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ORIGINAL ARTICLE

Staling kinetics of whole wheat pan bread

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Abstract Understanding the staling process of whole grain breads, especially in relation to the increase in firmness, can contribute to optimize the shelf life of these products. The aim of this work was to develop an equation (staling rate) capable of estimating the increase in firmness of whole wheat pan breads. The staling rate (K) demonstrated that the greater the bran content, the greater the increase in bread firmness (from 0.011 day^{-1} for 0% replacement, to 0.174 day^{-1} and 0.091 day^{-1} for 30% replacement of fine and coarse bran, respectively). Thereby, we established an equation to estimate the firmness of whole wheat pan bread on a given day, considering the concentration of bran in the formulation, thus helping baking industries to predict bread behavior during storage and optimize the use of additives.

Keywords Amylopectin retrogradation · Firmness · Shelf life · Wheat bran · Bread staling

Introduction

Bread staling is a complex phenomenon that has been widely studied. The main technological changes that occur during staling include loss of freshness, loss of crust crispness, increase in starch crystallinity, increase in crumb firmness, and loss of organoleptic properties (Curti et al. 2017; Nouri et al. 2017). Although the simplest way to evaluate bread staling is the measurement of firmness, analytical tools such as thermal analysis, spectroscopy, and microscopy have been used to understand and control this phenomenon (Gray and Bemiller 2003; Goesaert et al. 2005, 2009; Salinas and Puppo 2018).

For a long time, it was believed that amylopectin retrogradation was the only phenomenon responsible for increasing bread firmness during storage. However, some authors have reported that bread staling is not only due to amylopectin retrogradation (Ding et al. 2019). According to Martin et al. (1991), the increase in crumb firmness can be due to interactions between the remaining starch granules and gluten. Duran et al. (2001) have demonstrated through a model system that the addition of gluten did not alter the staling rate. Similar results were observed by Kim and D'Appolonia (1977), who reported that the protein can reduce firmness not by interacting, but only by a starch dilution effect.

The difference in water vapor pressure between the crust and the crumb of bread causes the migration of moisture from the crumb to the crust, which is another phenomenon responsible for the increase of the firmness of the crumb (Piazza and Masi 1995). Moisture redistribution between bread components (water release from gluten, and absorption by the retrograded starch) was suggested by Willhoft (1973) and Kay and Willhoft (1972) as a phenomenon that occurs during bread staling.

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However, other characteristics of the grain and/or the presence or addition of other components to the food matrix, such as fibers, can modify the firmness of bread. Purhagen et al. (2012) reported that fiber addition led to changes in staling rates, especially in relation to starch retrogradation, as fiber has a greater water retention capacity, when compared to starch. Also according to these authors, the quality of bakery products containing fibers depends on the source, particle size, concentration, and solubility of this component.

Some types of reactions in foods during storage occur due to changes in physical properties, including starch gelatinization, protein gelation, and textural changes during cooking and storage. These reactions exhibit hardening/softening kinetics (Toledo 2007). Bread firmness during shelf life is an example of kinetics limited by the process. Understanding the staling process of whole wheat breads, especially in relation to the increase in firmness, can help the baking industry to optimize product shelf life, as well as to use of additives and/or processing aids that can retard negative effects during storage. Thus, the aim of this work was to study the staling kinetics of whole wheat pan breads and develop an equation (staling rate) capable of estimating the increase in firmness of such breads during a storage period of 13 days.

Materials and methods

Material

Refined wheat flour (*Triticum aestivum* L.) (11.82% moisture, 11.07% protein, 1.20% fat, 0.57% ash, and 3.43% fiber), coarse wheat bran (11.88 moisture, 16.71% protein, 3.72% fat, 5.94% ash, and 54.17% fiber), and fine wheat bran (11.53 moisture, 17.77% protein, 3.75% fat, 5.54% ash, and 44.56% fiber) were kindly donated by Anaconda Mill (São Paulo, BRA). Bran containing 40% or more particles greater than 0.500 mm (32 mesh) was considered coarse, while bran with 60% or more of particles smaller than or equal to 0.500 mm (32 mesh) was considered fine.

Methods

Preparation of wheat bran premixes

Refined wheat flour (used as control) was partially replaced by fine or coarse wheat bran, in proportions of 5, 10, 20, 30%, generating 8 premixes (whole wheat flour), prepared in a V-blender (Tecnal, Piracicaba, BRA), in portions of 4 kg, by mixing during 20 min each.

Manufacture of pan breads

All breads were processed in duplicate following the formulation of Schmiele et al. (2012), with modifications, using (flour basis): wheat flour or premix (100%); sucrose (4%); sodium chloride (1.8%); instant dry yeast (2%); whole milk powder (4%); vegetable fat (4%); calcium propionate (0.6%), and fungal alpha-amylase (0.0025%). The amount of water was established from the water absorption determined by the farinograph analysis of the various premixes, which was 58.2, 61.0, 62.9, 66.9, and 68.9% for 0, 5, 10, 20 and 30% fine wheat bran and, 58.2, 60.5, 63.0, 67.8, and 68.3% for 0, 5, 10, 20 and 30% coarse wheat bran, respectively, according to study by Sehn and Steel (2017).

The ingredients were mixed in an automatic mixer, model HAE 15 (Hyppolito, Ferraz de Vasconcelos, BRA), at low speed (∼ 90 rpm) for 5 min, and at high speed (∼ 210 rpm) until complete development of the gluten network appeared to have been attained. Dough was divided into portions of 450 ± 1 g, which were molded in a molding machine, model MPS 350 (GPaniz, Caxias do Sul, BRA), placed in open pans (20 cm × 10 cm × 5 cm), and taken to a fermentation chamber, model CCKU 5868 20-1 (Super Freezer, Poços de Caldas, BRA), at 30 °C and 80% RH, until optimum fermentation time (maximum point of volume development without losing resistance to touch) had elapsed.

Breads were baked in an electric oven, model IP 4/80 (Haas, Curitiba, BRA), adjusted to temperatures of 170 °C (top) and 185 °C (hearth), for 30 min. After baking, breads were removed from the pans and cooled for 3 h at room temperature. Then, an alcoholic solution of sorbic acid was sprayed on the breads, to minimize fungal growth. Breads were packed in polyethylene bags and stored under controlled temperature (25 °C) until analysis.

Evaluation of pan breads during storage

Pan breads were evaluated on days 1, 5, 9, and 13 after processing, according to the determinations described below. The crumb was considered as the entire inner portion, leaving a margin of 1 cm from the edges.

Crumb moisture content Crumb moisture content was determined by AACC International (2010), approved method 44-15.02.

Amylopectin retrogradation Only the samples with replacement of 0, 10, and 30% wheat bran (fine or coarse) were subjected to amylopectin retrogradation measurements, using a differential scanning calorimeter (Slade and Levine 1987), model Pyris 1 DSC (Perkin Elmer, Boston, USA), previously calibrated with indium. Crumb samples were previously dried in a freeze-drier, model LS 3000 (Terroni, São Carlos, BRA), with vacuum of 50 mm Hg, and temperature of − 45 °C, ground with mortar and pestle, and passed through a sieve with opening of 0.500 mm. Then, 2.5–3.0 mg of lyophilized crumb were weighed in stainless steel pans (100 µL; 30 bar), mixed with deionized water at a 1:3 ratio, and hermetically sealed. The sealed pans were kept overnight at room temperature for water equilibration. The DSC sample pans were subjected to a heating rate of 10 °C/min from 30 to 95 °C. The melting enthalpy change values for retrograded amylopectin (ΔH) were obtained in triplicate.

Crumb firmness Crumb firmness was determined by AACC International (2010), approved method 74-10.02, in a TA-XT2 texture analyzer (SMS—Stable Micro Systems, Surrey, GBR), 25 kg load, using a cylindrical P/36 aluminum probe with long stem, and the following parameters: pre-test speed = 1.7 mm/s; test speed = 1.7 mm/s; post-test speed = 10.0 mm/s; force = 10 g; distance 40%; mode: compression force. Measurements were performed on ten replicates, by the compression of two 12 mm central slices arranged horizontally on the platform.

Statistical analysis

The results for pan bread crumb moisture content, amylopectin retrogradation and firmness were evaluated by ANOVA and Tukey's test to verify significant differences ($P < 0.05$) between means, using the Statistica 10.0 software (STATSOFT, Tulsa, USA).

Kinetics of bread firmness during storage

In this study, the rate of increase in crumb firmness was defined as the staling rate. The kinetics of crumb firmness may be defined according to Eq. 1, as described by Toledo (2007).

$$\ln\left(1 - \frac{C_{(t)}}{C^{*}}\right) = k \times t \tag{1}$$

where C (t) = value measured during the transient phase of the process as a function of time; C* = value of the attribute (Curti et al. 2017) during the course of the reaction; K = staling rate; t = storage time.

Equation 1 was adapted for firmness of breads produced with or without bran. The concentration C (t) was replaced by F (t), of firmness. The value of the attribute when it remains constant during the course of the reaction (C*), was replaced by 31 N. This was used as a most probable asymptotic value of the firmness of whole wheat bread under the experimental conditions of preparation and storage (defined after pre-tests).

Based on adapted Eq. 1 and the experimental results of the analysis of firmness of the breads, the firmness index was calculated, and these results were plotted (plot not shown) based on the bran content. Then, the reaction speed or staling rate (K), which corresponds to the slope of the curve, was calculated by simple linear regression, and the constant (K_0) was introduced in the equation as a staling constant, to improve or refine the fit of the equation (Eq. 2).

$$\ln\left(1 - \frac{F_{(t)}}{31N}\right) = k \times t \times K_0 \tag{2}$$

where F (t)=firmness measured at a given time (N in days); 31 N = most probable asymptotic value that a whole wheat bread can reach under the experimental conditions of preparation and storage; K = staling rate (day^{-1}); t = storage time (day); K_0 = staling constant (day^{-1}).

Model of staling rate of breads as a function of bran level in the formulation

The mathematical model to describe the staling rate of pan breads as a function of bran level in the formulations was based on a quadratic equation, as shown in Eq. 3.

$$y = ax^2 + bx + c \tag{3}$$

where y = dependent variable; x = independent variable; a, b, and c = function parameters.

Results and discussion

Changes in whole wheat pan bread during storage

The crumb of breads containing added wheat bran showed higher moisture contents content than the control on the 4 days evaluated during storage (Table 1), due to the higher water absorption by wheat bran, caused by the presence of pentosans (Arif et al. 2018), cellulose, and hemicellulose (Ishida and Steel 2014). Thus, the higher the bran level in the mixture, the greater the amount of water added (according to water absorption in farinograph analysis) to the formulation and, consequently, the higher the moisture content of the final product.

During staling, a decrease in moisture of the crumb of breads was observed for all formulations, probably due in part to migration of moisture from the moister crumb to the drier crust (Curti et al. 2014). A greater water decrease during storage was observed in the control sample without replacement of refined wheat flour by wheat bran (8.2% loss), when compared to the samples with 30% replacement (loss of 5.4 and 5.8% for fine and coarse bran, respectively), from day 1 to day 13. It was observed that

Table 1 Crumb moisture (%) of pan bread, with replacement of fine or coarse wheat, bran, during storage

Bran content (%)	Water absorption (%)*	Day 1	Day 5	Day 9	Day 13
Fine bran					
0	58.2	39.35 ± 0.04^{Ae}	38.51 ± 0.20^{Be}	36.97 ± 1.04^{Ce}	36.01 ± 0.95^{De}
5	61.0	41.08 ± 0.16^{Ad}	39.48 ± 0.77^{Bd}	38.33 ± 0.82^{Cd}	37.93 ± 0.21^{Dd}
10	62.9	41.69 ± 0.21^{Ac}	40.70 ± 0.35^{Bc}	38.92 ± 0.86^{Dc}	39.21 ± 0.36^{Cc}
20	66.9	42.95 ± 0.37^{Ab}	42.03 ± 0.21^{Bb}	40.60 ± 0.09^{Cb}	40.04 ± 0.12^{Db}
30	68.9	43.96 ± 0.15^{Aa}	42.85 ± 0.17^{Ba}	41.92 ± 0.18^{Ca}	41.57 ± 0.39^{Da}
Coarse bran					
0	58.2	39.35 ± 0.04^{Ae}	38.51 ± 0.20^{Be}	36.97 ± 1.04^{Ce}	36.01 ± 0.95^{De}
5	60.5	41.70 ± 0.39^{Ad}	39.88 ± 0.40^{Bd}	38.94 ± 0.15^{Cd}	38.61 ± 0.66^{Dd}
10	63.0	42.27 ± 0.06^{Ac}	40.14 ± 0.59^{Bc}	39.43 ± 0.19^{Cc}	39.00 ± 0.56^{Dc}
20	67.8	43.70 ± 0.80^{Ab}	42.14 ± 0.32^{Bb}	41.64 ± 0.14^{Cb}	41.06 ± 0.39^{Db}
30	68.3	43.96 ± 0.03^{Aa}	42.51 ± 0.07^{Ba}	42.09 ± 0.24^{Ca}	41.41 ± 0.65^{Da}

Mean ± standard deviation; *water absorption determined by the farinograph analysis; different uppercase letters in the same line indicate significant differences between days for the same sample ($P \leq 0.05$); different lowercase letters in the same column indicate significant differences between samples on the same day ($P \leq 0.05$)

the water reduction phenomenon occurred at a slower rate in whole wheat breads when compared to white breads. Possibly, a redistribution of water molecules among and/or within the components occurs in whole grain breads, in a more pronounced way, especially among starch, fiber and gluten (Slade and Levine 1987). However, further studies on the presumed water release and absorption by these components in a whole wheat flour system should be carried out.

Table 2 shows the results for enthalpy (ΔH) obtained from the measured thermal properties as a function of bran content and particle size. The melting enthalpy value is proportional to the extent of retrogradation, since this value represented the energy needed to melt the amylopectin crystallized or reorganized during storage (Slade and Levine 1987).

Table 2 Amylopectin retrogradation, determined from the measured enthalpy change as a function of storage time, for the crumb of whole wheat pan bread with replacement by fine or coarse wheat bran

Days	ΔH (J/g)		
	0%	10%	30%
Fine bran			
1	0.21 ± 0.01^{bD}	0.21 ± 0.01^{bD}	0.31 ± 0.01^{aD}
5	0.79 ± 0.03^{bC}	0.90 ± 0.01^{aC}	0.47 ± 0.01^{cC}
9	1.29 ± 0.04^{aB}	1.20 ± 0.06^{aB}	0.66 ± 0.01^{bB}
13	1.48 ± 0.03^{bA}	1.90 ± 0.07^{aA}	0.74 ± 0.02^{cA}
Coarse bran			
1	0.21 ± 0.01^{aD}	$0.13 \pm <0.01^{bD}$	$0.05 \pm <0.01^{cD}$
5	0.79 ± 0.03^{aC}	0.64 ± 0.01^{bC}	$0.38 \pm <0.01^{cC}$
9	1.29 ± 0.04^{aB}	0.75 ± 0.01^{bB}	$0.47 \pm <0.01^{cB}$
13	1.48 ± 0.03^{aA}	1.28 ± 0.01^{bA}	0.28 ± 0.02^{cA}

Mean ± standard deviation; 0%, 10% and 30% = wheat bran replacement; different lowercase letters in the same line indicate significant differences between samples ($P \leq 0.05$); different uppercase letters in the same column indicate significant differences between days for the same sample ($P \leq 0.05$). ΔH: melting enthalpy of retrograded amylopectin

A significant increase of amylopectin retrogradation was observed, for all breads, after 13 days of analysis. Retrogradation leads to the formation of amylopectin crystalline aggregates, or the reassociation of amylose and amylopectin molecules, with water migration resulting as a consequence of amylopectin crystal hydrate formation (Slade and Levine 1987). Amylose retrogradation occurs in the first hours after baking (being important for bread structure), while amylopectin retrogradation takes place over storage time and results in the increase of the firmness of the pan whole pan bread (Ding et al. 2019).

Amylopectin retrogradation can be considered a bread staling phenomenon (Goesaert et al. 2009; Purhagen et al. 2012). On the last day of analysis (day 13), the crumb of bread produced with 10% added wheat bran showed a large enthalpy change (or amylopectin retrogradation) (1.90 J/g), which was higher for the fine bran, when compared to the sample without bran (1.48 J/g). However, replacements of 30% resulted in lower enthalpy change values (0.74 J/g). At higher substitutions, bran fibers may have inhibited amylopectin retrogradation, possibly by preventing any association between amylose and amylopectin molecules, and also possibly due to their high water-retention capacity. Furthermore, the smaller enthalpy change values at higher replacement levels may have been due to a starch dilution effect in bread, leading to a reduced detection of amylopectin retrogradation. The coarse wheat bran appeared to inhibit retrogradation, possibly due to its greater physical impediment to the association of amylopectin chains (Santos et al. 2008).

Estimation of pan bread firmness

Firmness (N) values for breads during storage as a function of fine or coarse fiber content, are shown in Tables 3 and 4, along with the calculated firmness index (CFI), determined according to Eq. 2. These results were plotted on a graph (not shown), and the staling rate (K day^{-1}) and staling constant (K_0 day^{-1}) were calculated by simple linear regression, as a function of bran levels ranging from 0 to 30%.

An increase in crumb firmness was observed throughout the days evaluated ($P < 0.05$), with greater substitutions of fine and coarse wheat bran (20 and 30%) resulting in higher firmness values on all days. This behavior can be attributed to a thickening effect of the walls surrounding the air bubbles in the presence of bran fibers, resulting in bread with a more compact structure and a smaller specific volume in these substitutions (Gómez et al. 2003). The same behavior was observed for the results for staling rate (K) where greater levels of bran presented greater values for this parameter (from 0.011 day − 1 for 0% replacement, to 0.026 and 0.174 day − 1 for 20 and 30% replacement of fine bran, respectively; and 0,020 and 0.091 day − 1 for 20 and 30% replacement of coarse bran, respectively).

Based on these results, a function that relates the increase in firmness, or model for staling rate (K) and staling constant (K_0), of pan bread as a function of added bran content was constructed for fine and coarse bran, separately.

Equation 4 shows the mathematical model of staling rate (K) as a function of fine wheat bran content. The significance probability of 0.005 confirms that the linear regression model was statistically significant ($P < 0.05$), and the proportion of variance explained (R^2) was 0.995. Analysis of variance did not provide pure error or lack of fit.

$$ln(K) = 0.00449 \times FB^2 - 0.04517 \times FB - 4.46266 \qquad (4)$$

where K = staling rate (day^{-1}); FB = fine bran content (%).

Equation 5 shows the mathematical model for the staling constant as a function of fine wheat bran content. For the staling constant (K_0), the significance probability of 0.003 confirms that the linear regression model was statistically significant ($P < 0.05$), and the proportion of variance explained (R^2) was 0.997. Analysis of variance did not provide pure error and lack of fit.

$$K_0 = -0.000551 \times \text{FB}^2 + 0.003592 \times \text{FB} - 0.068035 \qquad (5)$$

Table 3 Kinetics of increase in firmness of breads as a function of fine bran content

Bran content (%)	Time (days)	Firmness (N)	CFI	K (day^{-1})	K_o (day^{-1})	R^2 (%)
0	1	1.98 ± 0.18^{dD}	− 0.066	0.011	− 0.060	97.14
0	5	3.62 ± 0.25^{cD}	− 0.124			
0	9	4.18 ± 0.13^{bD}	− 0.145			
0	13	5.64 ± 0.36^{aC}	− 0.201			
5	1	2.37 ± 0.20^{cCD}	− 0.080	0.012	− 0.075	98.58
5	5	4.13 ± 0.44^{bCD}	− 0.143			
5	9	5.18 ± 0.52^{aC}	− 0.183			
5	13	6.20 ± 0.84^{aC}	− 0.223			
10	1	2.71 ± 0.51^{cC}	− 0.091	0.011	− 0.092	95.38
10	5	4.77 ± 0.28^{bC}	− 0.167			
10	9	5.52 ± 0.46^{aC}	− 0.196			
10	13	6.47 ± 0.72^{aC}	− 0.234			
20	1	5.40 ± 0.68^{cB}	− 0.191	0.026	− 0.205	90.80
20	5	9.81 ± 0.60^{bB}	− 0.381			
20	9	11.55 ± 1.52^{abB}	− 0.466			
20	13	12.38 ± 1.13^{aB}	− 0.510			
30	1	14.29 ± 1.27^{bA}	− 0.618	0.174	− 0.461	95.91
30	5	23.96 ± 2.85^{aA}	− 1.482			
30	9	25.71 ± 2.64^{aA}	− 1.769			
30	13	29.19 ± 3.89^{aA}	− 2.839			

Mean ± standard deviation; different lowercase letters in the same column for the same bran content, and different uppercase letters in the same column for the same day of analysis and different bran contents, indicate significant differences between samples *($P \leq 0.05$)*; CFI = calculated firmness index, determined according to Eq. 2; K = staling rate calculated by simple linear regression; K_0 = staling constant; R^2 = regression coefficient of each adjustment

Table 4 Kinetics of increase in firmness of breads as a function of coarse bran content

Bran content (%)	Time (days)	Firmness (N)	CFI	K (day^{-1})	K_o (day^{-1})	R^2 (%)
0	1	1.98 ± 0.18^{dD}	− 0.066	0.011	− 0.060	97.14
0	5	3.62 ± 0.25^{cC}	− 0.124			
0	9	4.18 ± 0.13^{bD}	− 0.145			
0	13	5.64 ± 0.36^{aC}	− 0.201			
5	1	1.82 ± 0.16^{cD}	− 0.060	0.012	− 0.061	95.44
5	5	3.97 ± 0.54^{bC}	− 0.137			
5	9	4.71 ± 0.89^{abCD}	− 0.165			
5	13	5.77 ± 0.70^{aC}	− 0.206			
10	1	2.31 ± 0.13^{bC}	− 0.077	0.009	− 0.083	87.63
10	5	4.11 ± 0.59^{aC}	− 0.142			
10	9	5.03 ± 0.43^{aC}	− 0.177			
10	13	5.19 ± 0.73^{aC}	− 0.183			
20	1	3.99 ± 0.44^{cB}	− 0.138	0.020	− 0.139	95.57
20	5	7.26 ± 1.21^{bB}	− 0.267			
20	9	8.38 ± 0.93^{abB}	− 0.315			
20	13	9.87 ± 1.14^{aB}	− 0.383			
30	1	11.79 ± 1.40^{bA}	− 0.468	0.091	− 0.434	98.33
30	5	19.30 ± 1.96^{bA}	− 0.975			
30	9	22.16 ± 2.33^{abA}	− 1.254			
30	13	24.68 ± 2.42^{aA}	− 1.590			

Mean ± standard deviation; different lowercase letters in the same column for the same bran content, and different uppercase letters in the same column for the same day of analysis and different bran contents, indicate significant differences between samples ($P \leq 0.05$); CFI = calculated firmness index, determined according to Eq. 2; K = staling rate calculated by simple linear regression, K_0 = staling constant; R^2 = regression coefficient of each adjustment

where K_0 = staling constant (day^{-1}); FB = fine bran content (%).

Equation 6 shows the mathematical model of staling rate (K) as a function of coarse wheat bran content. The significance probability of 0.015 confirms that the linear regression model was statistically significant ($P < 0.05$). The proportion of variance explained (R^2) was 0.985. Analysis of variance did not provide pure error and lack of fit.

$$ln(K) = 0.00420 \times CB^2 - 0.05722 \times CB - 4.46397 \quad (6)$$

where K = staling rate (day^{-1}); CB = coarse bran content (%).

Equation 7 shows the mathematical model of the staling constant (K_0) as a function of coarse wheat bran content. The significance probability of 0.023 confirms that the linear regression model was statistically significant ($P < 0.05$). The proportion of variance explained (R^2) was 0.977. Analysis of variance did not provide pure error and lack of fit.

$$K_0 = -0.000672 \times \mathrm{CB}^2 + 0.008603 \times \mathrm{CB} - 0.075555 \quad (7)$$

where K_0 = staling constant (day^{-1}); CB = coarse bran content (%).

For the estimate of whole wheat bread firmness, the staling rate (K) and staling constant (K_0) for fine bran (Eqs. 4 and 5) and coarse bran (Eqs. 6 and 7), respectively, can be calculated by replacing the bran content in the equations. Then, by use of Eq. 2, it is possible to estimate bread firmness on a particular day of storage. This calculation, using Microsoft Excel spreadsheets or applications developed for this purpose, can help the bakery industry to validate the quality (best before date) of whole wheat breads (according to firmness), and also to determine the appropriate amounts of additives and processing aids needed to maintain product quality during storage.

Conclusion

During 13 days of storage, the evident phenomena responsible for the decrease in quality of whole wheat pan breads were water migration from crumb to crust, increased amylopectin retrogradation (observed by increased ΔH), and increased firmness (higher staling rate), this decrease in quality being more accentuated when such breads were produced with added fine wheat bran (especially with regard to the latter two phenomena). It was possible to establish an equation that estimates the firmness of these breads on a given day, thus providing the bakery industry with a means to predict the staling of these products during shelf life, to optimize the addition of wheat bran (coarse or fine), or additives and processing aids in adequate amounts, in order to maintain product quality during shelf life, thereby bringing benefits to both industry and consumers.

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