

Improvement of Sorghum-Wheat Composite Dough Rheological Properties and Breadmaking Quality Through Zein Addition¹

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ABSTRACT

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Addition of sorghum flour to wheat flour produces marked negative effects on rheological properties of dough and loaf volume. Although there are notable differences in the chemical composition of sorghum proteins (kafirins) compared with wheat gluten that might imply poor functionality in breadmaking systems, a larger constraint may be the unavailability of kafirins due to encapsulation in protein bodies. In this study, zein, the analogous maize prolamin to kafirin, was used to determine the potential effects of protein-body-free prolamins on dough rheology and baking quality of wheat-sorghum composite flour. Mixograms run at 35°C (above the

glass transition temperature of zein) were significantly ($P < 0.01$) improved with addition of zein. Mixogram peak heights increased while mixing time decreased uniformly with addition of zein. Dough extensibility studies showed an increase in maximum tensile stress, while baking studies showed an increase in loaf volume with increasing amounts of added zein. These data are supported by a previous study showing that, in a model system, zein mixed with starch can form viscoelastic networks, and suggest that kafirin, if made available, could contribute to dough formation.

Bread consumption is increasing in developing countries where bread was previously not an item of daily food, such as those of tropical Africa. Although crop production statistics have shown a significant increase in world wheat production, the increase occurred primarily in developed countries or temperate regions of the developing world (FAO 1997). This is attributed to the use of nitrogen fertilizers and improved new high-yielding cultivars (Mattern 1991). The increasing demand for bread in many developing countries has, therefore, caused high importation of wheat and, as a result, has drained critical hard currency reserves. One of the feasible approaches for overcoming this adverse economic problem is to substitute part of the wheat flour in wheat-based products with other flours such as cassava, maize, sorghum, and millets, which are readily available in these countries.

The use of sorghum-based composite flours in breadmaking has been studied for the last four decades (Bhatia et al 1968; Kim and De Ruiter 1968; Pringle et al 1969; Dendy 1970; Subramanian et al 1983). Results have shown a substitution of up to 15% sorghum flour to be feasible using the conventional breadmaking process. Further increase in the proportion of sorghum flour causes undesirable changes in bread characteristics, such as decrease in loaf volume and a firmer crumb structure. In all of these studies, addition of sorghum flour to wheat flour at higher levels negatively affected dough rheological properties.

It has long been thought that only wheat proteins have the ability to form a strong, cohesive, and viscoelastic dough that retains gas to produce light, aerated baked products (Matsumoto 1986; Hosoney and Rogers 1990; Shewry et al 1995; Lásztity 1996). Factors that contribute to this unique behavior of gluten are related to its amino acid composition, structure, and its polymeric nature (Lásztity 1996; Hosoney 1998; Shewry 1999). Gluten amino acid composition shows high content of glutamine residues, relatively high proline, and low amounts of basic amino acids (lysine, arginine, and histidine). Thirty-five percent of the total amino acids of gluten have hydrophobic side chains (leucine, isoleucine, and proline). Thiol groups and disulfide bonds from cysteine/cystine play an important role in determining gluten and dough properties (Schofield et al 1983). Sulfhydryl groups promote disulfide-sulfhydryl interchange that

involves cleavage and reformation of disulfide bonds, which contribute to dough strength and stability. Hydrophobic interactions from the hydrophobic side chains, coupled with the hydrogen bonding from high amide content as well as low charge density, also play important roles in stabilizing gluten structure and in creation of the rheological and leavening properties of wheat dough.

Zein and kafirin differ from gluten in structure and amino acid composition. They have a high helical content at $\approx 40\%$ (Wu et al 1971; Danzer et al 1975), whereas gluten is mostly a random coil (Hosoney 1998). The relatively high hydrophobicity of zein and kafirin resulting from higher content of hydrophobic residues makes them extractable in more nonpolar solvents than those commonly used for gluten.

Zein and kafirin are encapsulated in protein bodies in the endosperm of maize and sorghum kernels, which makes them unavailable for participation in dough fibril formation or other interactions. Protein bodies are formed by accumulation of prolamins in the lumen of the rough endoplasmic reticulum (Larkins et al 1984). Wheat differs from maize and sorghum in that its protein is mostly packaged into vacuoles that are disrupted on seed desiccation, and compressed by starch granules to form a continuous protein matrix in which starch granules are embedded (Shewry 1999). The insoluble protein matrix of wheat is an essential prerequisite for the formation of cohesive dough. Gluten present in the continuous matrix easily interacts during dough mixing to give continuous networks.

Recent studies on zein and kafirin have shown them to be analogous in various ways, such as having similar electrophoretic banding patterns, extractability, immunospecificity (Shull et al 1991), amino acid composition, and location within the protein body (Shull et al 1992). Zeins and kafirins have been subclassified as α -, β -, and γ -proteins based on similarities in molecular weight, composition, solubility, and structure (Esen 1987; Larkins et al 1984; Shull et al 1991). α -Kafirin (M_r 25,000 and M_r 23,000), β -kafirin (M_r 20,000, M_r 18,000, and M_r 16,000), and γ -kafirin (M_r 28,000) (Shull et al 1991) are analogous to α -zein (M_r 22,000 and M_r 19,000), β -zein (M_r 14,000), and γ -zein (M_r 27,000) (Larkins et al 1984). A high degree of sequence homology has been shown between γ -zein and γ -kafirin (De Barros et al 1991). α -Prolamin, the major storage protein subclass in both cereals, is found in the central part of protein bodies, whereas β - and γ -prolamins are found at the periphery and in dark staining inclusions within protein bodies (Larkins et al 1984; Shull et al 1991). These similarities between kafirin and zein indicate similar chemical reactivities.

All amorphous protein polymers exhibit a glass transition, which is a reversible physical change of states, from glassy to rubbery, promoted by addition of heat and uptake of plasticizer. The temperature at which an amorphous polymer changes from glassy

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to rubbery state is known as the glass transition temperature (T_g). It is an important physical parameter in dough rheology because it helps explain the physical and chemical behavior of proteins during mixing. Below the T_g , a polymer is in a rigid glassy state in which molecular mobility and diffusivity are extremely low. Above the T_g , glassy materials become rubbery and flexible due to occupation of increased free volume and increased mobility and, as a result, the reactivity of the polymer is enhanced (Levine and Slade 1989). The T_g of gluten is below room temperature at 16% or higher moisture content (Hoseney et al 1986), while that of zein is above room temperature even at relatively high moisture content (Lawton 1992).

Lawton (1992) showed that, above its glass transition temperature, zein in a model system with corn starch could form a viscoelastic dough. This suggests that, under the right conditions, zein and kafirin, if made available, might participate in the dough-forming process. The objective of this study was to investigate the behavior of protein-body-free zein in a sorghum-wheat composite flour model system and to determine its contribution to dough rheology and loaf volume. Due to the similarities between zein and kafirin, this knowledge could be used to predict the contribution of kafirin in the same system.

MATERIALS AND METHODS

Sorghum Flour Preparation

A normal sorghum cultivar, MR732, was decorticated using a tangential abrasive dehulling device (Venables Machine Works Ltd., Saskatoon, Canada) to remove 20% of its original weight and then milled through a 0.5-mm mesh screen in a cyclone mill (Tecator model 1093, Sweden).

Composite Flour Preparation

Composite flours were made to contain 10, 20, and 30% sorghum flour with the remainder being commercial wheat flour (13.3% protein, King Arthur Flour, Norwich, VT). Zein (Lot no.

18H0774, Sigma-Aldrich, St. Louis, MO) was added to the sorghum portion of a 20% composite flour at levels of 1, 5, and 10%. The composite flours were mixed thoroughly in a mixer to ensure uniform distribution of flour particles. Wheat flour (100%) was used as the control. All flour samples were kept overnight in a 35°C temperature-controlled room to equilibrate.

Dough Rheology Studies

Dough development properties were determined using the 35-g Swanson-Working Mixograph (National Mfg. Co., Lincoln, NE) in a 35°C temperature-controlled room. Mixing requirements and water absorption were estimated by Approved Method 54-40A (AACC 2000). Mixograph curves were run for 8 min.

The planar extensional flow test developed by Morgenstern and coworkers (1996) was used to determine dough extensibility. This method uses a sheet deforming device consisting of two plates with a circular aperture in the middle and a flat probe attached to a universal testing machine. Dough was mixed using the Swanson pin-type mixer (National Mfg. Co.) with capacity of 100–150 g of dough. The dough was divided into 50-g pieces, rolled into a ball, and passed once through sheeting rolls to give a final sheet of 5.5-mm thickness. The sheet of dough was placed between the plates and deformed using a probe moving at a constant speed of 10 mm/min. The test was conducted at 35°C using a load cell of 100 lb, a probe of 40-mm diameter, and plate aperture diameter of 55 mm.

Baking Test

Baking tests were conducted using the 100-g basic straight-dough breadbaking method (AACC Approved Method 10-09). The bread formula was 100 g of flour, 0.9 g of dry yeast (Fleischmann's Yeast, San Francisco, CA), 5 g of sugar, 1 g of salt (Morton International, Inc., Chicago, IL), and 0.1 g of ammonium phosphate, monobasic (lot no. 80H0086, Sigma-Aldrich). Mixing time was obtained from mixograms and amount of water added was as estimated by Approved Method 54-40A. All dry ingredients, except yeast, were weighed and placed in closed containers in a 35°C temperature-controlled room overnight to equilibrate. Dough was mixed in a Swanson pin-type mixer (National Mfg. Co.), with capacity of 100–150 g, and scaled to 120 g. Fermentation was done in a 32°C fermentation cabinet (Precision Scientific Co. Chicago, IL) for a total of 180 min with three punches at time intervals of 105 min (first punch), 50 min (second punch), and 25 min (third punch). Punching was done using a sheeter and molder (National Mfg. Co.) with a clearance of 9/32 in. for first and second punches, and 9/32 in. followed by 3/16 in. for third punch. The fermented dough was molded, proofed for 55 min at 32°C, and baked in a rotary electric oven (National Mfg. Co.) at 425°C for 25 min. The loaves were cooled on a rack for 10 min, and loaf volume was measured by the rapeseed displacement method. Weight of loaf was also measured for calculation of specific loaf volume: specific loaf vol. (cm^3/g) = loaf vol. (cm^3)/loaf weight (g).

Statistical Analysis

To determine the reproducibility of the baking test measurements, five loaves were baked each day for four days. This statistical design was used to calculate the coefficients of variation for the baking test.

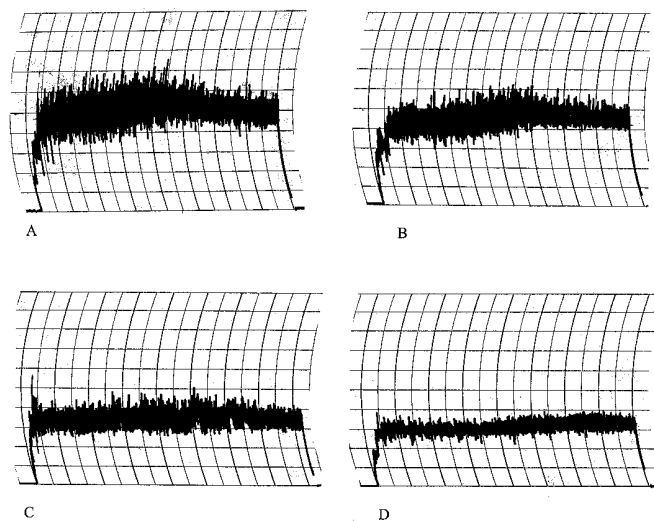


Fig. 1. Mixograms of sorghum-wheat dough. A, control (100% wheat); B–D, sorghum substitution rates of 10, 20, and 30%, respectively.

TABLE I
Effect of Sorghum Substitution on Dough Properties^a

Flour	Dough Development			Peak Height		
	Time (min)	± SD	Increase (%)	Height (cm)	± SD	Decrease (%)
100% wheat	4.2a	0.13	...	5.25d	0.29	...
10% sorghum	4.4a	0.08	4.8	4.83c	0.13	8.0
20% sorghum	5.2b	0.24	23.8	3.70b	0.25	29.5
30% sorghum	6.0c	0.10	42.9	3.23a	0.21	38.5

^a Values obtained from mixograms. Means followed by different letters within the same column are significantly different using Student-Newman-Keuls, $P < 0.01$.

Mixogram measurements (mixing time and peak height) were replicated five times. All other experiments were analyzed in triplicate. One-way analysis of variance and the Student-Newman-Keuls test were used to determine statistical differences among group means at $P < 0.05$.

RESULTS AND DISCUSSIONS

Effect of Sorghum Addition on Wheat Flour Dough

As expected, addition of sorghum negatively affected the properties of wheat flour dough (Fig. 1 and Table I). There was no significant difference ($P < 0.01$) in mixing time between 10% sorghum substitution (4.4 min) and the control 100% wheat dough (4.2 min); however, there was a significant decrease ($P < 0.01$) in peak height, from 5.3 cm for wheat to 4.8 cm for 10% sorghum substitution (8% decrease). As sorghum substitution levels increased to 20 and 30%, there were significant increases ($P < 0.01$) in dough development times and substantial decrease in peak heights, both of which are undesirable effects on dough quality for bread. At 20% substitution, dough formation time increased from 4.2 min to 5.2 min (23.8% increase) and peak height decreased from 5.3 cm to 3.7 cm (29.5% decrease). At 30% sorghum substitution, dough development time increased to 6 min (42.9% increase) and peak height decreased to 3.2 cm (38.5% decrease). These data support previous studies showing negative effects resulting from the addition of high proportions of sorghum flour in bakery products (Bhatia et al 1968; Kim and De Ruiter 1968; Pringle et al 1969; Dendy 1970; Subramanian et al 1983).

Effect of Zein Addition on Composite Dough

When mixed at a temperature above the T_g of zein, addition of zein at 5 and 10% concentrations significantly improved ($P < 0.01$) the sorghum-wheat composite flour dough properties (Table II and

Fig. 2). Dough development time decreased while peak height increased with increasing amounts of added zein. There was no significant difference in dough development time and mixogram peak height at 1% added zein. At 5% zein substitution, the mixing time was comparable to the wheat control, while at 10%, mixing time was further reduced (Table II). However, the dough formed with added zein was more susceptible to overmixing when compared with the control, as shown by the large drop in the descending part of the mixogram profiles (Fig. 2).

The improvement in composite dough properties with added zein could be attributed to two main factors. First, zein, free from protein bodies, was available for participation in fibril formation. Commercial zein is produced from corn gluten meal, a by-product of the wet-milling process, by extraction with aqueous alcohol (Freeman Industries, *personal communication*). Whereas corn gluten

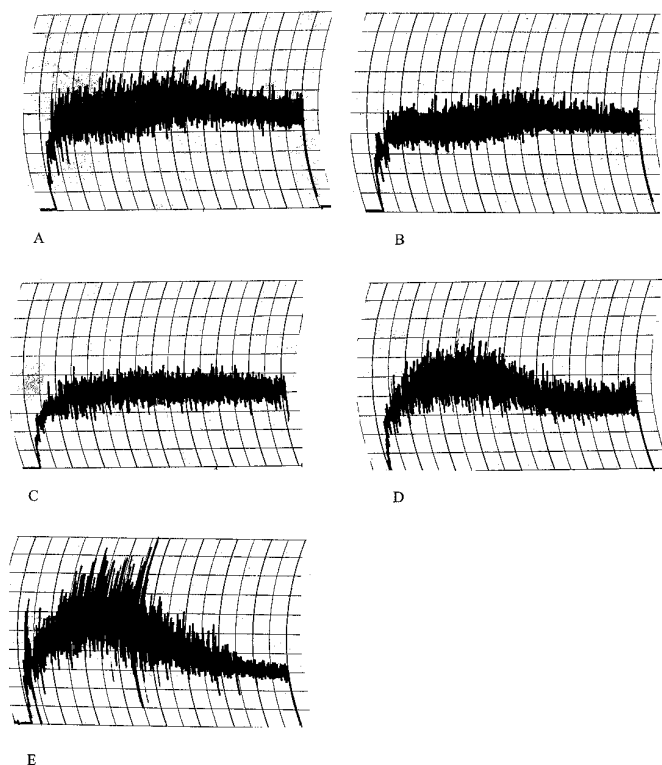


Fig. 2. Mixograms of 20% sorghum-wheat dough. A, control (100% wheat); B-E, added zein at levels of 0, 1, 5, and 10%, respectively.

TABLE II
Effects of Added Zein on Sorghum-Wheat Composite Flour^a

Flour	Dough Development		Peak Height	
	Time (min)	± SD	Height (cm)	± SD
100% wheat (no zein)	4.2b	0.13	5.20c	0.29
20% sorghum (no zein)	5.2c	0.25	3.70a	0.25
20% sorghum + 1% zein	5.1c	0.11	3.96a	0.09
20% sorghum + 5% zein	4.1b	0.14	4.40b	0.22
20% sorghum + 10% zein	3.1a	0.11	5.92d	0.11

^a Values obtained from mixograms. Means followed by different letters within the same column are significantly different using Student-Newman-Keuls, $P < 0.01$.

TABLE III
Peak Values of Fracture Properties

Sample	Peak Fracture Strain (-) ^a	Peak Fracture Stress (kPa)
100% wheat flour	1.29	14.58
20% sorghum	1.00	4.75
20% sorghum + 5% zein	1.05	5.76
20% sorghum + 10% zein	1.14	10.14

^a No units for strain.

TABLE IV
Statistical Variation of Baking Test Measurements^a

Sample	Loaf Parameter	Mean	± SD	Coefficient of Variation
Wheat flour	Volume (cm ³)	871.5	2.89	0.33
Wheat flour	Specific volume (cm ³ /g)	8.91	0.01	0.16
20% sorghum	Volume (cm ³)	727.5	1.73	0.24
20% sorghum	Specific volume (cm ³ /g)	7.45	0.03	0.36

^a Five loaves were measured for four separate days (20 observations).

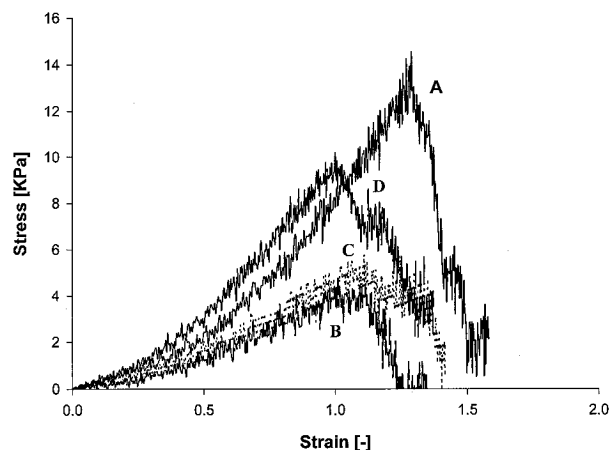


Fig. 3. Stress elongation curve for 20% sorghum-wheat dough. A, control (100% wheat); B-D, added zein at levels of 0, 5, and 10%, respectively.

TABLE V
Effect of Added Zein on Loaf Volume^a

Flour	Mixing Time (min)	Loaf Volume (cm ³)	± SD	Specific Volume (cm ³ /g)	± SD
100% wheat	4.40	883.3d	4.08	9.19c	0.06
20% sorghum	5.24	715.8a	3.76	7.37a	0.04
20% sorghum + 5% zein	3.10	739.2b	3.76	7.53a	0.26
20% sorghum + 5% zein +10% zein	2.56	809.2c	9.17	8.42b	0.08

^a Means followed by different letters within the same column are significantly different using Student-Newman-Keuls, $P < 0.01$.

meal contains zein encapsulated in protein bodies, commercial zein is protein-body-free (Batterman-Azcona et al 1999). Second, mixing was done above the T_g of zein, which was critical to its reactivity. T_g is an important factor in dough rheology because it explains the behavior of proteins during mixing. Above T_g , glassy polymeric materials become rubbery and flexible due to increased free volume and mobility and, as a result, the reactivity of the polymer is enhanced (Ferry 1980; Hoseney and Rogers 1990; Sperling 1986). Slade and coworkers (1989) hypothesized that gluten protein molecules gain sufficient mobility due to thermal and water plasticization above T_g to form the thermoset network by disulfide cross-linking which contributes to its rheological properties. Faubion and Hoseney (1989) also showed that as gluten takes up water it undergoes a glass transition at room temperature that renders it mobile to interact with other gluten polymers to form a dough during mixing. Zein differs from wheat gluten in that its T_g at high moisture content is above room temperature. Lawton (1992) showed that zein in a model system with starch forms viscoelastic fibrils only when mixed at $>25^\circ\text{C}$. Thus, when protein-body free-zein was mixed with the sorghum-wheat composite flour above its T_g , it formed networks that apparently strengthened the diluted gluten networks to improve dough properties.

Dough Extensibility

Dough extensibility is an important factor that contributes to thermal expansion of bread during baking to give good loaf volume (Faridi 1985). It is measured as a function of stress, which is the force per unit area required to extend the dough, and is calculated by dividing the force by the average cross-sectional area. Higher stresses indicate stronger dough that can extend more and thus have greater potential to hold the expanding air cells during fermentation.

The effect of added zein on peak stress and strain is shown in Table III. Stress values increased significantly ($P < 0.01$) with increasing amounts of added zein. Peak stress was 4.76 kPa with no zein, and 5.76 and 10.14 kPa at 5 and 10% added zein, respectively. At a constant stress, there was an increase in strain (elongation) with addition of zein (Fig. 3). Lawton (1992) showed that the dough formed by zein in a starch-based system was not as strong as wheat dough due to fewer intermolecular cross-links (covalent bonds) formed. This was demonstrated by addition of a cross-linking agent (formaldehyde), which resulted in greater and more stable resistance. The increase in stress observed suggests that the few cross-links formed by zein, together with the gluten networks, contribute to dough strength.

Loaf Volume

Loaf volume is an important quality of bread that is influenced by dough strength. Stronger doughs have greater potential to hold expanding air cells during fermentation, which expands the gluten network to give a porous structure and high loaf volume. To determine the reproducibility of the baking test measurements, five loaves were baked each day for four days.

This statistical design was used to calculate the coefficients of variation for the baking test. The results are shown in Table IV.

To determine whether the improved dough rheological properties translated into improved loaf volume, baking tests were done using sorghum-wheat composite flour (20:80) with added zein at sub-

stitutions of 5 and 10%. There was a significant ($P < 0.01$) increase in loaf volume with increasing amounts of added zein, which reflected the increasing trend in dough strength. Loaf volume of the composite flour bread increased from 715.8 cm³ without zein to 739.2 cm³ and 809.2 cm³ with 5 and 10% added zein, respectively (Table V). Addition of sorghum flour to wheat flour results in reduced loaf volume due to the dilution of the available gluten protein networks and unavailability of sorghum protein to participate in dough formation. Addition of zein to the sorghum-wheat composite flour resulted in higher loaf volume, which implies that the zein networks formed have the ability to entrap carbon dioxide released by yeast during fermentation.

CONCLUSIONS

Zein mixed at temperatures above its T_g improved the rheological and leavening properties of sorghum-wheat composite flour dough. Dough development time, mixogram peak height, extensibility, and loaf volume improved with increasing amounts of added zein $\leq 10\%$. These results show that the viscoelastic networks formed by zein in the composite flour dough system are capable of entrapping carbon dioxide to give higher loaf volume. However, it was not clear whether zein interacts with gluten proteins or acts independently in the dough to increase the loaf volume. Due to the projected similarities between zein and kafirin, this study suggests that kafirin, if made available, would likely contribute to dough formation properties in sorghum-wheat composite flour systems. Further work needs to be done to verify that native kafirin has the same properties as isolated commercial zein.

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LITERATURE CITED

- American Association of Cereal Chemists. 2000. Approved Methods of the AACCC, 10th ed. Method 10-09, Method 54-40A. The Association: St. Paul, MN.
- Batterman-Azcona, S. J., Lawton, J. W., and Hamaker, B. R. 1999. Microstructural changes in zein proteins during extrusion. *Scanning* 21:212-216.
- Bhatia, B. S., Chakrabarty, T. K., Mathur, V. K., Siddish, C. H., and Raghavan, P. K. U. 1968. Use of maize and milo flour in the preparation of bread. *Indian Food Packer* 22:33-35.
- Danzer, L. A., Ades, H., and Rees, E. D. 1975. Helical contents of zein and water insoluble protein in non-aqueous solvents. *Biochem. Biophys. Acta* 386:26-31.
- De Barros, E. G., Takasaki, K., Kirleis, A. W., and Larkins, B. A. 1991. Nucleotide sequence of a c-DNA clone encoding γ -kafirin protein from *Sorghum bicolor*. *Plant Physiol.* 97:1606-1607.
- Dendy, D. A. V. 1970. Composite flours. Pages 92-93 in: *Composite Flour Program*, Vol. I. Food and Agricultural Organization (FAO): Rome.
- Esen, A. 1987. A proposed nomenclature for the alcohol-soluble proteins (zeins) of maize (*Zea mays* L.). *J. Cereal Sci.* 5:117-128.
- FAO 1997. *Food and Agricultural Organization Yearbook*, Production, Vol. 51. FAO: Rome.
- Faridi, H. 1985. *Rheology: Theory and application to wheat flour dough in: Rheology of Wheat Products*. Am. Assoc. Cereal Chem.: St. Paul MN.
- Faubion, J. M., and Hoseney, R. C. 1989. The viscoelastic properties of

- wheat flour doughs. Pages 29-66 in: *Dough Rheology and Baked Product Texture*. H. Faridi and J. M. Faubion, eds. Van Nostrand Reinhold: New York.
- Ferry, J. D. 1980. Concentrated solutions, plasticizer polymers, and gels. Pages 486-544 in: *Viscoelastic Properties of Polymers*. John Wiley and Sons: New York.
- Hoseney, R. C. 1998. Proteins of cereals. Pages 65-79 in: *Principles of Cereal Science and Technology*, 2nd ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Hoseney, R. C., and Rogers, D. E. 1990. The formation and properties of wheat flour doughs. *Crit. Rev. Food Sci. Nutr.* 29:73.
- Hoseney, R. C., Zeleznak, K., and Lai, C., S. 1986. Wheat gluten as a glassy polymer. *Cereal Chem.* 63:285-286.
- Kim J. C., and De Ruiter, D. 1968. Bread from non-wheat flours. *Food Technol.* 22:867-878.
- Larkins, B. A. 1989. Changes in the zein composition of protein bodies during maize endosperm development. *Plant Cell* 1:1011-1023.
- Larkins, B. A., Perdesen, K., Mark, M. D., and Wilson, D. R. 1984. The zein proteins of maize endosperm. *Trends Biochem. Sci.* 9:306-308.
- Lásztity, R. 1996. Wheat proteins, maize proteins, and sorghum proteins in: *The Chemistry of Cereal Proteins*, 2nd ed. CRC Press: Boca Raton, FL.
- Lawton, J. W. 1992. Viscoelasticity of zein-starch doughs. *Cereal Chem.* 69:351-355.
- Levine, H., and Slade, L. 1989. Interpreting the behavior of low-moisture foods. Pages 71-134 in: *Water and Food Quality*. T. M. Hardman ed. Elsevier Applied Science: London.
- Matsumoto, H. 1986. The rheology of yeasted dough and the tension of gas cell membrane. Pages 55-62 in: *Fundamentals of Dough Rheology*. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Morgenstern, M. P., Newberry, M. P., and Holst, S. E. 1996. Extensional properties of dough sheets. *Cereal Chem.* 73:478-482.
- Mattern, P. J. 1991. Wheat. Pages 1-54 in: *Handbook of Cereal Science and Technology*. K. J. Lorenz and K. Kulp, eds. Marcel and Dekker: New York.
- Pringle, W., Williams, A. A., and Hulse, J. H. 1969. Mechanical developed doughs from composite flours. *Cereal Sci. Today* 14:114-129.
- Schofield, J. D., Bottomley, R. C., Timms, M. F., and Booth, M. R. 1983. The effect of heat on wheat gluten and the involvement of sulfhydryl-disulfide interchange reactions. *J. Cereal Sci.* 1:241-253.
- Shewry, P. R. 1999. The synthesis, processing, and deposition of gluten proteins in the developing wheat grain. *Cereal Foods World* 44:587-589.
- Shewry, P. R., Napier, J. A., and Tatham, A. S. 1995. Seed storage proteins: Structures and biosynthesis. *Plant Cell* 7:945-946.
- Shull, J. M., Watterson, J. J., and Kirleis, A. W. 1991. Proposed nomenclature for the alcohol soluble proteins (kafirins) of *Sorghum bicolor* (L. Moench) based on molecular weight, solubility, and structure. *J. Agric. Food Chem.* 39:83-86.
- Shull, J. M., Watterson, J. J., and Kirleis, A. W. 1992. Purification and immunocytochemical localization of kafirin in *Sorghum bicolor* (L. Moench) endosperm. *Protoplasm* 177:64-74.
- Slade, L., Levine, H., and Finley, J. W. 1989. Protein-water interactions: Water as a plasticizer of gluten and other protein polymers. Pages 9-123 in: *Protein Quality and the Effects of Processing*. R. D. Phillips and J. W. Finley, eds. Marcel Dekker: New York.
- Sperling, L. H. 1986. *Introduction to Physical Polymer Science*. John Wiley and Sons: New York.
- Subramanian, V., Jambunathan, R., and Sambasiva Rao, N. 1983. Textural properties of sorghum dough. *Cereal Chem.* 48:1650-1653, 1673.
- Wu, Y. V., Cluskey, J. E., and Jones, R. W. 1971. Sorghum prolamins: Their optical rotatory dispersion, circular dichroism, and infrared spectra. *J. Agric. Food Chem.* 19:1139-1143.

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