Exploration of Sugar Functionality in Sugar-Snap and Wire-Cut Cookie Baking: Implications for Potential Sucrose Replacement or Reduction

Meera Kweon, Louise Slade, Harry Levine, Ron Martin, and Edward Souza

ABSTRACT

The sugar series—xylose, glucose, fructose, and sucrose—can be used diagnostically to explore the effects of sugar type on differential scanning calorimetry (DSC), Rapid Visco-Analyser (RVA), and cookie baking performance because of the differences in glass-forming abilities (related to plasticization) and solubility parameters (related to solvent preference) of differential sugars. Sugar concentration (% S), total solvent (TS), and dough formulation defined a core experimental design for cookie baking with the four sugar types and two baking methods. Although wire-cut cookie baking (66% S and 64 TS) showed the same trends as sugar-snap cookie baking (73% S and 79 TS) for diameter, height, and moisture content, the wire-cut formulation enabled greater discrimination among the effects of different sugar types on dough and cookie responses. Use of two different crystal sizes of sucrose confirmed the dominant impact of both gluten development during dough mixing and starch pasting during cookie baking on collapse: the greater rate of dissolution of smaller sucrose crystals resulted in greater surface crack for sugar-snap cookies, and lower height for wire-cut cookies. Because the historical definition of an “excellent quality cookie flour” is based on the performance of a flour in a cookie formulated with sucrose, the effect of sugar type on cookie making is to transform the apparent baking performance of a flour. Whereas formulation with sucrose optimizes the flour performance for cookie baking, formulation with xylose exaggerates the worst aspects of cookie flour functionality and makes even the best cookie flour look like a “poor quality cookie flour”. Use of solvent retention capacity (SRC), DSC, RVA, and wire-cut cookie baking as predictive research tools demonstrated that identification of a flour with an optimized SRC pattern is the key to successful mitigation of the detrimental effects of sucrose replacement on cookie processing and product attributes.

Corresponding author. E-mail: kweon.11@osu.edu

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the kinetics of network development during mixing depend on both sugar type and initial crystal particle size.

Several publications have described sugar-snap cookie baking with various sugars (Curley and Hoseney 1984; Doescher and Hoseney 1985; Doescher et al. 1987a,b). But there are fewer reports on wire-cut cookie baking with various sugars, due to the more recent implementation of wire-cut cookie baking as an official Approved Method 10-53 (AACC International 2000), compared with the traditional official AACC Approved Method 10-50D for sugar-snap cookie baking. Abboud and Hoseney (1984) used analysis to show that only part of the sucrose in a sugar-snap formula dissolved during mixing, and the rest dissolved during baking. Doescher and Hoseney (1985) showed that substitution of a small portion of crystalline sucrose by crystalline glucose, fructose, maltose monohydrate, or high-fructose corn syrup changed baking behavior. Sugar-snap and wire-cut cookie formulas differ with respect to sugar concentration (% S) and total solvent (TS). The sugar-snap cookie formula contains 73% S and 79 TS; the wire-cut cookie formula contains 66% S and 64 TS.

Since both differences in crystal behavior (melting temperature, solubility, and particle size) and glass behavior (glass transition temperature and aqueous glass-forming ability) modulate the generic role of sugars, xylose (X), glucose (G), fructose (F), and sucrose (Su) were used as diagnostic sugars to explore the effects of sugar type on DSC, RVA, and two Approved Methods of cookie baking. The goal of these studies was to prepare for the replacement of sucrose by alternative sugars to produce cookies with lower glycemic impact and improved prebiotic nutritional benefits.

### MATERIALS AND METHODS

#### Materials

Croplan 594W wheat, a soft red winter cultivar, was tempered (to 14% moisture content) and milled with a Miag Mill to produce a straight-grade flour. This flour contained 13.3% water, 7.6% protein, and 0.396% ash (vs. 1.677% wheat ash). Xylose, fructose, glucose (monohydrate), and sucrose, all reagent grade, were used for SRC, DSC, RVA, and baking. A partially hydrogenated, all-vegetable shortening (Smuckers, Orville, OH) was used for baking with all sugars. For baking with sucrose, baker’s special sugar (ultra-fine, UF, from C&H) and fine-granulated (FG) sugar (Domino), representing two typical sucrose ingredients familiar to the biscuit-baking industry were used. All other chemicals were reagent grade.

#### SRC of Flour

SRC tests were conducted using Approved Method 56-11 (AACC International 2000) with four standard solvents: deionized water, 5% (w/w) lactic acid, 5% (w/w) sodium carbonate, and 50% (w/w) sucrose.

#### Image Analysis of Sugars

The particle size and morphology of each sugar were observed with an imaging system (Optem Zoom 160 Optical System, Avimo Precision Instruments, Fairport, NY).

#### DSC

The thermal behavior of the wheat flour starch in each sugar solution was measured by DSC (for details, see Slade and Levine [1987]). Equal weights of flour and 50% (w/w) predissolved sugar solution were mixed, ~40 mg of the mixture was transferred to a stainless steel DSC pan (Perkin-Elmer) and the pan sealed. Each sample was heated in the DSC instrument (DSC-7, Perkin-Elmer, Norwalk, CT) from 30 to 130°C, using a 10°C degree min⁻¹ heating rate. An empty pan was used as the reference. DSC was calibrated as described previously (Slade and Levine 1987).

#### RVA

The starch pasting behavior of the wheat flour in each sugar solution was measured by RVA (RVA-4, Newport Scientific Pty., Ltd., Warriewood, NSW, Australia), using the Standard 1 method. Flour (3.5 g, dry basis) was added to 25 mL of 50% (w/w) predissolved sugar solution in the sample canister and mixed thoroughly. Pasting temperatures were calculated with a software program (Thermocline for Windows).

#### Cookie Baking

AACC Approved Method 10-50D sugar-snap cookie baking and AACC Approved Method 10-53 wire-cut cookie baking were used for the experimental design (see Slade and Levine [1994] for...
many previously reported experimental details of sugar-snap and wire-cut cookie baking procedures). The ingredients and formula for the two methods, the standard ingredient weights (based on assumption of different flour water contents for the two methods), and the actual ingredient weights (based on the actual water content of the Croplan 594W flour) for each baking method, are shown in Table I A and B, respectively. To investigate the effect of sugar type on cookie baking, sucrose was replaced by each of the other sugars, and dough mixing and baking were conducted in duplicate. The anhydrous crystalline form was used for all sugars, except glucose. Glucose monohydrate was used, with proportional adjustment of added dough water (Table I A footnotes). Two different crystal sizes of sucrose (UF and FG, of standardized particle sizes) were used to investigate the effect of sugar particle size on baking.

Each of the duplicate doughs was divided into four 60-g portions and sheeted in a single pass to a height of 0.7 cm using a rolling pin. Before placing the baking sheet into the oven, weight of the baking sheet and the four (more or less) round cookie dough pieces was recorded. Dough weights were 102–114 g for four pieces. The cookies were baked for 11 min at 400°F. After baking, the baking sheet was removed from the oven and the weight of the baked cookies and baking sheet was recorded immediately. The difference in weights was used to calculate moisture loss as weight loss during baking. The baked cookies were cooled for 3 hr; height, width, and length (the latter two at perpendicular diameters) were measured. The final baked cookie width (dimension perpendicular to the direction of sheeting) reflects lateral flow of the cookie dough during baking. The final baked cookie length (dimension parallel to the direction of sheeting) reflects elastic recovery (“snap-back”) of the cookie dough during machining and baking. Thus, in contrast to conventional measurements of average cookie diameter, these more discerning measurements of cookie width/length—more common in industrial R&D (Slade and Levine 1994)—reveal important and practical information (the latter about issues of commercial product packaging) about any asymmetry in out-of-round cookies.

Separately, additional dough was prepared as described above, and time-lapse photographs were taken at 1-min intervals through a glass window in the oven door to record changes in cookie geometry during baking (Slade and Levine 1994). Only vertical expansion (height) and lateral flow (width) could be recorded as a result of the camera orientations, dough pieces, and baking sheet. As a reference for measuring dimensional changes, a 1-cm matte metal cube was placed on the baking sheet between two cookie dough pieces.

Dough Firmness Testing
A portion of each of the duplicate doughs was used to measure dough firmness with a TA instrument (TA.XT2i, Texture Technologies, Scarsdale, NY). A rolling pin was used in a single pass to compress ≈150 g of dough to make a flat surface with a height of 3.2 cm. Test mode measured maximum peak force in compression for three spots on the flat surface of the dough sample; test option was return to start; pretest speed was 2.0 mm/sec; test speed was 2.0 mm/sec; posttest speed was 5.0 mm/sec; probe was 0.5-in. ball; penetration distance was 15.0 mm. Dough firmness is reported as the average of the measurements of maximum peak force (g).

Statistical Analyses
Statistical analysis of dough firmness (data in Table II) and cookie geometry (data in Table III) was performed by Tukey-Kramer HSD multiple comparison of means, using JMP for Windows (v.7.0, SAS).

RESULTS AND DISCUSSION

Milling Performance and Flour Quality
The soft red wheat cultivar, Croplan 594W, exhibited excellent milling performance and produced a superior quality cookie flour. Its low kernel hardness enabled a 33% break flour yield, and the ease of separation of endosperm from bran resulted in a 74% milling yield (based on cleaned wheat). The pattern of SRC values in four solvents (47.8% water, 82.9% lactic acid, 64.5% sodium carbonate, and 83.4% sucrose) represents an excellent quality cookie flour (Kweon et al 2009) because it demonstrates that the

<table>
<thead>
<tr>
<th>Baking Method and Sugar Type</th>
<th>Dough Firmnessa (g force)</th>
<th>% Weight Loss During Bakingb (total dough weight basis)</th>
<th>% Water Retenccion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar snap</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sucrose UFd</td>
<td>203e</td>
<td>13.12</td>
<td>21.21</td>
</tr>
<tr>
<td>Sucrose FGd</td>
<td>195e</td>
<td>12.80</td>
<td>23.13</td>
</tr>
<tr>
<td>Fructose</td>
<td>98f</td>
<td>10.16</td>
<td>38.98</td>
</tr>
<tr>
<td>Glucose</td>
<td>653bf</td>
<td>9.17</td>
<td>44.93</td>
</tr>
<tr>
<td>Xylose</td>
<td>522cf</td>
<td>7.02</td>
<td>53.70</td>
</tr>
<tr>
<td>Wire cut</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sucrose UF</td>
<td>183ef</td>
<td>13.05</td>
<td>21.99</td>
</tr>
<tr>
<td>Sucrose FG</td>
<td>174ef</td>
<td>12.64</td>
<td>24.43</td>
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<td>Fructose</td>
<td>152ef</td>
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<td>35.40</td>
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<td>Glucose</td>
<td>818af</td>
<td>8.42</td>
<td>49.68</td>
</tr>
<tr>
<td>Xylose</td>
<td>368d</td>
<td>8.78</td>
<td>49.80</td>
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<table>
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<tr>
<th>Baking Method and Sugar Type</th>
<th>Cookie Geometrya (Width (cm) Length (cm) Height (cm))</th>
</tr>
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<tbody>
<tr>
<td>Sugar snap</td>
<td></td>
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<tr>
<td>Sucrose UF</td>
<td>8.48a</td>
</tr>
<tr>
<td>Sucrose FG</td>
<td>8.19b</td>
</tr>
<tr>
<td>Fructose</td>
<td>7.23d</td>
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<tr>
<td>Glucose</td>
<td>6.99ef</td>
</tr>
<tr>
<td>Xylose</td>
<td>6.65gh</td>
</tr>
<tr>
<td>Wire cut</td>
<td></td>
</tr>
<tr>
<td>Sucrose UF</td>
<td>8.34ab</td>
</tr>
<tr>
<td>Sucrose FG</td>
<td>7.95c</td>
</tr>
<tr>
<td>Fructose</td>
<td>7.14de</td>
</tr>
<tr>
<td>Glucose</td>
<td>6.82fg</td>
</tr>
<tr>
<td>Xylose</td>
<td>6.50h</td>
</tr>
</tbody>
</table>

a Dough firmness (average of six measurements, three measurements from each of the duplicate doughs). Mean values followed by the same letters in a column are not significantly different at P = 0.05, Tukey-Kramer test.
b Cookie weight loss during baking.
c Total water % in dough retained in the baked cookie.
d UF, ultra-fine, FG, fine-granulated.
e Dough was firm but not crumbly.
flour contains low levels of damaged starch and pentosans, so that machinable doughs can be formulated with a low water content. It also demonstrates the absence of excessive glutenin functionality, so that cookies with good symmetry and eating quality can be baked when the cookies are formulated with sucrose to retard glutenin development during mixing (Slade and Levine 1994).

**DSC**

DSC results for the flour in predissolved 50% w/w sugar solutions (flour-to-sugar-to-water 1:0.5:0.5) showed retardation of starch gelatinization compared with water in the order water < X < F < G < Su (Fig. 1). The gelatinization peak temperatures were 63.4°C in water, 76.6°C in X, 81.7°C in F, 84.3°C in G, and 92.0°C in Su. Kim and Walker (1992) reported similar values for gelatinization peak temperatures of wheat starch with crystalline sugars (starch-to-sugar-to-water 1:1.5:1.5): 62.0°C, 80.5°C, and 90.0°C for water, 50% glucose monohydrate, and 50% sucrose, respectively. But the thermogram for wheat starch with glucose monohydrate showed an anomalous peak at ≈45°C, which they explained as the melting of glucose monohydrate crystals. In contrast to sucrose, the solubility of glucose in water is lower than 50% w/w at room temperature, so glucose cannot dissolve completely when starch, crystalline sugar, and water are mixed for DSC sample preparation at room temperature, even when the crystal particle size is small. Similarly, Abboud and Hoseney (1984) showed an anomalous peak in the DSC thermogram for a cookie dough formulated with crystalline sucrose. As the dough was heated, sugar dissolution caused the appearance of a peak. In contrast, when a dough formulated with predissolved sucrose was heated, the peak was not observed. For our DSC experiments, we used predissolved 50% w/w sugar solutions to ensure that sugar dissolution was not convoluted with starch gelatinization during heating.

Slade and Levine (1991, 1994) explained that the retardation of starch gelatinization—resulting in gelatinization at a higher temperature, due to the elevation of the amylopectin glass transition temperature—by different sugars in solutions of the same concentration, is highly correlated with the dielectric rotational relaxation times of the sugar solutions. This correlation enables a direct comparison of the mobility of a sugar solution and its relative effectiveness as a plasticizer compared with water. The effect of an increasing concentration of a single sugar to depress the relative vapor pressure (rvp) of the solution and elevate the gelatinization temperature of starch has led to a hypothesis of the dependence of the gelatinization temperature on “water activity” (Spies and Hoseney 1982; Beliea et al. 1996). But this hypothesis has been called into question (Slade and Levine 1991) because a simple examination across several sugars in solutions with the same rvp values reveals that each sugar elevates the gelatinization temperature to a different extent, with no dependence on rvp (Spies and Hoseney 1982; Slade and Levine 1987). An additional factor of sugar interactions with the starch granule was invoked to explain the apparent dependence of the gelatinization temperature on the molecular size of the sugar (Spies and Hoseney 1982). But this factor has also been called into question (Slade and Levine 1991) because, in fact, both the extent of depression of rvp and the extent of elevation of the gelatinization temperature depend on the material-specific $T_g$ for each sugar (Slade and Levine 1987, 1991).

Abboud and Hoseney (1984) reported DSC thermal properties for a cookie dough formulated with sucrose and the corresponding baked cookies, and showed that there was no significant difference in the heat of transition of starch gelatinization between the raw cookie dough and the baked cookies. Doescher et al (1987a) also reported that the extent of starch gelatinization in baked cookies formulated with sucrose was not different from that in the unbaked doughs, but cookies formulated with glucose or fructose showed partial starch gelatinization.

**RVA**

RVA results for the flour in predissolved 50% w/w sugar solutions (flour-to-sugar solution 7:60.45–61.65) showed retardation onset of starch pasting compared with that in water, in the order of water < X < F < G < Su (Fig. 2), the same order as observed by DSC for the retardation of starch gelatinization (Fig. 1) because both events reflect first-stage swelling of amylpectin. The pasting temperatures, calculated by the RVA software and as defined by Batey (2007), were 69.8°C in water, 79.0°C in X, 83.1°C in F, 86.0°C in G, and 90.8°C in Su. The pasting temperatures occurred in the same order but in a higher temperature range compared with the DSC gelatinization peak temperatures because the large increase in pasting viscosity reflects second-stage swelling and leaching of amylose. We observed that the delay in pasting after first-stage swelling became progressively shorter as the first-stage swelling occurred at progressively higher temperatures. When the end of first-stage swelling (DSC peak temperature (Slade and Levine 1991)) occurred at a sufficiently high temperature, second-stage swelling (RVA pasting temperature) began even before first-stage swelling was completed, as observed for Su. The RVA peak (maximum hot-paste viscosity) represents two overlapping processes: the initial increase in viscosity due to second-stage granule swelling and network formation by leached amylose, followed by a decrease in viscosity due to shearing and disruption of the amy-

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**Fig. 1.** DSC thermograms for flour in water or predissolved sugar solutions. Flour-to-water 50:50 w/w (50:50 w/v); flour-to-sugar solution 50:50 w/w (50:40.55–41.36 w/v).

**Fig. 2.** RVA for flour in water or predissolved sugar solutions. Flour-to-water 7:50 w/w (7.50 w/v); flour-to-sugar solution 7:60.45–61.65 w/w (7:50 w/v).
lose network and excessively swollen granules. When viscosity development is sufficiently retarded in the first process, there is insufficient time for the subsequent disruption process before cooling and setback. The viscosity-time profiles of flour slurries in water and xylose were similar, in that the breakdown process was prominent, due to the extended time for high-temperature shearing after early initial development of maximum hot-paste viscosity. In contrast, the profiles for fructose, glucose, and sucrose were similar, in that the breakdown process was negligible, due to insufficient time before cooling and setback.

**Cookie Baking**

The effects of sugar type and method type on water retention in baked cookies were calculated from cookie weight loss during baking (Table II). The effect of sugar type on water retention increased in the order SuUF < SuFG < F < G < X. This rank order reflects the effect of sugar type on the extent of gluten and pasted starch network development. Formulation with sucrose results in the greatest retardation of both gluten development during mixing and starch gelatinization/pasting during baking (Slade and Levine 1994), whereas formulation with xylose allows the greatest development of water-holding gluten and pasted starch networks. DSC and RVA profiles (Figs. 1 and 2) confirm this description of the effect of sugar type on starch gelatinization/pasting. The effect of method type on water retention was more complex. Gluten network development during mixing is greater for wire-cut cookie doughs than for sugar-snap cookie doughs due to the much lower % S of the wire-cut formulation, and fluid flow is lower for wire-cut doughs due to the much smaller TS of the wire-cut formulation (Slade and Levine 1994). Both effects contribute to firmer wire-cut doughs than sugar-snap doughs for a single sugar type. In contrast to this typical behavior, the wire-cut dough made with xylose was dramatically softer than the corresponding sugar-snap dough. The softer wire-cut dough enabled greater expansion and consequent lower density during baking—as seen clearly for xylose—which evidently facilitated evaporation sufficiently to result in an anomalously low value for water retention by the baked wire-cut cookie formulated with xylose, compared with the corresponding sugar-snap cookie.

As presented in Table II, doughs made with sucrose UF and FG for either method are soft and consequently easy to sheet and cut. The sugar-snap dough made with glucose monohydrate was very firm and crumbly, whereas the corresponding wire-cut dough was even firmer but not crumbly. The water solubilities of glucose monohydrate (51 wt% at 25°C) and xylose (56 wt% at 25°C) are much lower than the calculated ultimate % S values for either baking method (Table IB). As a result, both types of dough are firmer for both glucose monohydrate and xylose because the actual instantaneous TS values during mixing are much smaller than the ultimate calculated values for both methods. In addition, the content of undissolved glucose monohydrate is so much greater in the sugar-snap dough that it results in the observed crumby texture. Doughs made with fructose by either method were very soft and sticky. The water solubility of fructose (80.0 wt% at 25°C) is much higher than the calculated % S values for either baking method (Table IB). As a result, both types of dough are soft and sticky because the actual instantaneous TS values are so high during mixing. Curley and Hoseney (1984) showed that the softness and stickiness of sugar-snap cookie doughs depended on the extent of dissolution of sucrose; a dough with 0% dissolved sucrose was firm and manageable, whereas a dough with 100% dissolved sucrose was very sticky and unmanageable. When crystalline sucrose was replaced by high-fructose corn syrup in sugar-snap cookies, softer and stickier doughs resulted. They suggested that the volume of total solution in a cookie dough system directly influenced its degree of softness and stickiness. On the other hand, even when the extent of dissolution is the same, resulting in the same actual instantaneous values of TS during mixing within each method type, variations in firmness and adhesiveness can be observed. Slade and Levine (1988) reported that xylose contributes anomalous rigidity because it has a $T_m/T_g$ ratio of 1.51, the highest known ratio of crystalline melting temperature to glass transition temperature for simple sugars. In contrast, fructose contributes anomalous fluidity because it has a $T_m/T_g$ ratio of 1.06, the lowest known for simple sugars. In comparison, the rheology of concentrated aqueous glucose and sucrose solutions is not anomalous because these sugars have $T_m/T_g$ ratios of 1.42 and 1.43, respectively, typical of those for many small sugars.

![Fig. 3. Sugar morphology and particle size observed under a 400× microscope for five crystalline sugars used for experimental baking. Dimension scale is the same for all images.](image)
In contrast to the thermodynamic extent of water solubility for each sugar type, the rate of dissolution also depends on crystal particle size. Therefore, predissolved sugars were used for DSC and RVA experiments. However, crystalline sugars were used for all baking experiments. The crystal particle sizes for fructose, glucose monohydrate, and xylose were roughly similar (Fig. 3). In contrast, the particle sizes for sucrose FG and UF were clearly different and represented the overall extremes: largest, sucrose FG; generally smallest, sucrose UF. In the case of such an extreme difference in particle size (as for sucrose), larger particles show delayed sugar dissolution during mixing, and even during baking, which enables more gluten development and starch gelatinization/pasting and consequently results in smaller cookie diameter relative to smaller particle sugars. In our baking experiments, even such an extreme difference in sucrose particle size was modulated by method type and stage of baking. No effects of sucrose particle size were observed on vertical expansion during baking or final cookie height for either method (Fig. 4 and Table III). In contrast, a large effect of sucrose particle size was observed on initial lateral expansion for the wire-cut method but not for the sugar-snap method. For both methods, a large effect of sucrose particle size was observed for final cookie width.

Cookie-baking results for the two methods are shown in Table III and Figs. 4, 5, and 6. The qualitative effect of sugar type on cookie width, length, and height was the same for both sugar-snap and wire-cut cookies. Width and length increased in the order X < G < F < SuFG < SuUF. In contrast, cookie height increased in the reverse order SuUF < SuFG < F < G < X.

The top- and side-view photos of the cookies are presented in Fig. 4. Of the sugar-snap cookies (Fig. 4A and C, and Tables II and III), the xylose cookie showed the most striking effect of sugar type on cookie geometry. The exaggerated out-of-round shape (cookie length << width) is diagnostic of gluten development during mixing and snap-back after sheeting of the dough. Although xylose is a reducing sugar, the dough had the least moisture loss during baking, which inhibited Maillard color development and resulted in the highest cookie moisture content (Table II). In contrast, fructose and glucose cookies were darker and browner because both those doughs showed higher moisture loss during baking than did the xylose dough. Sucrose cookies showed the greatest spread and the greatest collapse during baking (Fig. 5), resulting in the smallest height. Due to more rapid dissolution of the sugar during mixing and greater collapse of the cookies during baking, sucrose UF cookies developed greater surface crack than did sucrose FG cookies. In comparison, the effect of method type was observed for the wire-cut cookies (Fig. 4B and D, and Tables II and III). The effect of xylose on cookie geometry was qualitatively the same as for the sugar-snap method but the lower sugar concentration of the wire-cut dough enabled greater gluten development during mixing, resulting in greater height of the wire-cut xylose cookies than the corresponding sugar-snap cookies. The effect of method type was even greater for cookies formulated with glucose. In contrast to the sugar-snap cookies, wire-cut glucose cookies showed greater snap-back, resulting in an out-of-round shape, and greater height.

Time-lapse photography was used to record effects of method type and sugar type on changes in cookie geometry during baking. The extreme effect of sugar type, represented by sucrose FG and xylose, is illustrated in the photographs in Fig. 5, and the data analyses of cookie dimensions measured from time-lapse photographs of all the different sugar cookies are presented in Fig. 6. For sugar-snap cookies, the baking time at which the maximum lateral expansion occurred was in the order F < SuUF ≈ SuFG < G ≈ X, but the ultimate extent of lateral expansion (i.e., final cookie width after 3 hr of cooling following baking) was in the order X < G ≈ F < SuFG < SuUF. The effect of sugar type on lateral expansion was qualitatively the same for the wire-cut cookie method; baking time at maximum lateral expansion was in the order F ≈ SuUF < SuFG < X < G; ultimate extent of lateral expansion was in the order X < G < F < SuFG < SuUF. For sugar-snap cookies, the baking time at which the maximum vertical expansion occurred was in the order SuUF ≈ SuFG < F < G < X. This same order was observed for the ultimate extent of vertical expansion (i.e., final cookie height after 3 hr of cooling following baking), which is exactly the reverse of the order for the ultimate extent of lateral expansion. The effect of sugar type on vertical expansion was qualitatively the same for the wire-cut cookie method; baking time at maximum vertical expansion was in the

![Sugar-snap](image1.png) ![Wire-cut](image2.png)

**Fig. 4.** Top and side views of sugar-snap (A and C) and wire-cut cookies (B and D). Top view: upper row left, sucrose UF; right, sucrose FG; bottom row left, fructose; middle, glucose H2O; right, xylose. Side view: from left, sucrose UF, sucrose FG, fructose, glucose, xylose.
order $\text{SuUF} \approx \text{SuFG} < F < G < X$; ultimate extent of vertical expansion was in the order $\text{SuUF} \approx \text{SuFG} < F < G < X$.

The effect of sugar type on the cookie processing and product quality predominated over the effect of method type for sucrose, xylose, and fructose. Of the four sugar types, sucrose cookies showed the greatest maximum and ultimate extents of lateral expansion and the smallest height for both baking methods. Formulation with sucrose optimizes flour functionality for cookie baking (by way of least gluten development during mixing and least starch gelatinization/pasting during baking) (Figs. 1 and 2) which accounts for the historical definition of an “excellent quality cookie flour”. The diagnostics for a cookie dough made with an excellent quality cookie flour comprise facilitated expansion by film formation (with no significant functional network formation and consequently no network $T_g$), followed by structural collapse in a rubbery, predominantly thermoplastic polymer system above its molecular $T_g$ (Levine and Slade 1990). Sucrose UF in cookies resulted in greater lateral expansion, collapse, and surface crack than did sucrose FG due to more rapid dissolution of its smaller sized particles. Of the four sugar types, xylose cookies showed the least maximum and ultimate extents of lateral expansion but the greatest asymmetry due to snap-back. Xylose cookies exhibited the greatest maximum and ultimate extents of vertical expansion with the least collapse during baking, resulting in a cake-like cookie shape. In addition, for sugar-snap cookies, xylose retarded the time at which the maximum vertical expansion occurred (9 min) more than for any other sugar type. Of the four diagnostic sugars, xylose has the lowest $T_g$ (Slade and Levine 1991), resulting in the greatest extent of gluten development during mixing and starch gelatinization/pasting during baking (Figs. 1 and 2), and the greatest swelling of pentosans due to its significantly greater solvent compatibility with the xylan backbone (sucrose SRC 83.4%; xylose SRC 90.9%). As a result, formulation with xylose exaggerates the worst aspects of cookie flour functionality, which makes even the best cookie flour look like a “poor quality cookie flour”. The diagnostics for a cookie dough made with a poor quality cookie flour comprise shrinkage (elastic recovery) of a self-supporting rubbery network above its thermoset network $T_g$ (Levine and Slade 1990). The effect of sugar type on baking performance and cookie geometry for fructose predominated over method type because the water solubility of fructose (80.0 wt% at 25°C) is much higher than the calculated % S values for either baking method (Table IB). For all four sugars, the effect of method type was to decrease wire-cut cookie width and length but increase wire-cut cookie height. But especially for glucose, the effect of method type was predominant. The diameter of sugar-snap cookies was similar for glucose and fructose, whereas the wire-cut method differentiated between glucose and fructose: wire-cut glucose cookies showed smaller lateral expansion and cookie diameter than did wire-cut fructose cookies. Wire-cut glucose cookies showed the greatest retardation of maximum vertical expansion followed by elastic recovery, whereas sugar-snap glucose cookies showed collapse. Overall, the wire-cut baking method provided a better resolution of the effects of sugar type and particle size, resulting in an improved predictive correlation between the SRC pattern of a flour and its cookie-making performance.

Because the historical definition of an “excellent quality cookie flour” is based on the performance of a flour in a formulation with sucrose, the effect of alternative sugar type on cookie making is to transform the apparent baking performance of a flour, such that an excellent flour can appear to be a poor quality flour. When sucrose is replaced by an alternative sweetener, it is necessary to mitigate the detrimental effects sufficiently to produce cookies with the same desired product attributes as cookies formulated with sucrose. When an alternative sugar facilitates gluten development during mixing, the concomitant effect is excessive starch gelatinization/pasting during baking, but mitigation of these detrimental effects requires independent approaches. Excessive gluten development resulting in snap-back and greater cookie height and moisture retention can be mitigated by use of ice-cold water, smaller particle size, or predissolved sucrose al-

![Fig. 5. Time-lapse photography of sugar-snap and wire-cut cookies during baking for 11 min at 400°F. A and C, sucrose FG; B and D, xylose.](image-url)
ternative, and a flour with a lower lactic acid SRC value, all in order to minimize glutenin network formation. Excessive starch gelatinization due to formulation with a sucrose alternative with a lower $T_g$ can be mitigated by addition of a carbohydrate with higher molecular weight such as a maltodextrin or polydextrose (Slade and Levine 1991). Excessive starch pasting can be mitigated by decreasing the water level in the formula, either by selecting a flour with a lower sodium carbonate SRC value to decrease the contribution of damaged starch, or with a lower sucrose SRC value to decrease the contribution of solvent-accessible pentosans, particularly in the case of sugar alternatives (e.g., xylose) that are more compatible with the xylan backbone of pentosans and thereby exaggerate their detrimental contributions to cookie making. After identification of an optimum flour for use with a particular sucrose alternative, dimensional changes during baking and final cookie geometry can both be controlled by adjustment of leavening system. Because the typical effect of sucrose replacement is increased cookie height, the most effective mitigation by a leavening ingredient is through an increased level of ammonium bicarbonate to decrease cookie height (by facilitating collapse) with no effect on cookie pH.

**CONCLUSIONS**

A core experimental design for cookie-baking with four diagnostic sugars and two cookie-baking methods demonstrated that the effect of sugar type on cookie-making is to transform the apparent baking performance of a flour, such that an excellent cookie flour can appear to be a poor quality flour. As diagnostic sugars, xylose, glucose, fructose, and sucrose were used to explore the effects of sugar type on DSC, RVA, and cookie baking. DSC and RVA of flour in 50% sugar solutions showed retardation of starch gelatinization and retardation of the onset of starch pasting, respectively, compared with that for flour in water alone in the order of water $<$ X $<$ F $<$ G $<$ Su. Sugar concentration, total solvent, and baking method defined the core experimental design for baking with the four sugars. Sugar-snap cookie baking (73% S and 79 TS) gave diameters in the order Su $>$ F $>$ G $>$ X but the reverse order for height and moisture content. Excessive snapback was only observed for X (lowest $T_g$). Although wire-cut cookie baking (66% S and 64 TS) gave the same trends as sugar-snap cookie baking for diameter, height, and moisture content, the ranges of values for wire-cut cookie height and moisture content were expanded, providing better resolution of the effects of sugar type. In addition, significant snap-back was observed with G, as well as X. The goal of these studies was to prepare for the replacement (full or partial) of sucrose by alternative sugars to produce cookies with lower glycemic impact and improved prebiotic nutritional benefits. Use of SRC, DSC, RVA, and wire-cut cookie baking as predictive research tools demonstrated that identification of a flour with an optimized SRC pattern is the key to successful mitigation of the detrimental effects of sucrose replacement on cookie processing and product attributes. A follow-up cookie-baking study, using various alternatives with lower glycemic impact to replace sucrose will be conducted to explore the requirements for commercial production of cookies with lower glycemic impact and improved prebiotic nutritional benefits.

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