Water Activity and Moisture Content of Dough and Bread[1]

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ABSTRACT

Water activity (a_w) and moisture contents were determined in mixed dough, fermented dough, bread crumb, and crust of loaves baked with various amounts of water (optimum, +3%, or −3%) and/or for various times (21, 24, or 27 min). In addition, effects of changes in formulation, including replacement of original wheat flour by ball-milled wheat flour, on a_w and water content were determined. A decrease in added water considerably lowered loaf volume; an increase in baking time slightly decreased loaf volume. Proofed samples, generally, were higher than mixed doughs in water contents and a_w. Doughs mixed with optimum water were lower in a_w than doughs mixed with excess water. There were large differences in water contents of crumb in bread baked with various baking absorption levels but not in samples baked for various times with optimum baking absorption. There was little change in a_w between the 1- and 24-hr-old bread crumb. Moisture and a_w were higher in proofed dough than in 1-hr-old bread crumb. As time of baking increased, moisture and a_w in the crust of 1-hr-old bread decreased. In the crumb, a_w and moisture content were the lowest in bread baked by the full formula with the original flour. Exclusion of sugar or salt increased most moisture contents and water activity. The moisture and a_w, generally, were lowest in the crust of bread baked by the full formula with the original flour and highest in bread baked with flour in which the starch was damaged.

Water constitutes about 40% of standard bread dough and over 35% of baked bread. About 46% of the water in dough is associated with the starch, 31% with the protein, and 23% with the pentosan gums. The water absorption of a wheat flour dough is governed, in practice, by the protein content and quality and by the extent to which the starch is damaged mechanically (the greater the damage, the greater the absorption) (Bushuk and Hlynka 1964).

Water absorption and dough development are influenced by various ingredients used in breadmaking. As the salt (sodium chloride) concentration increases, water absorption and dough development time increase, presumably from the lowered water-holding capacity of the proteins. Fats decrease the hydration capacity of dough.

Water plays an important role in the major changes that take place during the baking of dough: starch gelatinization, protein denaturation, yeast and enzyme inactivation, and flavor and color formation. Water content and its distribution also govern the shelf life of bread, which is influenced by incidence of microbial damage, softness of the crumb, crispness of the crust, crumb hardening, crumbliness, and many other changes associated with overall staling and lowered consumer acceptance (Pomeranz 1985, 1987). It has been shown, however, that it is water activity (a_w) rather than water content that governs microbial spoilage of foods (Beuchat 1981). Approximate lower levels of a_w for microbial growth are 0.91 for bacteria, 0.88 for yeast, 0.80 for molds, 0.75 for halophilic bacteria, 0.65 for xerophilic fungi, and 0.60 for osmophilic yeast.

Several instruments with different operating principles may be used to measure a_w (Stroup et al 1987). They include change in electrical conductivity of immobilized salt solutions, change in electrical capacitance of polymer thin films, longitudinal change in dimensions of water-sorbing fiber, partial water vapor pressure by manometric system, relative weight of moisture sorbed by anhydrous hydrophilic solid, and dew point by a chilled mirror technique. The latter was used in this study.

Pomeranz (1959) reported that prolonged baking has little, if any, influence on the moisture content of bread crumb, which is a measure of the water content of the dough from which the bread was baked rather than a criterion of adequate baking and proper crust formation. This study was designed to determine the effects of the amount of water added to the dough and length of baking and dough composition on the water content and water activity of dough, bread crumb, and bread crust.

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MATERIALS AND METHODS

The commercial bread flour used in this study contained 12.2% protein (N × 5.7) and 0.45% ash on a 14% moisture basis; its optimum baking time was 3 min 25 sec, and optimum baking absorption was 71.2%. Optimum mixing time and optimum baking absorption were estimated on the basis of mixograph determinations and by an experienced experimental baker. Unless stated otherwise, the breadmaking formula included 100 g of flour (14% mb), water, 1.5 g of sodium chloride, 1.8 g of dry bakers' yeast, 4 g of nonfat dry milk, 6 g of sucrose, 0.3 g of malt extract (50–60 dextrinizing units/g; 20°C), 3 g of shortening, and 40 ppm of ascorbic acid. A straight-dough baking procedure with a 90-min fermentation at 30°C was used. Panning and punching were done mechanically. Proof time was 36 min at 30°C. Optimum baking time was 24 min at 218°C (Finney 1964, 1984).

The breadmaking conditions were varied to include baking absorptions of 71.2 (optimum), 68.2, and 74.2%, with optimum bake mixing times of 3 min 25 sec, 3 min 5 sec, and 3 min 45 sec, respectively. Bake times were also varied in some experiments, using 21 or 27 min. In addition, one series of baking experiments was conducted in which the following dough components were taken out (one at a time): sodium chloride, sugar, shortening, and milk solids. In one experiment, the original flour was replaced by the same flour after it was subjected to ball milling to damage the starch. Loaf weight was determined immediately after baking and was followed by loaf volume determination by the dwarf rapeseed displacement method.

Moisture content was determined at least in duplicate by oven drying 1.4-g samples of doughs for 5 hr and 1.4-g samples of bread for 4 hr at 130°C. Water activity was determined by the CX-1 water activity system (Decagon Devices, Inc., Pullman, WA). Samples are placed in disposable plastic sample dishes that are inserted in the CX-1. A small fan circulates the air above the sample, speeding vapor equilibrium. An infrared sensor measures the sample surface temperature, eliminating need for temperature equilibration. A small internal mirror is cooled until water condenses at the dew point temperature. The mirror and sample temperatures are used to compute water activity of the sample. A microprocessor controls the heating and cooling of the mirror and allows precise a_w readings to be made. Because vapor equilibration time is eliminated, most a_w readings can be taken in less than 5 min. Both the a_w and sample temperature are displayed. The instrument reads a_w of saturated salt solutions within 0.003 a_w values, after adjustment for temperature. For saturated solutions, the following a_w values were obtained at 20°C (±2°C): LiCl 0.117, CH_3COOK 0.233, K_2CO_3 0.432, KCl 0.851, and KNO_3 0.949; and for distilled purified water 0.999. For determination of a_w of doughs, the instrument was placed in a cabinet maintained at 33°C.

Individual loaves were stored for a_w and moisture determination in plastic bags at room temperature (about 22°C). Weight losses within 24 hr were up to 3 g/loaf; almost entirely during the first hour of cooling before placing in plastic bags. For a_w and water content determinations, the top crust was removed and three bread slices, 6–7 mm thick, were cut from the bread. From each slice, one cylinder of 30-mm diameter was taken out with a cutter from the center of the slice. The cylinders were placed into plastic cups of the instrument, and a_w was determined within 1–3 min in bread crumb or bread crust and within 2–3 min in dough. The cylinders were used afterwards for moisture determination. For each set of determinations, separate loaves were used.

Mixograms were determined by the 10-g method as described by Finney and Shogren (1972). Amylograms were determined on 60 g of flour (14% mb) in 450 ml water. Ash, protein, and experimental baking tests were made by AACC methods 8-01, 46-12, and 10-10B, respectively.

To obtain starch-damaged flour, the sample was ball milled for 24 hr. The extent of damage was assessed by drop in amylograph peak viscosity and by scanning electron microscopy (SEM) examination.

For SEM examination (using a Hitachi model S-570, Japan), the samples were placed on double-stick Scotch tape mounted on 9-mm diameter aluminum specimen holders. The samples were coated with a 15-nm layer of gold in the Technics Hummer V sputter coater. Next, they were viewed at 20 kV and photographed at a speed of 100 sec/picture at a 17-mm working distance.

Baking tests were made at least twice. Analytical determinations on each sample were made at least twice. All results were averaged. The results were subjected to analysis of variance and evaluated by Duncan's multiple range test. Statistically significant differences at the 5% level are presented.

RESULTS AND DISCUSSION

Mixograms of doughs with 66.5 (optimum), 63.5, and 69.5% water are shown in Figure 1. The mixing times were 3 min 35 sec, 3 min 15 sec, and 4 min 10 sec, respectively. Mixograms of doughs with ball-milled flour at an absorption of the original bread flour (66.5%) and at an optimum absorption (75.0%) are compared in Figure 2. For experimental baking of the ball-milled flour, a baking absorption of 71.2% was used. An additional 4.7% water was added to the mixograph absorption to compensate for dry yeast and nonfat dry milk solids. Actual baking absorptions and bake mixing times are given in the Materials and Methods section of this study. Amylograms of the original and ball-milled flours are shown in Figure 3. Ball milling for 24 hr lowered peak viscosity

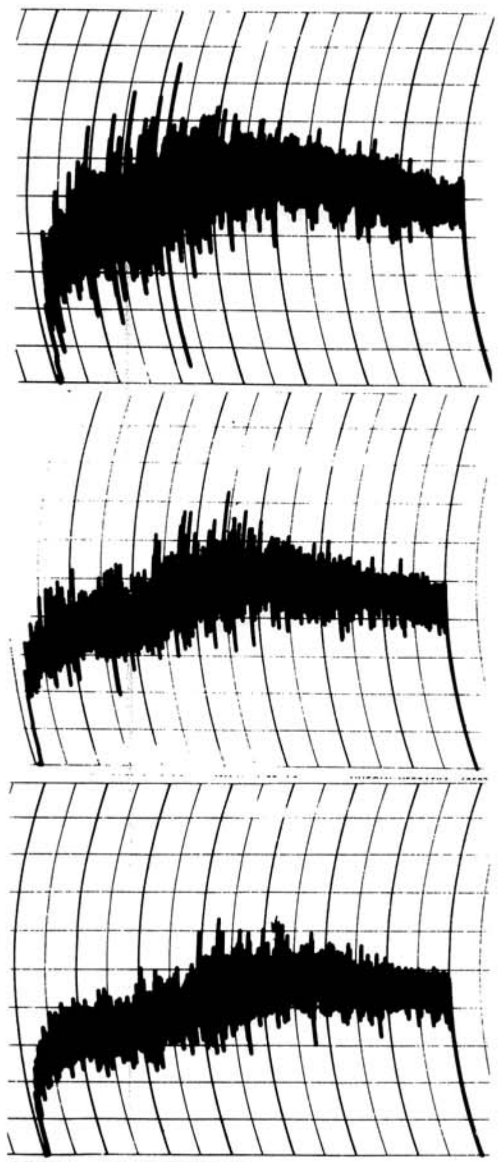

Fig. 1. Mixograms of doughs (from top to bottom) with 63.5, 66.5, (optimum), and 69.5% water (10 g of flour, 14% mb).

TABLE I
Weight and Volume of Bread Loaves from 100-g Flour Doughs that Varied in Baking Absorption and Baking Time

Baking Absorption and Baking Time	Weight[a] (g)	Volume[b] (cm³)
Baking absorption (%)		
Optimum (71.2)	150.9	888
−3% (68.2)	148.7	808
+3% (74.2)	151.6	890
Baking time (min)		
24 (optimum)	150.4	888
21	151.9	895
27	146.7	870

[a] Weighed 1 hr after baking.
[b] Immediately after baking.

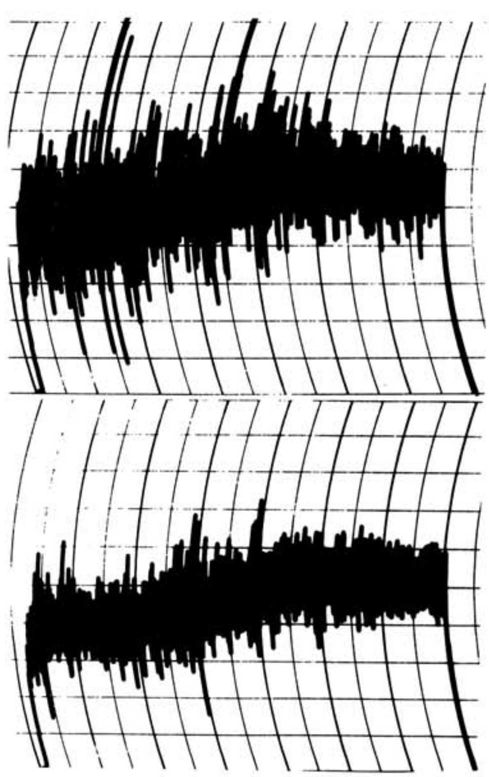

Fig. 2. Mixograms of doughs with ball-milled flour at 66.5% absorption (top) and 75.0% absorption (bottom).

from 565 to 405 BU. The inserts in Figure 3 show SEM micrographs of the original and ball-milled flours.

Weights of doughs mixed with optimum, −3%, and +3%, water were 183.1, 179.8, and 186.3 g, respectively; bread weights and loaf volumes are given in Table I.

Table II summarizes the results of water activity and moisture determination of doughs mixed various times and containing various levels of added water. The water contents of the doughs reflect the various amounts of added water. Proofed samples, generally, were higher than mixed doughs in water content, presumably as a result of fermentation and picking up some moisture in the fermentation cabinet. A comparison between fixed versus optimum bake mixing time revealed no difference in moisture content in corresponding pairs of samples. Water activity in proofed doughs, generally, was higher than in mixed doughs. Doughs mixed with optimum water were lower in a_w than doughs mixed with excess water. There were no significant differences between the proofed doughs. There were no significant differences in a_w among the proofed doughs or between doughs mixed with optimum or below optimum water, even though they differed in

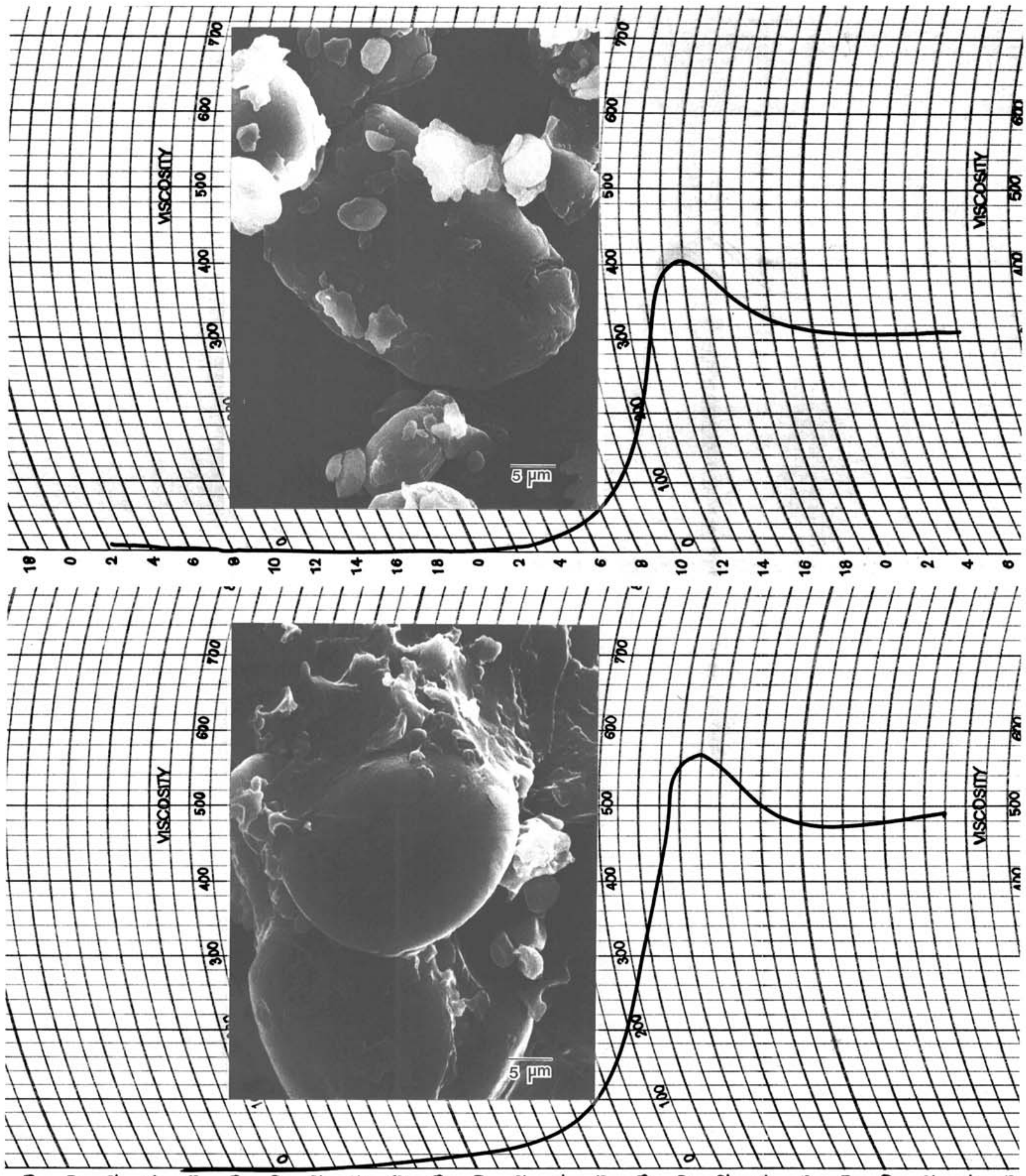

Fig. 3. Amylograms of suspensions (60 g of flour, 14% mb, in 450 ml of water) of the ball-milled (top) and original (bottom) flours. Inserts show scanning electron micrographs of the flours at high magnification (bar = 5 μm).

TABLE II
Water Activity (a_w) and Moisture Content of Doughs that Varied in Baking Absorption and Mixing Time[a]

Baking Absorption (%)	Mixing Time	a_w Mixed Dough	a_w Proofed Dough	Moisture (%) Mixed Dough	Moisture (%) Proofed Dough
Fixed mixing time					
Optimum (71.2)	3 min 25 sec	0.956 b	0.980 a	46.43 b	47.51 b
−3% (68.2)	3 min 25 sec	0.958 b	0.973 a	45.15 c	46.39 c
+3% (74.2)	3 min 25 sec	0.988 a	0.984 a	48.43 a	48.88 a
Standard deviation	···	0.003–0.006	0.004	0.06–0.20	0.134–0.191
Optimum mixing times					
Optimum (71.2)	3 min 25 sec	0.956 b	0.980 a	46.43 b	47.51 b
−3% (68.2)	3 min 5 sec	0.949 b	0.977 a	45.08 c	46.51 c
+3% (74.2)	3 min 45 sec	0.972 a	0.981 a	48.62 a	48.46 a
Standard deviation	···	0.002–0.004	0.001–0.005	0.06–0.21	0.014–0.255

[a]Values followed by different letters indicate statistically significant differences at the 5% level.

TABLE III
Water Activity (a_w) and Moisture Content of Crumb in Bread from Doughs that Varied in Baking Absorption and Baking Time[a]

Baking Absorption and Baking Time	a_w 1 hr	a_w 24 hr	Moisture (%) 1 hr	Moisture (%) 24 hr
Baking absorption (%)				
Optimum (71.2)	0.957 b	0.960 a	44.03 b	43.92 b
−3% (68.2)	0.956 b	0.962 a	43.26 c	43.03 c
+3% (74.2)	0.969 a	0.966 a	45.27 a	45.30 a
Standard deviation	0.001–0.004	0.001–0.003	0.127–0.346	0.057–0.396
Baking time (min)				
24 (optimum)	0.957 b	0.960 a	44.03 a	44.92 a
21	0.969 a	0.966 a	44.28 a	44.40 a
27	0.965 ab	0.966 a	44.08 a	44.05 a
Standard deviation	0.001–0.004	0.002–0.003	0.127–0.240	0.049–0.269

[a]Values followed by different letters indicate statistically significant differences at the 5% level.

TABLE IV
Water Activity (a_w) and Moisture Content of Crust in Bread from Doughs that Varied in Baking Absorption and Baking Time[a]

Baking Absorption and Baking Time	a_w 1 hr	a_w 24 hr	Moisture (%) 1 hr	Moisture (%) 24 hr
Baking absorption (%)				
Optimum (71.2)	0.886 a	0.890 a	18.03 a	25.01 a
−3% (68.2)	0.878 b	0.886 a	17.78 a	24.24 a
+3% (74.2)	0.888 a	0.895 a	18.47 a	24.84 a
Standard deviation	0.001–0.004	0.000–0.005	0.240–0.629	0.877–1.138
Baking time (min)				
24 (optimum)	0.886 b	0.890 b	18.03 b	25.01 a
21	0.912 a	0.909 a	21.60 a	26.00 a
27	0.849 c	0.872 c	15.50 c	22.81 a
Standard deviation	0.002–0.009	0.000–0.009	0.240–0.933	1.053–1.379

[a]Values followed by different letters indicate statistically significant differences at the 5% level.

moisture contents. On the other hand, in doughs mixed to optimum, a_w was lower than in doughs mixed for a fixed time (especially with excess water) even though the corresponding pairs differed little in moisture content.

Table III summarizes the results of water activity and moisture determination in bread crumb. There were large differences in water contents of the bread crumb for the three samples that were baked for various times with optimum baking absorption. There was little change from the 1-hr to the 24-hr-old bread crumb in a_w. Differences in water contents in 1-hr-old (but not in 24 hr old) bread crumb were reflected in an elevated a_w in crumb of the bread baked from the high-moisture dough (+3%). It is of interest that whereas moisture in mixed optimum dough (Table II) was 2.4% higher than in the crumb of optimum bread (Table III), there was no difference in a_w between the dough and the 1-hr-old bread crumb. Thus, the water in the freshly mixed dough seems to be more strongly bound than in the 1-hr-old bread crumb. The decrease of 3.5% moisture from proofed dough to 1-hr-old crumb points to some losses and/or redistribution within the baked bread.

Table IV summarizes the results of water activity and moisture determination in bread crust. Note the rapid increase in moisture in the bread crust from 1 to 24 hr. There were no consistent differences in crust moisture or a_w among breads from doughs with various baking absorptions. In the 1-hr-old bread, as length of baking increased moisture in the crust decreased; after 24 hr there was no significant difference. With regard to water activity, the main differences were in crust of bread baked various times; the longer the baking time, the lower the a_w. The differences still were significant after 24 hr.

Weight and volume of loaves from 100 g of flour baked with various formulations are given in Table V. Excluding any of the ingredients decreased loaf volume (decreases of 22 cm^3 are significant at the 5% level). Excluding sugar or shortening resulted in a larger loaf volume decrease than excluding salt or milk solids. The effects of excluding sugar were smaller than expected as the dough formula included 0.3 g of malt extract/100 g flour. By far the largest decrease in loaf volume resulted from replacing the original flour with ball-milled flour. When individual ingredients were excluded, bread weight decreased somewhat; when the original flour was replaced with ball-milled flour, bread weight was higher, apparently, because water was not completely baked out. The decreases in loaf volume were accompanied by large decreases in crumb grain and texture. Bread baked without salt had a light crust, and the crumb grain was uniform but heavy walled. In the absence of added sugar, the crust was thick, dense, and pale. The crust of bread baked without shortening was rubbery and the crumb grain and texture were impaired. Exclusion of milk solids impaired overall quality of crumb and crust and imparted "dryness" to the crumb. Replacement of the original flour by starch-damaged flour resulted in a very thin-crusted bread and a heavy, wet, and gummy crumb.

TABLE V
Weight and Volume of Bread Loaves from 100-g Flour Doughs Baked with Different Formulations

Formulation	Weight[a] (g)	Volume[b] (cm^3)
Full: original flour	151.3	889
No salt	147.3	731
No sugar	144.8	691
No shortening	149.9	658
No milk solids	147.1	757
Full: damaged starch	158.4	412

[a]Weighed 1 hr after baking.
[b]Immediately after baking.

TABLE VI
Water Activity (a_w) and Moisture Content in Crumb and Crust of Bread Baked with Different Formulations[a]

	Bread Crumb				Bread Crust			
	a_w		Moisture (%)		a_w		Moisture (%)	
Formulation	1 hr	24 hr	1 hr	24 hr	1 hr	24 hr	1 hr	24 hr
Full: original flour	0.959 d	0.961 d	44.20 e	44.29 e	0.831 c	0.901 c	15.51 c	24.93 d
No salt	0.979 a	0.982 a	45.29 b	45.54 b	0.923 a	0.924 ab	18.20 b	23.99 e
No sugar	0.981 a	0.982 a	45.96 a	46.13 a	0.921 a	0.933 a	17.27 b	25.11 d
No shortening	0.963 c	0.969 b	45.23 b	45.40 b	0.875 b	0.921 b	18.00 b	27.06 b
No milk solids	0.964 bc	0.966 c	44.97 c	45.05 c	0.892 b	0.915 b	18.48 b	25.99 c
Full: damaged starch	0.967 b	0.966 c	44.57 d	44.45 d	0.937 a	0.931 a	24.85 a	29.09 a
Standard deviation	0.001–0.003	0.000–0.001	0.010–0.085	0.001–0.092	0.001–0.011	0.001–0.006	0.000–1.456	0.042–0.735

[a]Values followed by different letters indicate statistically significant differences at the 5% level.

Water activity (a_w) and moisture content in crumb and crust of bread baked with different formulations is summarized in Table VI. In the crumb, both a_w and moisture contents were the lowest in bread baked by the full formula with the original flour. Exclusion of sugar or salt increased most moisture contents and water activity; exclusion of milk solids or use of flour with damaged starch had intermediate effects. Very minor changes in a_w and moisture contents took place in the crumb during storage for 24 hr.

The pattern was less consistent with regard to the bread crust (Table VI). The moisture was lowest (with one exception, 24 hr) in bread baked by the full formula with the original flour and highest in bread baked with flour in which the starch was damaged. Water activity was consistent with those results for moisture content. For bread baked by the other formulations, after 1 hr there were no significant differences in moisture, and a_w was higher in bread baked without salt or sugar than without shortening or milk solids. After 24 hr, the pattern was the same for a_w but not for moisture.

Those results must be interpreted, among others, in the context of the differences of loaf weights (Table V) as affected by exclusion of specific baking ingredients, and losses during fermentation and baking. We report here only on the net combined effects in the bread. An extensive study would be required to determine the effects of the individual factors and their interactions on the moisture content and a_w in bread crumb and crust.

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