest were available for cross-linking with uronic acid groups of pectin and lower ester pectins of the middle lamella. Thus, low levels of seed Ca²⁺ and Mg²⁺ and enhanced levels of phytic acid may be more conducive to good cooking quality in legumes. Such a balance may need to be established for each species of legumes for optimum cooking quality.

Ten samples of lentil, two of each cultivar grown in 1980 and 1981 and having extreme values for cooking quality, were selected from the hundred and one samples described previously and further investigated for differences in their cooking quality (Table IV). Seed size (Laird > Chilean > Eston) had no influence on cooking quality, nor was there any relationship between seed hardness and cooking quality. Some good-cooking lentil samples had marginally lower grind time and were thus softer. However, this relationship was not consistent and was even reversed in Chilean and Eston lentil grown in 1981. Therefore, it seemed that large-seeded lentil took longer to cook, but seed size did not contribute to intercultivar differences in cooking quality.

In preliminary experiments, the hydration coefficient for one sample each of Laird, Chilean, and Eston lentil was determined by soaking for various lengths of time. Water absorption was generally similar in the three cultivars and reached a maximum in about 8 h. Subsequently, this time was used to determine the hydration coefficients of Laird

and Eston lentil grown in 1980 and 1981. These two cultivars provided a contrasting seed size. Table IV shows that good cooking quality as associated with a higher hydration coefficient; the differences between each pair were statistically significant.

In another related experiment the rate of water uptake by the lentil was determined at boiling water temperature to coincide with the water temperature used during the cooking of lentil. The results showed positive correlations between water grain and log time (not given in Table IV); however, the rate of water uptake calculated from the slope of the regression equation was not significantly different. Thus, although the good-cooking samples absorbed more water than the poor-cooking samples, it diffused into the seed at a similar rate. However, many factors affect water absorption by seeds, some of which have been described for soybean by Hsu et al. (1983) and by Arechavaleta-Medina and Snyder (1981). The factors governing water uptake and their role in influencing cooking quality in lentil are beyond the scope of this study and need separate investigation.

The SEM photographs of starch isolated from good- and poor-cooking Laird and Eston lentil (1981 crop) were generally similar to those described previously (Bhatti and Slinkard, 1979). The large granules in Laird lentil starch were about 35–40 μm, and the small round granules about 10–20 μm. There was a similar size distribution in Eston lentil starch, though it seemed to have a higher frequency of the smaller granules than the Laird lentil starch. The amylose content of the starches varied from 39.0 to 47.4% and was generally similar for the good- and poor-cooking lentil.

Table V shows the DSC and viscoamylograph properties of starch obtained from good- and poor-cooking lentil. Although there appeared to be some differences in the DSC among the samples, these differences were not consistent. A higher Δ*H* would suggest a relatively more stable

Table V. DSC and Viscoamylograph Properties of Starch and Meal of Lentil Having Different Shear Force Values (Cooking Quality)

cultivar	year	shear, force, kg/g	DSC (starch)					viscoamylogram (meal)				
			v_1 , °C	T_0 , °C	T_p , °C	T_e , °C	ΔH , J/g	A, °C	B, BU	C, BU	D, BU	E, BU
		3.5	0.96	66.4	71.1	84.4	17.1	70.0	520	520	455	680
Laird	1980	6.3	0.98	65.0	69.5	79.4	11.5	^a	^a	^a	^a	^a
Chilean	1980	3.4	0.98	64.8	70.4	79.1	10.4	70	605	600	480	690
		5.2	0.97	65.9	70.6	81.9	14.6	68	440	435	372	560
Laird	1981	2.4	0.97	64.5	72.6	83.4	18.4	70	600	600	525	640
		4.6	0.97	66.3	70.1	81.2	17.2	68	340	340	320	405
Chilean	1981	3.1	0.96	65.0	71.9	87.0	18.3	72	565	555	430	610
		4.8	0.96	66.6	71.4	82.9	13.5	69	445	440	360	530
Eston	1981	3.7	0.96	61.5	65.5	79.5	13.6	65.5	560	555	490	650
		4.9	0.96	63.5	68.2	85.5	17.4	69.0	520	510	415	435

^a Insufficient sample.

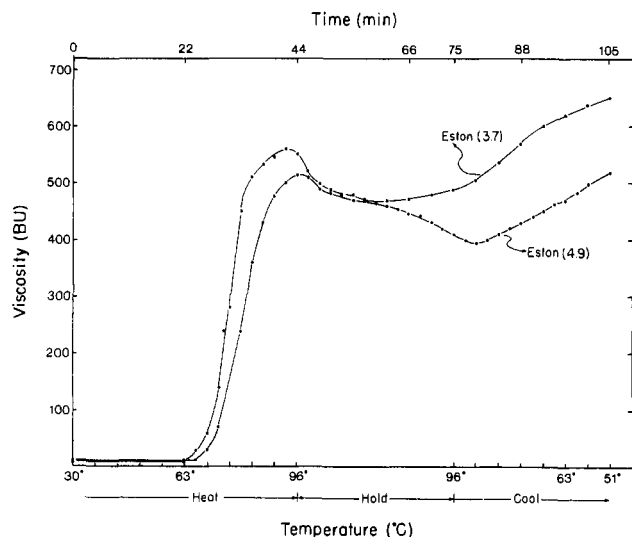


Figure 1. Viscoamylograph of a 12% slurry of a good- and poor-cooking Eston lentil meals. (The figures in parentheses indicate shear force in kg/g).

starch structure, having stronger bonding. The good-cooking samples of Laird 1980 and Chilean 1981 had higher T_0 , T_e , and ΔH values than the poor-cooking samples of these cultivars. However, these differences were not consistent since in other cases the ΔH of the poor-cooking lentil was either nearly equal to (Laird 1981) or greater than (Chilean 1980; Eston 1981) the ΔH for good-cooking lentil. Nevertheless, the differences in ΔH between the good- and poor-cooking Laird 1980 and Chilean 1981 samples were 35–49% and greater than the ΔH difference reported for soft- and hard-cooking faba bean by Youssef et al. (1982). However, because of lack of consistency of the present data, it is questionable whether DSC can distinguish between good- and poor-cooking lentil.

Unlike DSC properties of lentil starches, the viscoamylogram patterns of good- and poor-cooking lentil showed consistent differences in pasting temperature (A), peak viscosity (B), viscosity at the end of the holding period (D), and set-back viscosity (E) (Table V). Figure 1 shows a typical viscoamylogram of a good- and poor-cooking lentil meal. The difference in peak viscosities varied from 40 to 260 BU and, at first sight, may suggest the ability of viscoamylogram to distinguish between good- and poor-cooking lentil. It is likely the differences in the viscoamylogram properties of the meals were compounded by the presence in them of nonstarchy substances such as amylases, proteins, salts, pentosans, and sugars, all of which influence the pasting properties of starch. In one experiment, 200 mg of mercuric chloride was added to each slurry of five samples in the mixing bowl to inhibit α -

amylase. In each case, except one, the values for viscosity were decreased. If α -amylase was present in the meals and was inhibited by mercuric chloride, the viscosities would increase and not decrease as was the case in the four other samples.

The peak viscosity indicates the swelling power of the starch granule. Therefore, good-cooking lentil having higher peak viscosities may have a less crystalline structure than the poor-cooking lentil. Lentil samples having such a starch may take a shorter time to cook and may thus partially contribute to variability in the cooking quality. It is possible that environmental influences bring about some changes in the orientation of the starch granule during its synthesis. The viscoamylogram data obtained need to be confirmed with starch isolated from good- and poor-cooking lentil.

CONCLUSIONS

Two or possibly three factors singly or in combination were probably involved in the observed intracultivar variability in the cooking quality of lentil. First, environmental conditions altered the seed coat in such a way so as to partially impede water absorption into the seed during the cooking process. This retarded dissolution of the cell wall. Intact cell walls are typical of undercooked lentil. This conclusion is consistent with the higher water absorption of the good-cooking lentil samples. Second, the $(Ca^{2+} + Mg^{2+})/P$ ratio had some influence on the cooking quality of the lentil because it was positively correlated with shear force. Third, higher peak and set-back viscosities of good-cooking lentil meals indicated some role of starch and/or of other components in affecting the cooking quality of lentil. Further research is needed to establish the role of each of the above factors using lentil with larger differences in cooking quality and grown under experimentally controlled conditions.

ACKNOWLEDGMENT

We thank Professors A. Sumner and M. Steel for the use of their equipment, Drs. R. Baker and A. Slinkard for help with statistical analysis of the data, and M. Nielsen and G. Pocha for technical assistance.

Registry No. P, 7723-14-0; Ca, 7440-70-2; Mg, 7439-95-4; Na, 7440-23-5; K, 7440-09-7.

LITERATURE CITED

- AOAC. "Official Methods of Analysis", 13th ed.; Horwitz, W., Ed; AOAC: Washington, DC, 1980.
- Arechavalaeta-Medina, F.; Snyder, H. E. *J. Am. Oil. Chem. Soc.* 1981, 58, 976.
- Bhatty, R. S.; Nielsen, M. A.; Slinkard, A. E. *Can. Inst. Food Sci. Technol. J.* 1983, 16, 104.
- Bhatty, R. S.; Nielsen, M. A.; Slinkard, A. E. *Can. J. Plant Sci.* 1984, 64, 17.

- Bhatty, R. S.; Slinkard, A. E. *Can. Inst. Food Sci. Technol. J.* 1979, 12, 88.
- Chernick, A.; Chernick, B. A. *Can. J. Plant Sci.* 1963, 43, 174.
- Chong, J.; Ali-Khan, S. T.; Chubey, B. B.; Gubbels, G. H. *Can. J. Plant Sci.* 1983, 63, 1071.
- Crean, D. E. C.; Haisman, D. R. *J. Sci. Food. Agric.* 1963, 14, 824.
- Fasidi, I. O. *Nahrung* 1981, 25, 949.
- Halstead, R. L.; Gfeller, F. *Can. J. Plant Sci.* 1964, 44, 221.
- Hsu, K. H.; Kim, C. J.; Wilson, L. A. *Cereal Chem.* 1983, 60, 208.
- Hulse, J. H.; Rachie, K. O.; Billingsley, L. W. In "Nutritional Standards and Methods of Evaluation for Food Legume Breeders"; International Development Research Centre (IDRC)—Ts 7e: Ottawa, Canada, 1977.
- Kon, S.; Sanshuck, D. W. *J. Food Process. Preserv.* 1981, 5, 169.
- Lolas, G. M.; Markakis, P. *J. Agric. Food Chem.* 1975, 23, 13.
- Mattson, E.; Akenberg, E.; Eriksson, E.; Koutler-Andersson, E.; Vahtras, K. *Acta Agric. Scand.* 1950, 1, 40.
- Muller, F. M. *J. Sci. Food Agric.* 1967, 18, 292.
- Slinkard, A. E. *Can. J. Plant Sci.* 1981, 61, 733.
- Slinkard, A. E.; Bhatty, R. S. *Can. J. Plant Sci.* 1979, 59, 503.
- Steele, R. G. D.; Torrie, J. H. "Principles and Procedures of Statistics", 2nd ed.; McGraw-Hill: New York, 1980.
- Wassimi, N.; Abu-Shakra, S.; Tanhous, R.; Hallab, A. H. *Can. J. Plant Sci.* 1978, 58, 165.
- Williams, P. C.; Kuzina, F. D.; Hlynka, I. *Cereal Chem.* 1970, 47, 411.
- Youssef, M. M.; Bushuk, W.; Murray, E. D.; Zillman, R.; El-Tabey Shehata, A. M. *J. Food Sci.* 1982, 47, 1695.

Received for review March 26, 1984. Accepted July 2, 1984. This research was supported from grants by the Market Development Fund, Saskatchewan Agriculture, and the Agricultural Development Corporation of Saskatchewan, Regina, and from the Hantelman Trust, University of Saskatchewan, Saskatoon.

Steam Explosion of Mixed Hardwood Chips, Rice Hulls, Corn Stalks, and Sugar Cane Bagasse

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Southern hardwood chips, rice hulls, corn stalks, and sugar cane bagasse were steam exploded. The hemicelluloses of all biomass materials were at least partially degraded. The hemicelluloses remaining were generally soluble in hot water. The cellulose content decreased only slightly. A portion of the lignin was soluble in hot aqueous alkali. However, up to half of the cellulose was also extracted by hot aqueous alkali. Acid hydrolysis of exploded hardwood chips, corn stalks, and sugar cane bagasse showed no rate enhancement. Exploded rice hulls showed a hydrolysis rate increase of approximately 2-fold. Enzymatic hydrolysis rates showed a 10-fold increase for exploded hardwoods, sugar cane bagasse, and rice hulls. No enzymatic rate increase was observed for exploded corn stalks; untreated corn stalks hydrolyzed at a rate similar to that of filter paper. The results suggest that the steam explosion pretreatment may not be as promising as suggested by researchers who have exploded aspen.

If efficient and economical processes can be developed for converting low-value biomass into commercially useful products, mankind would benefit in a substantial manner. Biomass conversion could provide an abundance of useful food, fuel, and chemical products from the cellulose in urban trash and the residues from forestry and agriculture (Cowling and Kirk, 1976). It would also help improve the management of forests by providing a market for the large amounts of low-quality, small-stem hardwoods that are currently growing on southern pine sites.

A variety of chemical and physical pretreatment methods have been developed for increasing the susceptibility of lignocellulose materials to enzymatic and acid hydrolysis. The ideal pretreatment not only should disrupt the plant cell structure but also should use inexpensive chemicals and require simple equipment. In addition, the pretreatment should fractionate the lignin and hemicelluloses and lower the crystallinity and molecular weight of the cellulose. Another important characteristic of a pretreatment, but one which has been largely ignored, is that it needs to be effective with a large range of biomass materials.

One promising pretreatment appears to be steam explosion. This process was originally developed by Mason in 1925 and has been extensively used in the manufacture of hardboard (Spalt, 1977). In 1978, the Iotech Corp. Ltd., of Canada started using this process for the production of feed for ruminants. In view of the early results that showed the high digestibility of steam-exploded wood, Iotech decided to explore the use of this process as a method for pretreating aspen (Foody, 1980).

Since Iotech first reported their initial results, other investigators have also examined steam explosion as a biomass pretreatment for aspen (Marchessault et al., 1980, 1982; Marchessault, 1982; Foody, 1980; DeLong, 1981). These investigators have found that the following chemical changes occur in steam-exploded aspen: (1) The lignin is broken down into products with a molecular weight range of from 150 to 7000. Since the lignin is extensively depolymerized, it is soluble in alkaline solutions or certain organic solvents. (2) The hemicelluloses are partially broken down and are predominantly soluble in hot water. In addition, some degradation products are formed that apparently condense with lignin, thereby increasing the lignin content. (3) Steam explosion causes a large increase in the accessibility of the cellulose to enzymatic hydrolysis. Jurasek (1978) determined that the steam-explosion pretreatment resulted in approximately a 10-fold increase in the susceptibility of aspen wood to enzymatic hydrolysis.

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