LWT - Food Science and Technology 73 (2016) 123–130

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Effects of chemical leavening system and processing conditions on the opacity and other quality characteristics of whole-wheat flour tortillas

Ting Liu [a, b], Gary G. Hou [b, *], Sharon L. Book [c], Len Marquart [a]

[a] Department of Food Science and Nutrition, University of Minnesota, Saint Paul, MN 55108, USA
[b] Wheat Marketing Center, Inc., 1200 N.W. Naito Parkway, Suite 230, Portland, OR 97209, USA
[c] ICL Food Specialties, St. Louis, MO 63119, USA

ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form
22 March 2016
Accepted 4 June 2016
Available online 6 June 2016

Keywords:
Whole-wheat flour tortilla
Chemical leavening
Opacity
Texture

ABSTRACT

Chemical leavening is a neutralization reaction that can affect not only the opacity but also other physical and chemical properties of tortillas. Whole-wheat flour (WWF) tortillas is often associated with lack of sufficient opacity, generally considered as quality defect in tortillas. The objectives of this research were to evaluate the effects of types and amounts of leavenings (acids and base), hot press and dough temperature on the quality attributes of WWF tortillas. Three leavening acids, three levels of sodium bicarbonate (SBC) (1%, 1.5%, and 2%), hot-press temperatures of 160 °C, 177 °C, and 193 °C, and two dough temperatures (25 °C and 35 °C) were used. Sodium aluminum phosphate (SALP) produced more opaque tortillas than sodium acid pyrophosphate-28 (SAPP-28), followed by sodium aluminum sulfate (SAS). Increased amount of SBC and lower dough temperature improved opacity. Higher hot-press temperature produced lighter weight, thinner, and bigger diameter tortillas. Higher amount of SBC produced smaller, thicker, and brighter color tortillas. WWF tortillas made with SAS had the largest breaking force, while tortillas with SALP had the smallest breaking force as determined by TA-XTPlus Texture Analyzer. After 45 days of storage at room temperature, all tortillas showed decreased breaking force and extensibility.

1. Introduction

Considerable epidemiologic evidence suggests that whole grains are associated with reduced risk for certain chronic diseases (Marquart, Jacobs, McIntosh, Poutanen, & Reicks, 2007). The 2010 Dietary Guidelines for Americans (USDA & USDHHS, 2010), via MyPlate, is designed to encourage people to eat at least three whole grain servings per day as part of a healthy meal plan. In step with these recommendations, the food industry has been incorporating whole-wheat flour (WWF) into a variety of grain-based foods to meet consumer taste preferences and provide more whole grains in the U.S. diet (Marquart et al., 2006).

Incorporating WWF into tortillas is one approach to deliver whole grains into the American diet. Tortilla is a thin Mexican flatbread made from wheat flour or corn, with the versatility to be used in many dishes. The Tortilla Industry Association (TIA) reported tortillas were more popular than other types of ethnic breads in the U.S., as approximately 85 billion tortillas were consumed in 2000 (TIA 2015). Given current trends toward healthier food and the popularity of tortillas, manufacturers are striving to provide customers with healthier, more varied, and flavored tortillas. Although the use of WWF can significantly improve the nutritional profile of tortillas, WWF tortillas have encountered more quality issues compared to refined wheat flour tortillas.

Translucency, a lack of opacity, is generally considered a quality defect in tortillas because consumers perceive translucency as a characteristic of tortillas that are undercooked or high in fat (Alviola & Awika, 2010). A ‘translucent’ tortilla is dark or yellowish in color, while ‘opaque’ tortilla is bright white (Dann, 2014). The absence of small air bubbles in the baked tortilla is likely related to translucency since the tortilla appears opaque when light reflects on the surface of small air bubbles (Cepeda, Waniska, Rooney, & Bejosano, 2000). Thus, the formation of air bubbles in the dough and retention of air bubbles in the tortilla are critical factors for producing uniformly opaque tortillas (Casso, 2003; Cepeda et al., 2000). Leavening agents help to form fluffy, thick, and opaque tortilla products.

Unlike many bread products that use yeast as leavening agents,

* Corresponding author.
E-mail address: ghou@wmcinc.org (G.G. Hou).

http://dx.doi.org/10.1016/j.lwt.2016.06.009
0023-6438/

flour tortillas are produced using a chemical leavening system. Chemical leavening is a neutralization process where bicarbonate is neutralized by an acid or acids yielding carbon dioxide in the presence of moisture and heat (Heidolph, 1996). A chemical leavening system contains two components: a base (bicarbonate) and an acid or acids (Adams & Waniska, 2002). The most commonly used leavening bases in baked foods are sodium bicarbonate (SBC), potassium bicarbonate (KBC), and ammonium bicarbonate (ABC). The different types, amounts, and grades of bicarbonates have been studied relative to tortilla properties (Bejosano & Waniska, 2004; Casso, 2003). Leavening acids vary in the neutralization value (NV) and the rate of reaction (ROR). Based on ROR, leavening acids can be divided into three categories. Nucleating agents release acids during mixing such as calcium phosphates (monocalcium phosphate [MCP]) and organic acids (fumaric, citric, lactic, and tartaric). Time-released agents release acids after a period of time (sodium acid pyrophosphate [SAPP] and calcium acid pyrophosphate [CAPP]). The third category, a heat-activated agent, reacts when triggered by heat. Sodium aluminum sulfate (SAS) and Sodium aluminum phosphate (SALP) are included in this category (Cepeda et al., 2000; Casso, 2003). Nucleating agents are seldom used as a leavening by themselves. Instead, the combinations of fast and slow leavening acids are used to produce a double reaction (Heidolph, 1996; La Baw, 1982).

In the tortilla dough system, previous research demonstrated that chemical leavening showed effects on end-product opacity. Time-released and heat-activated leavening acids yield more opaque tortillas compared with nucleating agents (Adams & Waniska, 2002; Cepeda et al., 2000). Slower acids partially dissolve during mixing and nucleate the dough with a sufficient yield of gas bubbles to produce opaque tortillas. During dough resting, dividing, and rounding, some insoluble leavening compounds need to be retained to allow for later chemical neutralization and reactions during the baking process (Adams, 2001). In addition, the tortilla opacity is generally associated with the amount of leavenings used (Adams, 2001; Adams & Waniska, 2002; Bejosane & Waniska, 2004). However, Cepeda et al. (2000) observed small or insignificant improvements in opacity when using more SALP, SAS, and SAPP, while adverse effects were observed when using more MCP. Furthermore, the effects of leavening systems on other tortilla attributes (moisture, pH, diameter, texture, etc.) have been investigated (Adams & Waniska, 2002; Adams, 2001; Bejosano & Waniska, 2004; Book, Brill, & Heidolph, 2002; Cepeda et al., 2000).

With higher dough temperature, less mixing time is required to form dough (Hlynka, 1962). However, more acid solubilizes and reacts faster with the base in tortilla dough; thus, the leavening reaction increasingly occurs in warmer dough, which reduces the potential for bubble enlargement during tortilla processing and yields more translucent tortillas (Cepeda et al., 2000). Cepeda et al. (2000) studied the effect of dough temperature (34 °C and 38 °C) and determined that at 38 °C, more leavening acid and base were needed to compensate for the loss of carbon dioxide incurred during mixing and resting to yield tortillas with comparable opacity.

Other than dough temperature, hot-press conditions of pressure, time, and temperature directly affect the tortillas. Typical hot-press operating conditions range from 300 to 2000 psi pressure, 0.7–3.5 s time, and 149–232 °C temperature (TIA 2014). Adams and Waniska (2005) examined the effects of dwell time and pressure on tortilla quality. However, the hot-press temperature has not yet appeared in the literature to determine its influence on flour tortilla characteristics.

Although considerable research has focused on the chemical leavening system for wheat flour tortillas, there is little research on WWF tortillas. Barros, Alviola, and Rooney (2010) compared the quality of refined and WWF tortillas and found that the WWF tortillas had lower opacity scores than their corresponding refined flour tortillas. The high fiber content in WWF weakens the gluten network and results in dough less resistant to hot pressing (Barros et al., 2010). Therefore, WWF tortillas have weaker dough structure and integrity to retain the air bubbles created during baking. Thus, it is necessary to modify the chemical leavening system and processing conditions in WWF tortilla production to improve opacity and overall quality characteristics.

The objectives of this study were to examine the effects of varying types of leavening acids, amounts of leavening base, hot-press temperature, and dough temperature on the opacity and other quality properties of WWF tortillas.

2. Materials and methods

2.1. Materials

A 100% hard white WWF with 9.6% moisture content, 13.3% protein (14% mb) and 1.4% ash (14% mb) was kindly provided by Bay State Milling Company (Minneapolis, MN). The leavening acids, SALP, SAS, and SAPP-28 were provided by ICL Food Specialties (St. Louis, MO). Encapsulated fumaric acid was kindly provided by Clabber Girl Inc. (Terre Haute, IN). SBC (powder ACS) was purchased from ChemProducts (Portland, OR). Sodium stearoyl lactylate (SSL) was obtained from Corbion (Kansas City, KS). Salt, Crisco vegetable shortening and sugar were purchased from a local supermarket (Portland, OR). Potassium sorbate and calcium propionate were obtained from Muhlenchemie GmbH & Co KG (Ahrensburg, Germany).

2.2. Preparation of WWF tortilla

The WWF tortilla formula is listed in Table 1. The ingredients were weighed and added to a Horbart 5-Quart Mixer (Model A-120, Hobart MFG. Co, Troy, OH) with water jacket and constant temperature circulator (Model 1165, PolyScience, Div. of Preston Industries, Inc. Niles, IL) and mixed for 4 min at the 1st speed and 2–8 min at the 2nd speed until the dough was fully developed. The dough temperature was measured using a thermometer. After resting for 15 min at room temperature, 1400 g dough was flatted on the Dutchess Divider/Rounder tray (model JN-3, Dutchess Baker's Machinery Co. Inc. Superior, WI) with uniform thickness. The dough was divided and rounded into pieces of dough balls (40 g each) after resting for 5 min. The dough balls were then placed in a covered box and proofed for 20 min. Finally, each dough ball was hot-pressed by using an automatic Tortilla Press (Model Wedge Press, Bakery Equipment & Service Co. San Antonio, Texas) and baked on a griddle (model TW2025, DoughPro, Perris, CA) for 30 s

Table 1
Whole-wheat flour tortilla formulation.

Ingredients	Dough	
	%	g
Whole-Wheat Flour	100	1000
Water	58	580
Salt	1.5	15
Sugar	0.5	5
Shortening	7	70
Sodium bicarbonate	1/1.5/2	10/15/20
Leavening acids	Varied per trial	
Encapsulated fumaric acid	0.5 5	
Sodium stearoyl lactylate	0.5	5
Potassium sorbate	0.4	4
Calcium propionate	0.5	5

on each side. The fresh tortillas were cooled and packed into Ziploc bags and stored at room temperature.

2.3. Evaluation of WWF tortilla

Tortillas were analyzed one day after baking and after 45 days of room temperature storage. Tortilla weight and diameter were determined as the average of ten randomly selected tortillas. Thickness was measured with a plastic dial caliper as the average of ten randomly selected tortillas. The moisture content of tortillas was measured using 3 g of tortilla pieces (cut by scissors) via an infrared moisture analyzer (model: HS 153, Mettler-Toledo International Inc.). The pH of the final product was determined by homogenizing 10 g tortilla with 90 ml distilled water in a blender and measuring the pH using a glass electrode (S20 SevenEasy™ pH meter, Mettler-Toledo International Inc.) (Book et al., 2002). A continuous scale of 100% being completely opaque (white) and 0% being completely translucent (not white) was used for opacity analysis.

The color values of the WWF tortillas were determined by a Minolta Colorimeter (Model CR-410, Konica Minolta Sensing, Inc. Japan). Lightness (L*), redness (a*), and yellowness (b*) were recorded. In addition, the breaking force and extensibility of the tortillas were measured with the TA-XTPlus Texture Analyzer (Texture Technologies Corp., Scarsdale, NY). Force (N) and distance (mm) were determined using a 7/16-in. (1.11 cm) diameter cylindrical probe with rounded end (TA-108a) with pre-test speed of 1.0 mm/s, test speed of 1.0 mm/s and post-test speed of 10.0 mm/s.

2.4. Experimental design

Three types of leavening acids, including SALP, SAS, and SAPP-28 were initially evaluated for their effects. The second variable was the amount of SBC. Three levels of SBC (1%, 1.5%, and 2% of flour weight) were used, and the amount of each leavening acid was determined based on the level of SBC and its acid NV. The NVs of SALP, SAS and SAPP-28 were 100, 104 and 72, respectively. Encapsulated fumaric acid was added to lower dough pH level (Cepeda et al., 2000). The third variable was the dough temperature (25 °C and 35 °C) and the last variable was the hot-press temperature (160 °C, 177 °C, and 193 °C). The study was a four factor-Taguchi orthogonal “L” array design, in duplicate, in random order. This design contained 18 runs, with each run duplicated; thus, 36 runs in total. All measurements were performed at least in triplicate.

2.5. Statistics analysis

Statistical analyses were carried out with the software SPSS 22 for Mac using one-way analyses of variance (ANOVA). General linear models (GLMs) were created with terms for between-subjects effects of type of leavening acid, amount of SBC, hot-press temperature, dough temperature, and 2-way interactions between the type of leavening acid, amount of SBC, and hot-press temperature. ANOVA were run separately for data on day 1 and day 45 (Table 2). Due to differences in sample size and factor level, the interaction between dough temperature and the other three factors are not shown. Coefficient of determination (R^2), which indicates how well data fit the GLMs, is presented in Table 2. With R^2 closer to 1, the model was a better fit for the data. In addition, Table 2 shows the P value for each factor in the model for each response. $P < 0.05$ suggested that this factor had a significant effect on the response.

3. Results and discussion

3.1. Effect of type of leavening acid

On day 1, the type of leavening acids was significant ($p < 0.05$) for all parameters except for extensibility (Table 2). Tortillas made with SALP had lower moisture content (30.17%) than SAS (31.00%) and SAPP-28 (31.95%) (Table 3). These findings were different from the results obtained by Adams (2001), which showed little effect of leavening acid on moisture content but were similar to Book et al. (2002). A possible explanation as to why SALP yielded the lowest moisture content tortilla may be the timing of chemical leavening reactions. As a heat-activated leavening acid, most SALP reacted with SBC during baking. Water, as one of the neutralization reaction products, evaporates under high baking temperature. Therefore, more SALP and SBC reactions were attributed to more water evaporation. Due to more water loss, the leavening system with SALP produced the lightest-weight tortillas compared to SAS and SAPP-28. However, SALP resulted in the largest-diameter tortillas, followed by SAPP-28 and SAS (Table 3). These results were in agreement with the findings of Book et al. (2002). SAPP-28 produced the thickest tortillas among the three acids. SAPP is a time-released acid, while both SAS and SALP are heat-activated acids. More gas produced by SALP and SAS during baking was quickly released after cooling and yielded thinner tortillas.

Encapsulated fumaric acid was added to lower pH, and it was released gradually over time. On day 1, tortillas made with SAPP-28 had a higher pH (6.57), followed by SALP (6.27), and SAS (5.34) (Table 3). Previous studies conducted by Book et al. (2002) and Cepeda et al. (2000) showed the same trend. SAS produced darker tortillas compared to SALP and SAPP-28, while SALP yielded greener and bluer tortillas (Table 3). Similar to the trend in brightness, SALP produced more opaque tortillas, followed by SAPP-28 and SAS (Fig. 1). As a heat-activated agent, SALP would react with SBC when triggered by heat. Thus, more carbon dioxide was produced during baking, which would make the tortilla puffier and appear more opaque. SAS is also a heat-activated agent; however, 35–40% of carbon dioxide formed during mixing and resting stages were not retained as effectively as the gas released by SAPP (Book et al., 2002), which resulted in more translucent tortillas. Unlike SALP and SAS, SAPP-28 is a time-released acid, and it reacts after a period of time. These findings were different from the results obtained by Cepeda et al. (2000), who found that SAPP-28 produced more translucent tortillas than SAS and SALP. The differences may be attributed to the large excess of acid used in their study and different flour dough systems in both studies (WWF tortilla in this study vs. white flour tortilla in their study).

The rupture force (N) and distance (mm) of tortillas were measured by the TA-XTPlus Texture Analyzer at day 1. The maximum force required to completely puncture the tortillas indicates the firmness of tortillas, and the distance until rupture indicates the extensibility of the tortillas. Larger force and distance values indicate a stronger and more stretchable product (Texture Technologies, 2009). In contrast, a tortilla exhibiting a smaller rupture force tends to break more easily when being filled with meat and vegetables and other ingredients. Tortillas made with SAS (1053.3 g) required the greatest force to break compared to SAPP-28 (887.9 g) and SALP (832.4 g) (Fig. 2). This was because SAS produced much denser tortillas than other acid types, as reported by Book et al. (2002).

3.2. Effect of SBC amount

On day 1, the amount of SBC was significant ($p < 0.05$) for weight, diameter, thickness, pH, color, and opacity but not for

Table 2
ANOVA results.

Parameter	R^2	P-Values[a]						
		Acid[b]	SBC[c]	Press temp.	Dough temp.	Acid- SBC	Acid-press temp.	SBC-press temp.
Day 1								
Weight	0.96	0	0.006	0	0.025	0.019	0.183	0.994
Diameter	0.971	0	0	0	0.266	0.32	0.933	0.261
Thickness	0.975	0.003	0	0	0.355	0.206	0.216	0
Moisture	0.8	0.001	0.5	0	0.501	0.225	0.325	0.84
pH	0.992	0	0	0.021	0.028	0	0.015	0.363
Color (L*)	0.979	0	0	0.527	0.032	0.172	0.348	0.507
Color (a*)	0.955	0.001	0	0.003	0.013	0.099	0.756	0.193
Color (b*)	0.973	0	0.003	0.001	0	0	0.013	0.059
Opacity (Top)	0.953	0	0	0.006	0.009	0.061	0.09	0.086
Opacity (Bottom)	0.941	0	0	0.031	0.01	0.003	0.797	0.338
Breaking Force	0.82	0	0.672	0.353	0.912	0.358	0.645	0.409
Extensibility	0.615	0.224	0.141	0.053	0.257	0.603	0.789	0.164
Day 45								
Weight	0.918	0	0.035	0	0.01	0.038	0.374	0.949
Diameter	0.957	0	0	0	0.143	0.128	0.385	0.336
Thickness	0.952	0.004	0	0	0.075	0.082	0.634	0.005
Moisture	0.937	0	0.058	0	0.006	0.08	0.788	0.011
pH	0.998	0	0	0.06	0.733	0	0.332	0.626
Color (L*)	0.971	0	0	0.137	0.005	0.011	0.885	0.134
Color (a*)	0.94	0	0	0.008	0.008	0.02	0.628	0.665
Color (b*)	0.966	0	0.955	0	0.466	0	0.029	0.708
Opacity (Top)	0.944	0	0	0.001	0.009	0.009	0.408	0.306
Opacity (Bottom)	0.953	0	0	0.51	0.098	0.001	0.332	0.019
Breaking Force	0.892	0	0.191	0.307	0.022	0.125	0.294	0.623
Extensibility	0.872	0.001	0	0.012	0.037	0.04	0.302	0.17

[a] $P < 0.05$ was considered statistically significant.
[b] Types of leavening acids: Sodium aluminum phosphate, Sodium aluminum sulfate, Sodium acid pyrophosphate-28.
[c] Sodium bicarbonate amount.

moisture, breaking force, and extensibility ($p > 0.05$) (Table 2). Higher amounts of SBC produced smaller diameter but thicker tortillas (Table 3), which may be caused by increased dough toughness and gas retention capacity. Similar findings were obtained from Bejosano and Waniska (2004), noting that a decrease in diameter occurred when they increased the amount of leavening from 8.7 to 17.4 g/kg with an acid-to-base ratio of 1.90, and from 6.7 to 13.5 g/kg with a ratio of 1.24.

Higher amount of SBC contributed to a higher pH (Table 3), which suggested that more encapsulated fumaric acid should be used to reduce pH. However, Bejosano & Waniska (2004) found that pH was not affected by the amount of leavening, which might be due to the different acid-to-base ratios used in their study. With a higher amount of SBC, the tortillas were brighter and redder (Table 3). Winstone (2010) reported an increase in L* value from 76.2 to 78.4 when leavening agents were increased from 1.0 to 1.4%. In our study, tortillas made with 1.5% of the leavening were slightly bluer than 1% and 2% levels. Similarly, the tortillas were more opaque when produced with more SBC (Fig. 1). Adams (2001) and Bejosano and Waniska (2004) found similar trends in the refined flour tortillas. Nevertheless, the opacity scores of WWF tortillas were much lower than those of refined flour tortillas, as reported in the literature. The high fiber content in WWF weakens gluten strength, so the dough is less resistant to hot press, which makes it difficult to retain the gas created during baking (Barros et al., 2010). Thus, translucency is more severe in the WWF tortilla system and higher levels of leavenings were necessary. However, the amount of SBC did not show effects on breaking force and extensibility (Fig. 2).

Table 3
Effects of leavening acid, SBC amount, hot-press temperature and dough temperature on whole-wheat flour tortilla properties at day 1[a].

	Moisture	pH	Weight (g)	Diameter (cm)	Thickness (cm)	Color		
						L*	a*	b*
Leavening acid								
SALP[b]	30.2[a]	6.27[b]	35.59[a]	16.90[c]	2.78[a]	74.46[b]	4.31[a]	21.87[a]
SAS[c]	31.0[b]	5.34[a]	36.25[b]	15.60[a]	2.68[a]	70.76[a]	4.73[b]	24.01[b]
SAPP-28[d]	31.9[c]	6.57[c]	36.33[b]	16.10[b]	2.93[b]	74.16[b]	4.63[b]	23.73[b]
Amount of SBC								
1%	31.0[a]	5.74[a]	36.07[b]	16.55[b]	2.39[a]	71.29[a]	5.21[c]	23.30[b]
1.5%	31.3[a]	6.03[b]	35.90[a]	16.36[b]	2.76[b]	73.53[b]	4.39[b]	22.89[a]
2%	30.8[a]	6.40[c]	36.20[b]	15.69[a]	3.25[c]	74.56[c]	4.07[a]	23.42[b]
Hot-press temperature								
160 °C	32.0[b]	6.09[b]	36.58[c]	15.31[a]	3.26[c]	73.14[a]	4.48[a]	23.54[b]
177 °C	31.4[b]	6.13[b]	36.24[b]	16.05[b]	2.87[b]	73.35[a]	4.30[a]	22.79[a]
193 °C	29.7[a]	5.96[a]	35.34[a]	17.24[c]	2.26[a]	72.90[a]	4.90[b]	23.28[b]
Dough temperature								
25 °C	31.3[a]	6.15[b]	36.27[b]	16.06[a]	2.86[a]	73.68[b]	4.29[a]	22.41[a]
35 °C	30.8[a]	5.97[a]	35.84[a]	16.35[a]	2.74[a]	72.57[a]	4.83[b]	24.00[b]

[a] Values under each factor section and in the same column followed by the same letter (a, b, c) are not significantly different (P > 0.05).
[b] Sodium aluminum phosphate.
[c] Sodium aluminum sulfate.
[d] Sodium acid pyrophosphate-28.

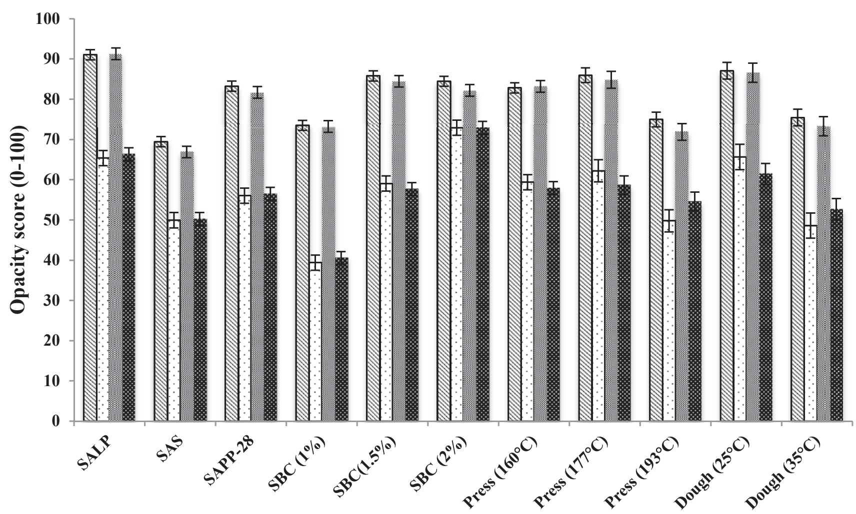

Fig. 1. Effect of leavening acid, SBC, hot-press temperature and dough temperature on the opacity of whole-wheat flour tortillas on day 1 and 45. Data shown are means ± standard deviations (3 replicates). SALP: Sodium aluminum phosphate; SAS: Sodium aluminum sulfate; SAPP-28: Sodium acid pyrophosphate-28; SBC: Sodium bicarbonate. ▧ Day1- Opacity (top), ◻ Day 1- Opacity (bottom), ■ Day 45- Opacity (top), ■ Day 45- Opacity (bottom).

3.3. *Effect of hot-press temperature*

Hot-press temperature significantly ($p < 0.05$) affected most parameters one day after baking (day 1) except for color (L*), breaking force, and extensibility ($p > 0.05$) (Table 2). At a higher press temperature, tortillas tended to lose more water during pressing; as a result, the higher press temperature (193 °C) yielded lower moisture and lower-weight tortillas (Table 3). A higher hot-press temperature made the dough less viscous and more extensible; thus, larger-diameter and thinner tortillas were produced with higher hot-press temperature. In addition, tortillas made at 193 °C hot-press temperature had a significantly ($p < 0.05$) lower pH than those at 160 °C or 177 °C on day 1 (Table 3). The reason for this could be that encapsulated fumaric acid pre-released faster at 193 °C hot-press temperature during baking and yielded lower pH. After 45 days, with the release of encapsulated fumaric acid, tortillas made with 160 °C, 177 °C, and 193 °C hot-press temperatures did not have significant differences in pH ($p > 0.05$). Hot-press temperature did not show much influence ($p > 0.05$) on tortilla color and opacity. However, tortillas made with 193 °C hot-press temperature had much lower opacity scores, indicating that 193 °C press temperature was considered too high for WWF tortillas to have an acceptable opacity score. It was speculated that higher hot-press temperature caused higher degree of starch gelatinization, and tortillas became more translucent. Moreover, tortilla breaking force and extensibility were not significantly ($p > 0.05$) influenced by hot-press temperature.

3.4. *Effect of dough temperature*

On day 1, higher dough temperature produced lower weight tortillas due to greater moisture evaporation, while diameter and thickness was not significantly ($p > 0.05$) affected by dough temperature (Table 3). Tortillas made with higher dough temperature (35 °C) had a lower pH on day 1 than those with a lower dough temperature (25 °C), which may be attributed to more encapsulated fumaric acid being dissolved under a higher mixing temperature. Additionally, we noticed a higher dough temperature

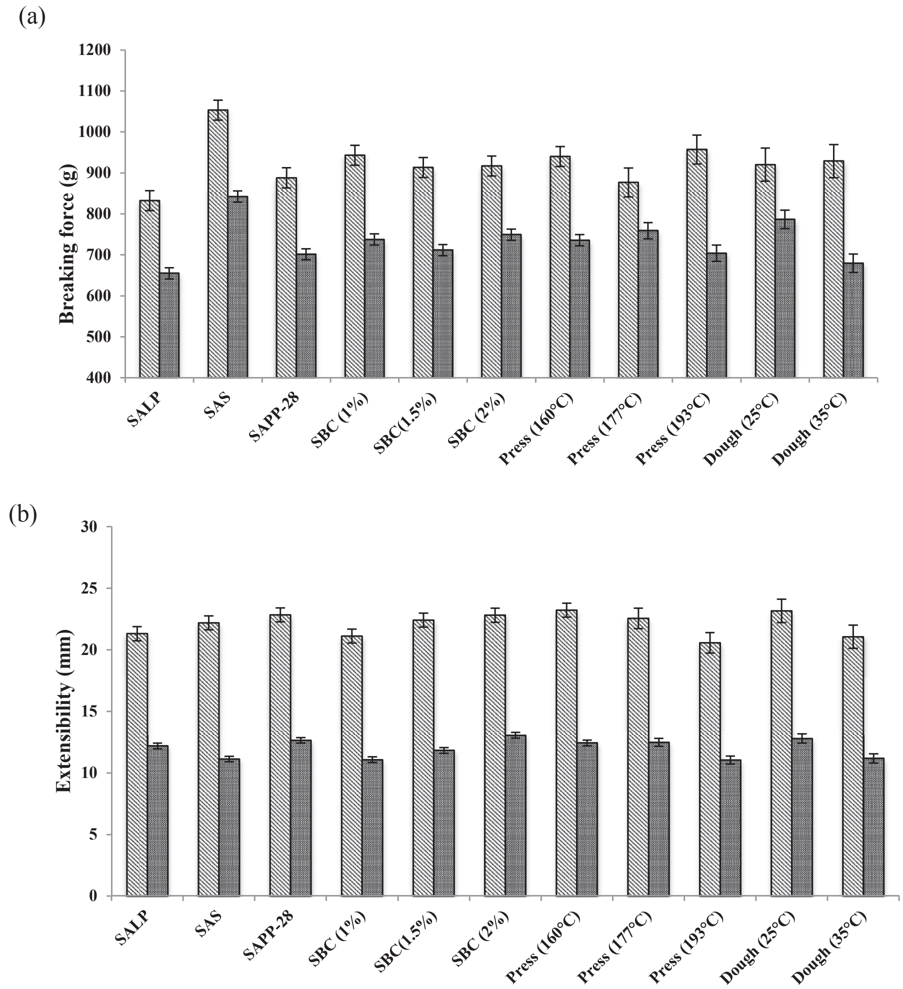

Fig. 2. Effect of leavening acid, SBC, hot-press temperature and dough temperature on the (a) breaking force and (b) extensibility of whole-wheat flour tortillas on day 1 and 45. Data shown are means ± standard deviations (3 replicates). SALP: Sodium aluminum phosphate, SAS: Sodium aluminum sulfate, SAPP-28: Sodium acid pyrophosphate-28, SBC: Sodium bicarbonate Fig. 2(a): ▨ Day1 ■ Day 45, Fig. 2(b): ▨ Day1 ■ Day 45.

reduced the amount of time to mix the dough to optimum development.

Higher dough temperature yielded darker, redder, and yellower tortillas (Table 3). With a higher dough temperature, the tortillas were more translucent (Fig. 1). About 20–30% of total carbon dioxide is generated from SALP, SAPP within the first 2 min of mixing at 27 °C (Molins, 1990). Even without leavening acids, due to the acidity of flour and other ingredients, there is reaction of SBC that will generate gas (Stauffer, 1990). The solubility of leavening base and acids, even the slow-acting acids, increase during mixing and resting under a higher dough temperature (Heidolph 1996; Cepeda et al. 2000). This will lead to less gas formation during baking and produce less opaque tortillas. Cepeda et al. (2000) found that higher amount of leavenings were required at 38 °C dough than at 34 °C to achieve a desired opacity. Previous studies (Hlynka, 1962; Waniska, 1999) reported that higher dough mixing temperature decreased mixing time and dough-resting time, which may explain why the industry would use a higher dough temperature even though a lower dough temperature produced more opaque products.

3.5. Effect of storage time

After 45 days of storage (day 45), some changes were found in tortilla parameters. Due to moisture loss, the moisture content and weight of tortillas were slightly reduced from day 1. The pH values of tortillas decreased after 45 days of storage as a result of a gradual release of encapsulated fumaric acid over time (Tables 3 and 4). Due to the full solubility and reaction of leavening acids and base, hot-press temperature and dough temperature did not affect the pH values of tortillas on day 45, but the type of leavening acids and the amount of SBC significantly ($p < 0.05$) influenced the tortilla pH. A pH < 6.1 was required to obtain extended shelf life for tortillas (Friend, Ross, Waniska, & Rooney, 1995). Although some tortillas had initial pH values higher than 6.1, after 45 days of storage all pH values were decreased to 6.1 or below, and no mold growth was noticed on any tortilla.

Tortillas of all leavening systems became darker and redder, and most tortillas tended to be slightly bluer after 45 days (Tables 3 and 4). Polyphenol oxidase (PPO) activity might contribute to the discoloration of tortillas during storage. Niu, Hou, Lee, and Chen (2014) found that the whole-wheat noodles became darker, redder and bluer after 24 h storage at room temperature, which was attributed to the production of colored substances by PPO activity. However, slight changes were found in opacity scores in all tortilla leavening systems (Fig. 1).

For all leavening systems, the breaking force and extensibility decreased after 45 days of storage. A similar decreasing trend has been found in previous research (Alviola & Awika, 2010; Book et al.,

Table 4
Effects of leavening acid, SBC amount, hot-press temperature and dough temperature on whole-wheat flour tortilla properties at day 45[a].

	Moisture	pH	Weight (g)	Diameter (cm)	Thickness (cm)	Color		
						L*	a*	b*
Leavening acid								
SALP[b]	30.0[a]	5.91[b]	35.20[a]	16.82[c]	2.67[a]	71.70[b]	4.45[a]	21.48[a]
SAS[c]	31.0[b]	5.18[a]	35.99[b]	15.50[a]	2.61[a]	66.81[a]	4.67[b]	22.45[b]
SAPP-28[d]	31.0[b]	6.17[c]	35.93[b]	15.93[b]	2.80[b]	71.20[b]	5.00[c]	23.69[c]
Amount of SBC								
1%	30.6[a]	5.39[a]	35.69[a,b]	16.57[c]	2.28[a]	68.06[a]	5.32[c]	22.57[a]
1.5%	30.5[a]	5.80[b]	35.59[a]	16.20[b]	2.66[b]	70.28[b]	4.57[b]	22.53[a]
2%	31.0[a]	6.07[c]	35.85[b]	15.47[a]	3.15[c]	71.37[c]	4.23[a]	23.54[a]
Hot-press temperature								
160 °C	31.5[b]	5.73[a]	36.14[b]	15.29[a]	3.13[c]	69.87[ab]	4.60[a]	22.90[b]
177 °C	31.3[b]	5.75[a]	36.03[b]	15.74[b]	2.79[b]	70.47[b]	4.52[a]	22.87[b]
193 °C	29.3[a]	5.77[a]	34.96[a]	17.22[c]	2.16[a]	69.37[a]	5.00[b]	21.86[a]
Dough temperature								
25 °C	31.3[b]	5.76[a]	36.05[b]	15.69[a]	2.85[a]	70.94[b]	4.41[a]	22.66[a]
35 °C	30.1[a]	5.75[a]	35.36[a]	16.47[a]	2.53[a]	68.87[a]	5.00[b]	22.43[a]

[a] Values under each factor section and in the same column followed by the same letter are not significantly different (P > 0.05).
[b] Sodium aluminum phosphate.
[c] Sodium aluminum sulfate.
[d] Sodium acid pyrophosphate-28.

2002; Winstone, 2010). During storage, the amorphous starch transformed gradually to a partially crystalline, retrograded state and dispersed (Bejosano, Joseph, Lopez, Kelekci, & Waniska, 2005). Changes in starch functionality were mainly responsible for staling of tortillas (Alviola & Waniska, 2008), which resulted in a weaker and less flexible texture. The differences in breaking force among the three acids were greater on day 45 compared to day 1 (Fig. 2). SALP required a significantly ($p < 0.05$) smaller force to break compared to SAPP-28 and SAS. Similar to day 1, tortillas made with SAS had the biggest breaking force on day 45. The leavening amount and hot-press temperature did not show significant ($p > 0.05$) effects on breaking force, but dough temperature had a significant ($p < 0.05$) influence. Tortillas made with a higher dough temperature required less force to break, which may be attributed to more moisture loss.

Although the tortilla extensibility was not significantly ($p > 0.05$) affected by any of the four factors on day 1, significant ($p < 0.05$) differences were observed on day 45, partly because the tortillas became more uniform in structure after storage and test variations of extensibility were much smaller (Fig. 2). On day 45, tortillas made with SAS (11.1 mm) had a shorter distance compared to those made with SALP (12.2 mm) and SAPP-28 (12.6 mm). The dense and firm tortilla dough with SAS contributed to the shorter extensibility. The amount of leavening significantly ($p < 0.05$) increased the extensibility of tortillas as thicker tortillas were produced with a higher amount of leavening. There was no difference in tortilla extensibility between 160 °C and 177 °C press temperatures ($p > 0.05$), but tortillas made at 193 °C press had a significantly ($p < 0.05$) shorter extensibility than others because they were the thinnest and required less time to rupture. Dough temperature significantly ($p < 0.05$) decreased the extensibility as higher moisture loss caused the tortillas to break more easily.

4. Conclusions

The type of leavening acid, SBC amount and dough temperature were the major factors influencing the opacity of WWF tortillas. A leavening system including 2% SBC (and equivalent SALP acid), 177 °C hot-press temperature, and 25 °C dough temperature would be most suited to produce more opaque WWF tortillas. Since each variable showed a different effect on each quality parameter, the tortilla industry should choose an ideal leavening system for their products based on their specific quality objectives. Future research to examine the differences in leavening acids (composition, mineral effects, gas production, etc.) will be beneficial to further understand the differences in their effects on WWF tortilla properties.

Acknowledgments

The authors would like to thank ICL Food Specialties (St. Louis, MO) for sponsoring this study.

References

Adams, J. L. (2001). *Effects of the timing and amounts of leavening during processing of wheat flour tortillas*. Doctoral dissertation. Texas A & M University.
Adams, J. G., & Waniska, R. D. (2002). Effects of amount and solubility of leavening compounds on flour tortilla characteristics. *Cereal Foods World, 47*, 60–64.
Adams, J., & Waniska, R. D. (2005). Flour tortilla attributes affected by hot-press conditions. *Cereal Foods World, 50*, 72–75.
Alviola, J. N., & Awika, J. M. (2010). Relationship between objective and subjective wheat flour tortilla quality evaluation methods. *Cereal Chemistry, 87*(5), 481–485.
Alviola, J. N., & Waniska, R. D. (2008). Determining the role of starch in flour tortilla staling using α-amylase. *Cereal Chemistry, 85*(3), 391–396.
Barros, F., Alviola, J. N., & Rooney, L. W. (2010). Comparison of quality of refined and whole wheat tortillas. *Journal of Cereal Science, 51*, 50–56.
Bejosano, F. P., Joseph, S., Lopez, R. M., Kelekci, N. N., & Waniska, R. D. (2005). Rheological and sensory evaluation of wheat flour tortillas during storage. *Cereal Chemistry, 82*(3), 256–263.
Bejosano, F. P., & Waniska, R. D. (2004). Functionality of bicarbonate leaveners in wheat flour tortillas. *Cereal Chemistry, 81*(1), 77–79.
Book, S. L., Brill, R. V., & Heidolph, B. B. (2002). Effects of leavening acids on characteristics of fresh and 30-day-old tortillas. *Cereal Foods World, 47*(8), 390–393.
Casso, J. B. G. (2003). *Effects of amounts and types of sodium bicarbonate in wheat flour tortillas*. Doctoral dissertation. Texas A&M University.
Cepeda, M., Waniska, R. D., Rooney, L. W., & Bejosano, F. P. (2000). Effects of leavening acids and dough temperature in wheat flour tortillas. *Cereal Chemistry, 77*(4), 489–494.
Dann, O. E. (2014). *Selecting wheat varieties for tortilla production*. Doctoral dissertation. Kansas State University.
Friend, C. P., Ross, R. G., Waniska, R. D., & Rooney, L. W. (1995). Effects of additives in wheat flour tortillas. *Cereal Foods World, 40*(7), 494–497.
Heidolph, B. B. (1996). Designing chemical leavening systems. *Cereal Foods World, 41*, 118–126.
Hlynka, I. (1962). Influence of temperature, speed of mixing, and salt on some rheological properties of dough in the farinograph. *Cereal Chemistry, 39*, 286–303.
La Baw, G. D. (1982). Chemical leavening agents and their use in bakery products. *Baker's Dig, 56*(1), 16–21.
Marquart, L., Chan, H. W., Orsted, M., Schmitz, K. A., Arndt, E. A., & Jacobs, D. R., Jr. (2006). *Gradual incorporation of whole-grain flour into grain-based products*. Cereal Foods World.
Marquart, L., Jacobs, D. R., McIntosh, G. H., Poutanen, K., & Reicks, M. (2007). *Whole*

grains and health. Iowa: Blackwell Publishing Professional (Chapter 3, 5 & 6).
Molins, R. A. (1990). *Phosphates in food*. CRC Press (Chapter 6).
Niu, M., Hou, G., Lee, B., & Chen, Z. (2014). Effects of fine grinding of millfeeds on the quality attributes of reconstituted whole-wheat flour and its raw noodle products. *LWT-Food Science and Technology, 57*(1), 58–64.
Stauffer, C. E. (1990). *Functional additives for bakery foods*. Springer Science & Business Media (Chapter 22).
Texture Technologies Corporation. (2009). *Texture exponent 32 V3.0 5.0*. NY: Scarsdale.
Tortilla Industry Association (TIA). (2014). *On-site technical report*. http://www.tortilla-info.com Accessed on September 2015.
Tortilla Industry Association (TIA). (2015). *Tortilla talk: Tortilla facts*. http://www.tortilla-info.com Accessed on May 2015.
U.S. Department of Agriculture & U.S. Department of Health and Human Services. (2010). *Dietary Guidelines for Americans, 2010* (7th ed.). Washington, DC: U.S. Government Printing Office (Chapter 4).
Waniska, R. D. (1999). Perspectives on flour tortillas. *Cereal Foods World, 44*, 471–473.
Winstone, L. M. (2010). *Leavening and temperature effects on the physical and rheological properties of wheat flour tortillas*. Doctoral dissertation. Oklahoma State University.