Effects of endoxylanases, vital wheat gluten, and gum Arabic on the rheological properties, water mobility, and baking quality of whole-wheat saltine cracker dough

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Abstract

The aim of this study was to improve the baking quality of whole-wheat saltine cracker (WWSC) using endoxylanases, vital wheat gluten (VWG), and gum Arabic. SRC results showed both water-SRC and sucrose-SRC of soft white whole-wheat flour (SWWW) were significantly reduced by gum Arabic (r = 0.94, P < 0.05). Alveograph results indicated that the tenacity and extensibility of the whole-wheat dough (WWD) were increased by VWG. Rheometer G′ and G″ moduli increased with higher addition levels of endoxylanases, VWG, and gum Arabic. Low-field nuclear magnetic resonance (LF-NMR) detected three CPMG proton populations (T21, T22, and T23) in WWD. T21 peak area ratio (tightly bound water) reduced and T22 peak area ratio (less tightly bound water) increased with the levels of each additive. LF-NMR results revealed increased water mobility from T21 population to T22 population with addition of these additives, which was beneficial for gluten to form a continuous network. Both stack height and specific volume of WWSC were improved by the use of endoxylanases, VWG, and gum Arabic, but the breaking strength varied. The results of orthogonal experimental design showed that the most-improved quality WWSC could be produced by combining 0.035% endoxylanases, 1.5% VWG, and 1.5% gum Arabic into SWWW flour.

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1. Introduction

Crackers are low-moisture content products that have a unique crispy texture. In commercial production of saltine crackers, flour of low water absorption but relatively strong gluten strength is required (Kweon et al., 2011). As a result, soft wheat is commonly used for cracker flour, but hard red winter wheat offers some quality characteristics that are desired for making saltine crackers by providing gluten strength (Slade et al., 1994). Whole-wheat flour (WWF) is rich in dietary fiber, phenolic compounds, enzymes, vitamins, minerals, and phytoestrogens. The regular consumption of whole-grain flour can provide health benefits such as the reduced risk of cardiovascular disease, type II diabetes, and cancers (Liu, 2007). However, to the best of our knowledge, the practical application of WWF in saltine cracker has not been reported elsewhere in the scientific literature.

In the manufacture of whole-grain flour products, high water absorption and weak gluten strength of WWF present many challenges in processing and product quality attributes. Loaf volume of whole-wheat bread tends to be lower than that of bread made from white flour (Bruckner et al., 2001). In the case of whole-wheat saltine crackers (WWSC), additional water is required in the formulation and weak gluten strength of soft white whole-wheat flour (SWWW) increases the difficulty of cracker dough preparation and reduces puffedness and breaking strength (more fragile) (Li et al., 2013). Additional water of whole-grain dough (WWDD) must be baked out through baking evaporation, which results in prolonged baking time and energy consumption (Rogers and Hoseney, 1987).

Arabinoxylans (AX) are the major non-starch polysaccharides in wheat endosperm cell walls and the primary components responsible for water absorption in WWF. Wheat flour contains approximately 1.5−2.5% AX, of which 25−30% is water extractable AX (WE-AX) and 70−75% is water unextractable AX (WU-AX) (Courtin and Delcour, 2002). WE-AX can form highly viscous solutions, whereas WU-AX has a high water-holding capacity.
The water holding capacity of AX has been demonstrated to have significant influences on dough rheological behaviors and quality attributes of baked products (Courtin and Delcour, 2002). Bettge and Morris (2000) reported a negative relationship between cookie diameter and WE-AX in soft wheat flour, as dough viscosity (mainly controlled by WE-AX) appears to control cookie spread; low-viscosity cookie dough tends to spread more and yields larger diameter (Gutierrez et al., 2001).

In general, endoxylanases (EC 3.2.1.8) hydrolyze the glycosidic bonds within the xyloglucans, degrading the WU-AX into high molecular weight WE-AX, and/or decomposing the latter into low molecular weight WE-AX (Sunna and Antranikian, 1997); therefore, it was stated that endoxylanases decrease the water holding capacity of AX and redistribute water in a dough system (Courtin et al., 1999).

In addition, endoxylanases were shown to improve dough handling and machinability (Slade et al., 1994), which are beneficial to WWSC dough preparation. Vital wheat gluten (VWG) is traditionally noted for its functional properties in various bakery applications, such as improving strength and network forming of dough, reducing breakage in snack products, improving gas retention and product volume, and improving structure in whole-grain products (Kalin, 1979). It is expected that VWG may improve the quality of WWSC by increasing gluten strength of SWWW flour and oven spring during baking. Gum Arabic was reported to bring many benefits to bakery products in terms of processing, texture and shelf life due to its moisture regulation and film-forming properties (Thevenet, 2010). The use of gum Arabic in WWSC is expected to make positive contributions to its quality.

The molecular mobility of water and biopolymers in food products can be studied with proton nuclear magnetic resonance (1H NMR). It was successfully applied to examine the water mobility between macromolecule complexes in various dough systems. By determining the spin–spin relaxation time (T2) with LF-NMR, Lu and Seetharaman (2013) used a 1H NMR spin–spin relaxation time (T2) to study the water mobility in various dough systems containing barley flour. Bosmans et al. (2012) investigated starch–water, gluten–water, and flour–water model systems as well as straight-dough bread with 1H NMR relaxometry and identified different populations in these systems.

The objectives of this study were: 1) to examine the individual effects of endoxylanases, VWG, and gum Arabic on physicochemical and rheological properties of WWF and baking performance of WWSC; 2) to determine the optimal addition of combined endoxylanases, VWG, and gum Arabic that provide the most improvement to the end-product quality attributes, and 3) to detect the effect of each additive on water mobility between populations in a WWD system using LF-NMR in order to explain the mechanism of end product quality improvement.

2. Experimental

2.1. Materials

Soft white whole-wheat (SWWW) flour (Ultragain®): moisture, 10.3%; protein, 9.77%; ash, 1.52%; wet gluten, 22.2%; starch damage, 3.3%; protein, ash, wet gluten and starch damage were reported on a 14% moisture basis) was supplied by ConAgra Mills, Inc. (Omaha, NE). This commercial flour was ultrafine WWF that has higher water absorption than traditional cookie flour due to higher damaged starch. VWG was provided by MGP Ingredients, Inc. (Atchison, KS). Pentopan Mono BG is a purified (1, 4)-β-xylanases and was provided by Novozyme Company (Franklinton, NC). Pre-Hydrated gum Arabic-FT was from Tic gums, Inc. (Belcamp, MD). The chemical reagents (ACS grade) used for testing solvent retention capacity (SRC) were purchased from Nurnberg Scientific Company (Portland, OR). Baking soda (ARM & HAMMER Div. of Church & Dwigh Co., Inc., Princeton, NJ), mineral yeast food (ADM Arkady Inc., Olathe, KS), salt (Morton Salt, Inc., Chicago, IL), Crisco vegetable shortening (trans-fat free) (J.M. Smucker Company, Orrville, OH) and instant dry yeast (Lesaffre Yeast Corporation, Milwaukee, WI) were purchased from a local supermarket (Portland, Oregon).

A sourdough starter was originally supplied by Oregon State University and was fed daily using old starter (50 g), HRW flour (100 g), and distilled water (50 g) during the course of the study.

2.2. WWF blends preparation

Different levels of endoxylanases (0.01%, 0.02%, 0.03%, and 0.04%), VWG (1.0%, 2.0%, 3.0%, and 4.0%) and gum Arabic (0.5%, 1.0%, 2.0%, and 3.0%) (flour basis) were blended into the SWWW flour, respectively. The addition levels of each ingredient were based on the usage ranges recommended by ingredient suppliers and confirmed by our own trials. Each blending was done in a blender (model 71, IMER International Inc., Poggibonsi, Italy) for 20 min to achieve uniform mixture prior to dough preparation. Control flour was 100% SWWW flour.

2.3. SRC testing

To determine the effects of endoxylanases, VWG, and gum Arabic on water absorption of SWWW flour, the SRC values of flour blends added with different ingredients described in Section 2.2 were tested. The SRC values with the four solvents as lactic acid SRC (LA-SRC), sodium carbonate SRC (SC-SRC), sucrose SRC (Suc-SRC), and water SRC (W-SRC) were determined according to the AACC International Approved Method 56-11.02.

2.4. Rheological measurements

2.4.1. Alveograph analysis

Alveograph parameters of different dough samples were determined by the Alveo-Consistograph (Chopin, Villeneuve-La-Garenne, France) according to the AACC International Approved Method 54-30.02. Dough tenacity (T), extensibility (L) and deformation energy (W) were determined.

2.4.2. Dynamic viscoelasticity

The effect of adding endoxylanases, VWG, and gum Arabic on rheological properties (storage modulus, G'; loss modulus, G'') of SWWW flour were determined using an AR1000 Rheometer (TA Instruments, New Castle, USA). A standard steel parallel plate (20-mm diameter, 1 mm-gap distance) was selected as the testing probe. The conditions of the frequency sweep test were 0.1–100 Hz (frequency) and 28 °C (temperature). An oscillatory strain sweep test at constant frequency (1 Hz) was performed to determine the maximum deformation in the linear viscoelastic range. On the basis of this data, the target strain was 1%, which was within this linear region. A 3-g SWWW dough added with different levels of each additive was placed between the plates immediately after optimum dough mixing in the Farinograph with a constant water absorption of 60%, in order to observe and compare the effects of each additive on the dynamic viscoelasticity of WWD. The excess dough was cut off and mineral oil was coated on the rim of the sample to prevent it from drying during the test. The dough was allowed to rest for 5 min to release the residue strain before testing. Triplicate measurements for each sample were performed.

2.5. Whole-wheat saltine cracker preparation

A modified sponge and dough method was used to prepare WWSC in the laboratory. Sponge ingredients of WWSC included...
SWWW flour (65%) (added with different levels of endoxylanases, VWG, or gum Arabic as described previously), sourdough starter (4%), instant dry yeast (0.3%), yeast foods (0.03%), and water (34%). The dough ingredients included SWWW flour (35%), shortening (14%), salt (0.8%), water (1%), and baking soda (determined by the total titratable acidity of the sponge). The detailed processing procedures were described by Li et al. (2013).

2.6. End-product quality evaluation

The stack height, stack weight, specific volume, and breaking strength of WWSC were determined (Li et al., 2013) to evaluate the effects of endoxylanases, VWG, and gum Arabic on the end-product baking quality. All measurements were conducted at least three times.

2.7. LF-NMR determination

Spin–spin relaxation time ($T_2$) was determined using the LF-NMR system to observe the effect of endoxylanases, VWG, and gum Arabic on water mobility between proton populations in the WWF system. The relaxation time measurements were performed on a Niumag Desktop Pulsed NMR Analyzer (Shanghai Niumag Electronics Technology Co. Ltd., China). Transverse relaxation ($T_2$) was measured using the Carr–Purcell–Meiboom–Gill (CPMG) pulse sequence. The detailed parameters and procedures of measurements were described in our previous study (Li et al., 2012).

2.8. Orthogonal experimental design

Effects of combined endoxylanases, VWG, and gum Arabic on the end-product quality were determined via a L9 ($3^3$) orthogonal experiment. The array was designated involving three factors, $A$ (endoxylanases), $B$ (VWG), and $C$ (gum Arabic), each at three levels which were selected from the single-factor experiment. Nine groups of experiment were designed to determine the optimum conditions of combined experimental factors based on the evaluation of stack weight, stack height, specific volume, and breaking strength of four dependent variables.

2.9. Statistical analysis

Statistical analyses of orthogonal experimental data were analyzed with the Statistical Package for the Social Sciences (SPSS) Analysis software 17.0 (SPSS Institute, USA). The mean values based on at least three individual measurements, were compared ($\alpha = 0.05$) using the general linear model and multivariate ANOVA procedure.

3. Results and discussion

3.1. Effects of the endoxylanases, VWG, and gum Arabic on the SRC values of SWWW flour

The effects of different levels of endoxylanases on the SRC values of SWWW flour are shown in Fig. 1a. The W-SRC and Suc-SRC values of SWWW flour reduced only slightly with the increasing level of endoxylanases, mainly because the enzyme reaction time with the flour components was not long enough as the standard SRC procedures were used. Kweon et al. (2011) reported that the W-SRC values of flours added with xylanases were consistently decreased. Treatment of European commercial wheat flours with aculeatus xylanase also caused a decrease in all SRC values (Duyvejonck et al., 2011). The authors further noted that WE-AX only contributed to the Suc-SRC values, whereas the solvent-accessible AX generally contributed to all SRC values, and particularly to the Suc-SRC values. The reduced water absorption of WWF is preferred for crackers to obtain a crispy texture and to reduce the baking time (Li et al., 2013). The LA-SRC and SC-SRC values of WWF flour did not show a linear change with the level of endoxylanases because both glutenins and damaged starch were not affected by the endoxylanases. The differences between this study and other reported results might be caused by the complex system of WWF, and the type and dosage of endoxylanases used in this study.

In bread making, the use of endoxylanases is to degrade WU-AX that interfere with the formation of gluten network, into high molecular weight WE-AX, resulting in increased viscosity and dough stability (Courtin and Delcour, 2001), improved oven spring, and softer crumb (Heldt-Hansen, 2006). In contrast, the most

![Fig. 1. Effects of different addition levels of endoxylanases (a), vital wheat gluten (b), and gum Arabic (c) on the solvent retention capacity (SRC) values (W-SRC: Water-SRC; LA-SRC: Lactic Acid-SRC; SC-SRC: Sodium Carbonate-SRC, and Suc-SRC: Sucrose-SRC) of 100% soft white whole-wheat (SWWW) flour.](image-url)
favorable endoxylanases for making crackers are those that preferentially hydrolyzed WE-AX and are poorly reactive on WU-AX, so they can reduce both the water holding capacity and viscosity of dough, which are beneficial for crackers to expand and obtain crispy texture.

The W-SRC, LA-SRC and SC-SRC values showed positive correlations ($r = 0.91, P < 0.05$) with the addition level of VWG, but the W-SRC increased significantly ($r = 0.98, P < 0.05$) only upon addition of the highest level at 4%. Addition of VWG increased the total gluten content of WWF and its water absorption. VWG can also enhance the existing gluten network formed by the gluten present in the WWF and mitigate the dough weakening effect by the presence of bran particles in such flour. However, the Suc-SRC value had no clear relationship with the added VWG (Fig. 1b) since Suc-SRC was mainly affected by WE-AX (Duyvejonck et al., 2011).

The W-SRC, LA-SRC, SC-SRC and Suc-SRC values of SWWW flour all reduced with the level of gum Arabic (Fig. 1c). Compared to other water-soluble polysaccharides with a similar molecular weight, gum Arabic exhibits very low viscosity in water due to its globular, highly branched structure which hinders the formation of cross-links or hydrogen bonding with water (Thevenet, 2010). Hydration properties of gluten were not affected by the presence of gum Arabic at the tested levels of 0.002–0.013 g per gram of gluten as its compact structure could inhibit possible interactions between its polar groups and the peptide chains of the gluten (Bárcenas et al., 2009).

For optimum cracker flour, a higher level of LA-SRC value and lower levels of W-SRC and SC-SRC values were preferred (Kweon et al., 2011). As the individual performance of endoxylanases, VWG, and gum Arabic did not meet the desired quality requirements of whole-wheat cracker flour, the combined effects of these ingredients must be investigated.

3.2. Effects of the endoxylanases, VWG, and gum Arabic on rheological behaviors of SWWW flour

Alveograph and rheometer are two methods that can observe the rheological behaviors of dough. However, there are some differences between the two methods. Alveograph testing assists in predicting the biaxial extension produced during dough bubble inflation, which is well linked, from a physical point of view, to the process of dough stretching during fermentation. Rheometer, on the other hand, determines the viscoelastic properties of dough under a certain oscillatory frequency without destroying their structure. It is expected the results of these two methods are not necessarily linked to each other.

3.2.1. Alveograph

The effects of endoxylanases on the alveograph values of SWWWW are shown in Fig. 2a. The dough tenacity ($P$ value) decreased with the levels of endoxylanases, especially between the 0.01 and 0.02% levels, making the cracker dough softened and thus easy to handle during processing, and increased the tenderness of the baked products. The dough extensibility ($L$ value) had a positive correlation ($r = 0.98, P < 0.01$) with the level of endoxylanases. This may be caused by the hydrolysis of WE-AX by endoxylanases so that dough viscosity was reduced and became more extensible. The $P/L$ ratio had a negative correlation ($r = -0.97, P < 0.01$) with the endoxylanases. Lower $P$ value and higher $L$ value are desirable for the cracker flour since too high $P$ value exerts a detrimental effect on the crispy and puffy texture of cracker (Kweon et al., 2011). The deformation energy ($W$ value) had no clear correlation with the amount of endoxylanases.

The $P$, $L$, and $W$ values all increased with the addition of VWG, while the $P/L$ ratio showed no clear trend, meaning that $P$ and $L$ values increased in similar proportions (Fig. 2b). These results indicated that incorporation of VWG reinforced the existing gluten network, which could partially offset the negative effect of bran particles on the formation of gluten network in the WWD system. However, the increased $P$ value could increase dough toughness, making the cracker too hard in texture for optimized production. The increased $L$ value could improve the extensibility and the gas retention capacity of the whole-wheat cracker dough, which was expected to increase the puffiness (thickness) of the end products. Therefore, the addition level of VWG should be carefully controlled to optimize the end product quality.

The $P$, $W$ and $P/L$ values of SWWWW flour all reduced with the addition of gum Arabic, while the $L$ values of SWWWW flour had a positive correlation ($r = 0.99, P < 0.01$) with the amount of gum Arabic (Fig. 2c). These results indicated that the tenacity of WWD reduced and the extensibility of the WWD increased by the incorporation of gum Arabic, both of which are considered beneficial to cracker production. There are at least two possible explanations for
these results. First, since the alveograph was run on the fixed water absorption, as gum Arabic reduced the dough water absorption (reduced W-SRC), the dough became wetter and softer, so the P value reduced and the L value increased. Second, gum Arabic has a highly branched compact arabinogalactan structure that gives a low-viscosity solution and also contains a central protein fraction that provides good emulsification properties. These properties would aid in the extensibility of the dough. Meanwhile, from the observation during dough preparation, the cohesiveness of the WWSC dough pieces was increased by gum Arabic, making the dough easier to handle during processing. Thus, the gum Arabic contributed to the overall quality improvement of WWSC.

3.2.2. Dynamic viscoelasticity

$G'$ represents the dynamic elasticity and $G''$ represents the dynamic viscous property. Both the $G'$ and $G''$ moduli of WWF increased with the higher levels of endoxylanases, VWG, and gum Arabic in the frequency sweep test (Fig. 3). According to the results of the SRC test, the W-SRC value of WWF components (especially the AX) was significantly reduced ($r = -0.95$, $P < 0.05$) by the presence of gum Arabic at higher addition levels. Presumably, the water may be redistributed from the AX matrix into the gluten network in the WWSC system in the presence of gum Arabic. Formation of the gluten network which attributed to its adequate water absorption, enhanced the elasticity of gluten and increased the $G'$ modulus of WWSC. As for endoxylanases, it was possible that the aggregation of the gluten network was enhanced by the hydrolytic action of xylanases on WE-AX (Wang et al., 2004a). On the other hand, additional VWG also contributed to the increases of dough elasticity ($G'$ modulus) because VWG enhanced the network formation together with the existing gluten in the flour.

The degradation of WU-AX into WE-AX by endoxylanases increased the mobility of polysaccharide molecules (Meuser and Suckow, 1986) and resulted in a more viscous gel structure (Wang et al., 2004b), leading to a higher $G''$ modulus. Also, the viscosity of the WWSC system was increased by the enhanced adhesiveness of VWG and gum Arabic, yielding increases of the $G''$ modulus of WWSC. High-levels of $G'$ and $G''$ values indicate a better dough elasticity and extensibility for more expansion in baking whole-wheat products.

3.3. Effects of the endoxylanases, VWG, and gum Arabic on the baking quality of WWSC

The quality attributes of WWSC were measured after production. The moisture content of baked crackers was controlled to be in the range of 3–5%. Evaluation results showed that the stack height and specific volume of WWSC increased with the amount of endoxylanases; while the stack weight and breaking strength of end products decreased with the amount of endoxylanases (Table 1). Baking performances of the end products are determined by dough rheological properties especially in relation to the volume and internal structure of the leavened products. The use of endoxylanases in the baking process modifies the rheological properties of dough such as dough extensibility and resistance to breakage (Sørensen, 2003). As more endoxylanases were added, cracker dough became much softer (lower P) and more extensible (high L), which helped the cracker to expand during baking. The decreased dough crumbliness during lamination also demonstrated the modified effects of endoxylanases on the cracker-baking performance (Carey et al., 2002). The high water-holding capacity of the AX affects the distribution of moisture among the WWSC constituents, thereby modifying the rheological properties of WWSC system. It was reported that the use of xylanase also resulted in the formation of gluten characterized by a lower average glutenin macropolymer particle size that was associated with modified gluten rheological properties of a lower $R_{max}$ and larger $E$ at $R_{max}$ (Wang et al., 2004b). These observations were in agreement with our alveograph results.

As the addition level of VWG increased, the stack weight, stack height, specific volume, and breaking strength of end products were all gradually increased (Table 1). The original SWWW flour was lacking necessary gluten strength due to the presence of bran and germ, resulting in the breakage of cracker dough sheet during lamination and less gas retention capacity during fermentation and baking. Upon addition of VWG, the dough strength ($P$ and $L$ values) was increased, and both elasticity and the dynamic viscous property ($G'$ and $G''$ moduli) of dough were enhanced; as a result, the WWSC dough was strong enough to retain gas, and the oven spring was improved. However, too much gluten would greatly increase the tenacity of the cracker dough and restrict the puffiness of the end products.

The stack height and specific volume of end products increased with the added gum Arabic; however, the breaking strength of the cracker had a negative correlation ($r = -0.89$; $P < 0.05$) with the amount of gum Arabic. The stack weight of the end products had no significant correlation with the amount of gum Arabic (Table 1).

Results of SRC testing showed that the water absorption of WWF was reduced by the presence of gum Arabic, which was beneficial for gluten proteins to absorb adequate water and form stronger gluten network. Meanwhile, gum Arabic reduced dough tenacity ($P$) and increased dough extensibility ($L$), making WWF softened; thus the oven spring and the crispy texture of the end products were expected to benefit from it.

3.4. Effects of the endoxylanases, VWG, and gum Arabic on water mobility in WWSC

A typical curve of $T_2$ relaxation time distributions of fresh dough usually shows one to three CPMG proton populations, namely $T_{21}$, $T_{22}$, and $T_{23}$ (Li et al., 2013; Lu and Seetharaman, 2013), but they are affected by the dough moisture content and compositions (Lu and Seetharaman, 2013), the degree of interactions between polymers and water, and the type of NMR measurements [free induction decay (FID) and/or CPMG pulse sequence] (Bosmans et al., 2012; Lu and Seetharaman, 2013): detected three CPMG water populations in the fresh dough moisture range of 1.1–2.0 g/g db, namely, tightly ($T_{21}$, 2–5 ms), less tightly ($T_{22}$, 20–50 ms), and weakly ($T_{23}$, 100–200 ms) bound water. As the dough moisture was below 1.1 g/g db, the $T_{23}$ peak disappeared, and the $T_{31}$ and $T_{32}$ peaks seemed to merge into a broad single peak with further decrease of moisture level (<0.9 g/g db). When the moisture was higher than 2.0 g/g db, $T_{23}$ merged into $T_{22}$ and formed a broader $T_{22}$ peak, but a new peak was separated from $T_{22}$. However, both peak times and distribution patterns were shifted with the blend ratio of whole-grain barley flour in the dough; peak time dramatically reduced with the increase of whole-grain barley flour in the dough ($r = -0.96$, $P < 0.05$). Therefore, both peak positions and their distribution patterns vary with the dough system being researched.

In our WWSC system, a typical curve of $T_2$ relaxation time profile showed three CPMG proton populations: $T_{21}$ (0.02–0.5 ms), $T_{22}$ (0.5–30 ms), and $T_{23}$ (30–100 ms), which represented tightly bound water, less tightly bound (immobilized) water, and weakly bound (free) water of the moisture in the dough system, respectively, as defined by Lu and Seetharaman (2013). However, the peak times reported here were much shorter than those reported by Lu and Seetharaman (2013) because our dough system was 100% WWD. In their study, $T_2$ peak times were significantly reduced as the blending ratio of whole-grain barley flour was increased in the dough, indicating that some components of whole-grain barley flour...
Fig. 3. Effects of different addition levels of endoxylanases on $G'(a)$ and $G''(b)$, vital wheat gluten on $G'(c)$ and $G''(d)$, and gum Arabic on $G'(e)$ and $G''(f)$ of 100% soft white whole-wheat (SWWW) flour.
Table 1

<table>
<thead>
<tr>
<th>Addition level (%)</th>
<th>Stack weight(^a) (g)</th>
<th>Stack height(^b) (nm)</th>
<th>Specific volume (ml/g)</th>
<th>Breaking strength (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.1 ± 0.01</td>
<td>26.2 ± 0.6</td>
<td>1.0 ± 0.08</td>
<td>70.8 ± 68.5</td>
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<tr>
<td>Endoxylanases</td>
<td>0.01 24.9 ± 0.1</td>
<td>26.7 ± 0.6b</td>
<td>1.05 ± 0.09an</td>
<td>70.1 ± 58.5</td>
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<tr>
<td></td>
<td>0.02 24.5 ± 0.1</td>
<td>27.4 ± 0.4b</td>
<td>1.09 ± 0.10</td>
<td>65.4 ± 55.7</td>
</tr>
<tr>
<td></td>
<td>0.03 23.9 ± 0.1</td>
<td>28.8 ± 0.3b</td>
<td>1.15 ± 0.05</td>
<td>51.2 ± 45.9</td>
</tr>
<tr>
<td></td>
<td>0.04 23.4 ± 0.1</td>
<td>29.1 ± 0.2b</td>
<td>1.26 ± 0.05</td>
<td>50.2 ± 38.4</td>
</tr>
<tr>
<td>Vital wheat gluten</td>
<td>1.0 24.9 ± 0.1</td>
<td>27.9 ± 0.6b</td>
<td>1.10 ± 0.09ab</td>
<td>73.6 ± 29.8ab</td>
</tr>
<tr>
<td></td>
<td>2.0 25.1 ± 0.1</td>
<td>28.3 ± 0.2b</td>
<td>1.19 ± 0.04</td>
<td>800 ± 27.6b</td>
</tr>
<tr>
<td></td>
<td>3.0 24.4 ± 0.1</td>
<td>30.0 ± 0.2</td>
<td>1.20 ± 0.07</td>
<td>858.4 ± 28.0c</td>
</tr>
<tr>
<td>Gum Arabic</td>
<td>0.5 25.9 ± 0.1</td>
<td>37.2 ± 0.6b</td>
<td>1.40 ± 0.06</td>
<td>861.5 ± 48.1c</td>
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<tr>
<td></td>
<td>1.0 25.9 ± 0.1</td>
<td>37.3 ± 0.3b</td>
<td>1.10 ± 0.02</td>
<td>651.9 ± 30.8a</td>
</tr>
<tr>
<td></td>
<td>2.0 26.5 ± 0.2c</td>
<td>41.9 ± 0.4d</td>
<td>1.21 ± 0.02</td>
<td>530.6 ± 19.8c</td>
</tr>
<tr>
<td></td>
<td>3.0 25.9 ± 0.1</td>
<td>42.2 ± 0.2</td>
<td>1.27 ± 0.03</td>
<td>527.4 ± 20.1c</td>
</tr>
</tbody>
</table>

\(^a\) Values are means ± S.D. (based on at least 10 replicate measurements). Values for each ingredient (for the four levels) were compared to the control value. Values for each ingredient within the same column followed by the same letters are not significantly different (P < 0.05).

\(^b\) Stack of 7 crackers.

Table 2

<table>
<thead>
<tr>
<th>Addition level (%)</th>
<th>(T_2)(^a) ms</th>
<th>(T_2)(^b) ms</th>
<th>(T_2)(^c) ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.0864 ± 0.0018a</td>
<td>0.8954 ± 0.0013a</td>
<td>0.0202 ± 0.002b</td>
</tr>
<tr>
<td>Endoxylanases</td>
<td>0.01 0.0824 ± 0.006b</td>
<td>0.0896 ± 0.0015a</td>
<td>0.0207 ± 0.003b</td>
</tr>
<tr>
<td></td>
<td>0.02 0.0770 ± 0.007c</td>
<td>0.0905 ± 0.0011b</td>
<td>0.0195 ± 0.001a</td>
</tr>
<tr>
<td></td>
<td>0.03 0.0758 ± 0.005d</td>
<td>0.0909 ± 0.0013b</td>
<td>0.0203 ± 0.002b</td>
</tr>
<tr>
<td></td>
<td>0.04 0.0713 ± 0.005e</td>
<td>0.0901 ± 0.0017c</td>
<td>0.0206 ± 0.002c</td>
</tr>
<tr>
<td>Vital wheat gluten</td>
<td>1.0 0.0741 ± 0.0007b</td>
<td>0.0912 ± 0.0014c</td>
<td>0.0250 ± 0.004cde</td>
</tr>
<tr>
<td></td>
<td>2.0 0.0734 ± 0.006b</td>
<td>0.0908 ± 0.0015b</td>
<td>0.0208 ± 0.002bced</td>
</tr>
<tr>
<td>Gum Arabic</td>
<td>0.5 0.0701 ± 0.0006c</td>
<td>0.0902 ± 0.0014b</td>
<td>0.0204 ± 0.002b</td>
</tr>
<tr>
<td></td>
<td>1.0 0.0665 ± 0.0004c</td>
<td>0.0910 ± 0.0017c</td>
<td>0.0215 ± 0.003cde</td>
</tr>
<tr>
<td></td>
<td>2.0 0.0659 ± 0.0004c</td>
<td>0.0912 ± 0.0016b</td>
<td>0.0217 ± 0.0003e</td>
</tr>
<tr>
<td></td>
<td>3.0 0.0646 ± 0.0005b</td>
<td>0.0914 ± 0.0014d</td>
<td>0.0210 ± 0.002cde</td>
</tr>
</tbody>
</table>

\(^a\) Values are means ± S.D. (based on at least three replicate measurements).

\(^b\) Peak area ratio, ratio of each peak area to total area (\(T_{21}, T_{22}, \text{ and } T_{23}\)).
conditions of factors and levels (Table 3). In Table 3, range value (R value) is the determination of how much variation each factor has contributed to variables. Mean value (K value) shows the effect of factor levels on variables. If the K value is higher, it means more significant impact of independent factors on variables. Results of multiple factor range analysis show that the rank of K-value of cracker stack weight was: \( K_3 > K_2 > K_1 \), and the minimum \( K_1 \) to \( K_3 \) was divided by three; respectively, so the optimum conditions for the cracker stack weight was \( A_2B_2C_1 \) (although the K value of \( B_2 \) was equal to \( B_3 \), the lower addition level was selected). Based on the same selection principles, the optimum condition factors and levels for the cracker stack height, specific volume, and breaking strength were \( A_2B_3C_2 \), \( A_2B_2C_1 \), and \( A_2B_3C_1 \), respectively. In summary, \( A_2 \) had the most significant impact on the stack height, stack height, specific volume, and breaking strength of crackers; \( B_2 \) had the most significant impact on the stack height and breaking strength of crackers; and \( C_1 \) had the most significant impact on the stack weight and breaking strength of crackers. Thus, the optimum condition factors and levels of all three ingredients for the most quality improvement of end products were: \( A_2B_2C_1 \) (0.035% endoxylanases, 1.5% VWG, and 1.5% gum Arabic).

4. Conclusions

The dough extensibility of SWWV flour was much improved by endoxylanases due to increased mobility of polysaccharide molecules and reduced dough viscosity. VWG reinforced the existing gluten network, which mitigated the negative effect of bran particles on the formation of a continuous gluten network in the WWD. Gum Arabic was very effective in reducing the tenacity and improving the extensibility of WWD. All three additives increased \( G’ \) and \( G'' \) moduli of WWD, indicating a better dough elasticity and extensibility balance for more expansion in cracker baking. LF-NMR revealed an increase of water mobility from the \( T_2 \) proton population with the incorporation of endoxylanases, VWG, or gum Arabic. These results suggested that accessible water became more available for gluten to develop a continuous network and the improved baking quality of WWSC was realized.

### Table 3

Orthogonal array \( I_4(3^3) \) design and multiple factors range analysis.

<table>
<thead>
<tr>
<th>No.</th>
<th>A (%)</th>
<th>B (%)</th>
<th>C (%)</th>
<th>Stack height weight ( \text{(g)} )</th>
<th>Specific volume ( \text{(ml/g)} )</th>
<th>Breaking strength ( \text{(g)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.025</td>
<td>0.5</td>
<td>1.5</td>
<td>28.1</td>
<td>20.6</td>
<td>1.09</td>
</tr>
<tr>
<td>2</td>
<td>0.025</td>
<td>1.0</td>
<td>2.0</td>
<td>27.9</td>
<td>22.8</td>
<td>1.12</td>
</tr>
<tr>
<td>3</td>
<td>0.025</td>
<td>1.5</td>
<td>2.5</td>
<td>28.3</td>
<td>26.2</td>
<td>1.21</td>
</tr>
<tr>
<td>4</td>
<td>0.030</td>
<td>0.5</td>
<td>1.5</td>
<td>28.0</td>
<td>21.0</td>
<td>1.18</td>
</tr>
<tr>
<td>5</td>
<td>0.030</td>
<td>1.0</td>
<td>2.0</td>
<td>28.7</td>
<td>23.2</td>
<td>1.27</td>
</tr>
<tr>
<td>6</td>
<td>0.030</td>
<td>1.5</td>
<td>2.5</td>
<td>28.5</td>
<td>26.5</td>
<td>1.39</td>
</tr>
<tr>
<td>7</td>
<td>0.035</td>
<td>0.5</td>
<td>2.5</td>
<td>28.4</td>
<td>26.5</td>
<td>1.39</td>
</tr>
</tbody>
</table>

**A**: endoxylanases; **B**: vital wheat gluten; **C**: gum Arabic.

**K**: mean value; **K**: sum of the variables at the first level of each factor which is divided by three; **K**: sum of the variables at the second level of each factor which is divided by three; **R**: range value, difference of the maximum of \( K \) and the minimum of \( K \) in one variable. The higher \( R \) value means the more significant effect of a factor on variables.

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**References**


