



## Smoked Sugar Improves Flavor Stability of Frozen Sliced Food Service Bacon<sup>1,2</sup>

Allison Hobson<sup>3</sup>, John M. Gonzalez<sup>4</sup>, Travis O'Quinn<sup>3</sup>, Elizabeth A. Boyle<sup>3</sup>, J. Scott Smith<sup>3</sup>, Faris A. Karim<sup>3</sup>, Christopher I. Vahl<sup>5</sup>, Robert Johnson<sup>6</sup>, and Terry A. Houser<sup>3\*</sup>

<sup>3</sup>Department of Animal Sciences and Industry, Kansas State University, Manhattan, KS 66506, USA

<sup>4</sup>Department of Animal and Dairy Science, University of Georgia, Athens, GA 30602, USA

<sup>5</sup>Department of Statistics, Kansas State University, Manhattan, KS 66506, USA

<sup>6</sup>Red Arrow Products, Manitowoc, WI 54220, USA

\*Corresponding author: Email: houser@ksu.edu (T.A. Houser)

**Abstract:** Aerobically packaged frozen bacon has significant challenges to flavor and odor properties as storage length advances. Naturally smoked sugar (NSS), a food ingredient made from applying hardwood smoke to liquid sugar, may possess antioxidant functionality that is beneficial in controlling lipid oxidation in bacon. Therefore, the objective of this study was to determine if NSS could be added directly to a bacon formulation to limit the rate of lipid oxidation in frozen, aerobically packaged bacon. Three replications of this experiment were conducted using 5 pork bellies per replication. Individual bellies were cut in half yielding an anterior and posterior section and then randomly assigned to a treatment combination with either the anterior or posterior section receiving the NSS treatment. Treatment brines consisted of a control (CON) brine or a brine with added NSS injected to retain 12% added solution. After injection, smoking, cooking, and slicing, bacon slices were frozen ( $-17.8 \pm 2^\circ\text{C}$ ) and stored aerobically for 0, 40, 80, and 120 d for sensory and gas chromatography mass spectrometry (GCMS) analyses or 0, 20, 40, 60, 80, 100, and 120 d for thiobarbituric acid reactive substances (TBARS) analysis. There were significant ( $P < 0.01$ ) Treatment  $\times$  Day interactions for oxidized flavor intensity, TBARS, and hexanal concentration. Panelist oxidized flavor intensity scores, TBARS values, and hexanal content increased from d 0 to 120 ( $P < 0.01$ ) for CON, whereas these measures in bacon manufactured with added NSS did not change ( $P > 0.16$ ). Sensory ratings for saltiness, smoke intensity, and bacon flavor intensity were higher ( $P < 0.01$ ) for the NSS treatment compared to CON. The ability of NSS to function as an effective antioxidant in frozen bacon was confirmed by the inhibition of lipid oxidation products and improved sensory panel scores over time.

**Keywords:** bacon, oxidation, pork, sensory, smoked sugar

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## Introduction

Aerobically packaged, “layout” style bacon is a popular means of merchandising sliced bacon to food-service establishments due to its ease of use, limited

slice adhesion, and relatively low packaging costs compared with vacuum or modified atmosphere packaging formats. However, length of frozen storage period can increase rates of lipid oxidation in aerobically packaged bacon products. Lowe et al. (2014) demonstrated increased trained sensory panel off-flavors and odor scores for frozen aerobically packaged bacon manufactured from fresh bellies as storage time advanced from 0 to 90 d. This increase in off-flavors has been attributed to increased lipid oxidation products as Lowell et al. (2017) reported increased thiobarbituric reactive substances

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(TBARS) concentrations for frozen foodservice layout style bacon that had been stored frozen for 90 d. Lowe et al. (2014) also showed increased TBARS values as storage time increased from 0 to 90 d for frozen food service bacon manufactured from bellies previously frozen for 2 to 7 mo. These studies confirm that frozen, aerobically packaged bacon can be susceptible to development of off-flavors due to lipid oxidation because of advancing storage time.

The application of hardwood smoke by burning wood chips or sawdust is a common practice in US bacon manufacturing. Although the traditional smoking process has served as a simple way to add more complex flavors to meat, hardwood smoke has also served as source of natural antioxidant activity (Rozum, 2009). However, applying traditional hardwood smoke to the surface of the pork belly limits the penetration depth of naturally occurring antioxidants of the smoke to the surface. Liquid smoke, produced by burning hardwood sources, has been reported to contain multiple phenolic compounds, such as syringol, that possess antioxidant activity (Montazeri et al., 2013). Unlike traditional smoke, liquid smoke and smoked ingredients such as naturally hardwood smoked sugar (NSS), a product of applying natural hardwood smoke to liquefied sugar, can be added directly to a curing brine. It is hypothesized that by moving the functional phenolic antioxidants found in hardwood smoke to the interior portions of the bacon slice through the addition of NSS to a curing brine that a desirable antioxidant effect might be achieved. Therefore, the objective of this study was to determine the effectiveness of adding NSS to a curing brine to prevent lipid oxidation in frozen, sliced, aerobically packaged foodservice bacon.

## Materials and Methods

Approval from the Kansas State University (KSU) Animal Care and Use Committee was not needed for this project because the raw pork bellies were sourced from a commercial pork harvest facility. The KSU Institutional Review Board (IRB #7440.5, Sept. 2018) approved all research components utilizing human subjects in sensory evaluation.

### *Belly selection*

Twenty-four hours postmortem, fresh pork bellies (IMPS #409) were collected at a commercial processing facility and transported under refrigerated conditions ( $3 \pm 1^\circ\text{C}$ ) to the KSU Meat Laboratory (Manhattan,

KS). Bellies were stored for 3 d at  $2 \pm 1^\circ\text{C}$  before processing. Immediately prior to processing, 5 bellies for each replication were trimmed and cut in half yielding an anterior and posterior belly section weighing approximately 2.8 kg each. Each belly was randomly assigned to a control curing brine (CON) and a curing brine with added naturally hardwood smoked sugar (NSS; RA12032; Red Arrow Products, Manitowoc, WI) to either the anterior or posterior sections so that both treatments were represented in each belly. Bellies were cut in half so that both the control and treatment brines could be applied within the same belly with the objective to decrease experimental variation due to potential differences in raw belly characteristics.

### *Bacon processing*

The CON and NSS brines were formulated for a 12% final brine retention rate. The CON curing brine consisted of 76.4% water, 11.8% salt, 8.00% sugar, 1.70% sodium phosphate (Brifisol 450 Super, ICL Performance Products, St. Louis, MO), 1.60% modern cure (6.25% nitrite, Excalibur, Pekin, IL), and 0.450% sodium erythorbate (0700139-V, Excalibur). The NSS brine contained 72.4% water, 11.8% salt, 7.00% sugar, 1.70% sodium phosphate (Brifisol 450 Super, ICL Performance Products), 1.60% modern cure (6.25% nitrite, Excalibur), 0.450% sodium erythorbate (0700139-V, Excalibur), and 5.00% smoked sugar (RA12032, Red Arrow Products).

Initial belly weights were collected immediately prior to injection for each belly half. Next, the half belly was placed in a multineedle injector (Model N30; Wolftec Inc., Werther, Germany), and injected to approximately 16% of initial weight to yield 12% retained brine after equilibration. Initial brine injection percentage was calculated immediately following injection by subtracting the initial weight from the injected weight then dividing by initial weight multiplied by 100. All injected bellies were hung on a smokehouse truck for 2 h to equilibrate prior to thermal processing. After equilibration, weights were collected and bellies were placed onto a single truck smokehouse (D7752; Maurer Inc., Reichenau, Germany) for thermal processing (smoking/cooking). Retained brine percentage was calculated subtracting the initial weight from the weight after equilibration divided by the initial weight multiplied by 100. A standard thermal processing schedule was utilized and included 4 stages (stage 1 =  $57^\circ\text{C}$  dry bulb and  $30^\circ\text{C}$  wet bulb for 30 min; stage 2 =  $54^\circ\text{C}$  dry bulb,  $44^\circ\text{C}$  wet bulb, and natural smoke applied for 30 min; stage 3 =  $54^\circ\text{C}$  dry bulb and  $35^\circ\text{C}$  wet bulb for 150 min; and stage 4 =  $57^\circ\text{C}$

dry bulb and 30°C for wet bulb for 130 min to reach an internal belly temperature of at least 54°C). Cooked bellies were placed into a chiller (2 ± 1°C) for 12 hr and then sliced with a horizontal slicer (Model Puma 700 F; Treif, Oberlahr, Germany) from the anterior to posterior end yielding 1.5 mm thick bacon slices. Product yield was calculated by dividing the chilled bacon weight prior to slicing by the initial weight of the belly prior to injection multiplied by 100 (USDA, 1995).

Immediately after slicing, 6 slices were selected randomly throughout each half belly to form a composite sample for proximate and fatty acid analyses for each half belly. The remaining slices were laid out randomly on non-coated bacon sheet paper (28 × 43 cm; Formax, Mokena, IL) at a count of 8 slices per sheet and a total of 11 sheets per half belly. Each sheet of bacon was then randomly assigned to 1 of 4 storage times (0, 40, 80, or 120 d) for sensory and gas chromatography mass spectrometry (GCMS) analyses or 7 storage times (0, 20, 40, 60, 80, 100, or 120 d) for TBARS. All d 0 bacon slices were collected the day of slicing, vacuumed packaged, and stored in -80°C freezer to prevent further lipid oxidation. The remaining sheets were stacked by storage day and placed in a clear, 3-mm thick poly-liner bag (Cargill, Wichita, KS) and a corrugated cardboard box with a fitted lid (43.8 × 28.6 × 10.2 cm, Uline, Pleasant Prairie, WI). All boxed slices were stored aerobically at a temperature of -17.8 ± 2°C for the assigned storage time. The experiment was replicated 3 times, with all replications being manufactured and cooked separately from one another.

### ***Fat, moisture, and protein analysis***

Composite samples of bacon slices were cut into small pieces, frozen in liquid nitrogen, pulverized in a blender (Model 33B179; Waring Products, New Hartford, CT), and stored at -80°C. Proximate samples were collected from the pulverized composite samples. Fat and moisture percentages were analyzed with a CEM Smart System 5 (Model 907875 CEM, Matthews, NC) using the AOAC International (AOAC) PVM-1 (AOAC, 2003) method. Additionally, protein composition was determined by utilizing a LECO protein analyzer (Model 630-300-800, LECO Corporation, St. Joseph, MO) according to the AOAC 992.15 method (AOAC, 1994). Fat, moisture, and protein values were presented as a percent of total composition.

### ***Fatty acid analysis***

Fatty acid analysis was performed with some modifications from Sukhija and Palmquist (1988). One gram

of pulverized composite bacon sample was weighed into screw-cap tubes with Teflon-lined caps. Samples were mixed with methanolic-HCL and an internal standard, flushed with nitrogen and capped tightly, and heated in a water bath for 120 min at 70°C. After heating, benzene and K<sub>2</sub>CO<sub>3</sub> were added, samples were centrifuged for 5 min at 1,000 × g, and the top solvent layer was removed and placed into a glass vial sealed with a Teflon-lined cap. Fatty acid composition was analyzed using a Shimadzu Gas Chromatograph (model GC-17A, Shimadzu Scientific Instruments Inc. Columbia, MD). Fatty acid separation was achieved using a Supelco fused silica capillary column (Model SP-2560, 100 m × 0.25 mm × 0.2 μm film thickness, Supelco Inc. Bellefonte, PA) with hydrogen as the carrier gas. An initial oven temperature of 80°C for 1 min was followed by an increase of 14°C per min until 240°C was reached and held for 3 min. A Supelco 37 external standard (47885-U Supelco, Supelco Inc.) was used to identify individual fatty acids based on retention time. Fatty acid composition percentages are reported as a percentage of total fatty acids. Iodine value (IV) was determined by the following equation: C16:1(0.95) + C18:1(0.86) + C18:2(1.732) + C18:3 (2.616) + C20:1 (0.785) + C22:1(0.723), (AOCS, 1998).

### ***Sensory evaluation***

Attributes and reference sample were chosen with guidance from Gatlin et al. (2006), in addition to a descriptive panel performed by the Kansas State University Meat Science Group before training sessions. Panelists participated in 8 panel training sessions to familiarize themselves with scale anchors and reference samples. Panelists evaluated bacon samples on a continuous 100-point line scale. Zero denoted a sample that was extremely not salty, not smoky, and bland, along with no oxidized or other off-flavors, whereas a 100 on the continuous line scale denoted a sample to be extremely salty, smoky, along with intense bacon flavor, oxidized flavor, and other off-flavors. Final scale anchors consisted of the following solutions: 0.5% salt in deionized water indicated a 60 on the saltiness scale and 0.125% smoked sugar dissolved in deionized water exhibited an 80 on the smoke intensity scale. Aerobically packaged bacon stored for 2 yr at -29°C was utilized as an oxidized flavor anchor of 100.

In order to reduce the variation of panelists scores, a reference bacon brand was chosen during the descriptive panel, similar to Gatlin et al. (2006). A commonly available commercial brand of bacon was used as the reference sample due to the inclusion of liquid

smoke as an ingredient and similarities to the research bacon. The reference bacon had the following sensory values: saltiness (40 to 50), smoke intensity (30 to 40), bacon flavor intensity (40 to 55), and no oxidized or other off-flavors detected.

After samples reached their target storage time, they were collected and stored at  $-80^{\circ}\text{C}$  for an average of 2.5 mo (range 1 to 4 mo) prior to sensory analysis. After all samples were collected and stored, bacon samples from the same belly were randomly assigned to a single trained sensory panel testing session. This random sample assignment allowed for CON and NSS to be evaluated in 1 panel. Sensory samples were placed on wire cooking racks in a Blodgett dual-flow, forced-air oven (DFD-201, G.S. Blodgett Co., Inc., Burlington, VT) set to cook at  $176.7^{\circ}\text{C}$  for 6 min, while pans were rotated  $180^{\circ}$  halfway through the cooking process. After cooking, slices were blotted with paper towels to remove excess grease as described by Lowe et al. (2014).

At least 8 panelists were used for each panel. Panelists were stationed in individual booths under a combination of red and green light. Apples, crackers, and water were provided to cleanse the palates between samples (Olson et al., 1985). Salt (0.5%) and smoke (0.125%) solutions were offered to panelists before warm-up samples for reference. The reference bacon was provided as a warm-up sample prior to every sensory panel. After the warm-up sample, samples from the same belly (CON and NSS) at all frozen storage times were evaluated in random order by the trained panelists.

### ***Thiobarbituric acid reactive substances analysis***

Lipid oxidation was determined by a distillation method of TBARS as described by Sebranek et al. (2001) utilizing a pulverized composite sample made up of an entire sheet of bacon (8 slices) from 1 belly and treatment combination. Ten grams of pulverized sample was mixed with deionized water, sulfanilamide (0.5% sulfanilamide, 20% HCl, and deionized water), HCl (50% HCl and deionized water), and antifoam in a round bottom flask. The sample mixture was heated to boil and condensation from the boiling mixture was collected and cooled through a glass condenser, until 50 mL of distillate was collected. Five milliliters of distillate were combined with 5 mL of thiobarbituric acid (TBA; 0.28% and deionized water) in a 15-mL plastic tube and capped tightly; this step was repeated twice to create duplicate samples. Tubes were placed in a boiling water ( $100^{\circ}\text{C}$ ) bath for 35 min, then transferred to a cold water ( $20^{\circ}\text{C}$ ) bath for 10 min. Once cooled, the mixture was transferred

into a spectrophotometer cuvette and absorbance was measured (Eon, BioTek Instruments, Winooski, VT) at 532 nm. Samples were blanked to a cuvette containing 1 mL deionized water and 1 mL TBA reagent. Thiobarbituric acid reactive substances were expressed as mg of malonaldehyde per kg of sample.

### ***Volatile analysis***

Volatiles were analyzed using GCMS and solid phase microextraction (SPME) according to Yu et al. (2008). The gas chromatograph used was 5890 Series II Plus (Agilent Technologies, Santa Clara, CA,) connected to 5972 Series mass spectrometer (Agilent Technologies). The injector was fitted with a split/split-less injection port containing a 0.75 mm I.D. ultra-high inert liner. Chemstation software (G1701BA Version B.01.00) was used for data acquisition, volatiles were separated on HP-5ms column (5% phenyl-methylpolysiloxane;  $60\text{ m} \times 2.5\text{ mm} \times 2.5\text{ }\mu\text{m}$ , Agilent Technologies). The SPME fiber (75 $\mu\text{m}$  thickness, fused silica, CAR/PDMS; Supelco) was placed in a manual SPME holder and utilized for headspace extraction. Prior to sample injection the SPME fiber was subjected to  $300^{\circ}\text{C}$  for 30 min in the GCMS port for preconditioning. The SPME fiber was cleaned between each injection by placing the SPME fiber in the GC injection port for 5 min.

Three grams of pulverized bacon were mixed with 2 mL of water and 1 ppm of 2-Chlorophenol as the internal standard (MilliporeSigma, St. Louis, MO.) and placed into a 20-mL vial and capped tightly with Teflon silica septum (VWR International, LLC; Radnor, PA). Closed vials were vortexed for 1 min and then transferred to a heating block for 15 min at  $60^{\circ}\text{C}$  to equilibrate. The SPME fiber was exposed to the head-space of the sample for 30 min at  $60^{\circ}\text{C}$  (Ruiz et al., 1998). Samples were injected in split-less mode with the injector temperature set to  $250^{\circ}\text{C}$  and purge-off time set to 1 min. Oven temperatures were set to the following:  $40^{\circ}\text{C}$  held for 1 min, ramped to  $185^{\circ}\text{C}$  at  $10^{\circ}\text{C min}^{-1}$  then held for 2.5 min. The total run time was 18 min. The carrier gas was ultra-high purity helium with a constant flow rate of 1 mL/min.

The selected ion monitoring (SIM) function of the mass detector was utilized to select individual ions that are specific to each analyte. The MS system was routinely calibrated using the auto-tune calibration function of the mass selective detector. The aldehydes selected to determine lipid oxidation were based on correlated values to TBARS from Ahn et al. (1999). The aldehydes and their specific ion makeup chosen were hexanal (56, 57, 72, 82 m/z), heptanal (55, 70, 81, 96 m/z), and non-

**Table 1.** Processing characteristics for bellies injected with a control brine or a brine with added naturally smoked sugar

Item	Brine formulation		SEM	P-value
	Control	Smoked sugar		
Brine pH	5.66	4.79	0.025	0.01
Initial belly weight, kg	2.84	2.75	0.093	0.22
Initial brine injection <sup>1</sup> , %	16.7	17.3	0.695	0.50
Retained brine <sup>2</sup> , %	12.3	11.8	0.437	0.37
Chilled bacon weight, kg	2.92	2.79	0.107	0.07
Product yield <sup>3</sup> , %	102.8	101.2	0.545	0.01

<sup>1</sup>Initial brine injection = weight immediately after injection – initial weight / initial weight × 100.

<sup>2</sup>Retained brine = belly weight after equilibration – initial weight / initial weight × 100.

<sup>3</sup>Product yield = chilled bacon weight after cooking / initial weight × 100.

anal (56, 57, 70, 98 m/z). Phenolic compounds selected were creosol (95, 123, 138, 139 m/z) and syringol (93, 111, 139, 154 m/z). A standard curve was generated for each compound to calculate concentrations in ppm. The standard curves are as follows: hexanal was prepared at 0.1, 0.25, 0.5, and 0.75 ppm; heptanal was arranged at 0.1, 0.25, 0.5, and 0.75 ppm; nonanal was prepared at 0.05, 0.1, 0.2, and 0.5 ppm; creosol was prepared at concentrations of 0.25, 0.5, 1, and 1.5 ppm; syringol concentrations were 20, 50, 100, and 200 ppm. A stock solution of 1,000 ppm of each standard was prepared in ethanol and then diluted to specific working standard concentrations in water for all compounds. The quantified aldehydes and phenolic compounds from frozen foodservice bacon was reported in ppm. Analytical standards of hexanal, nonanal, heptanal, creosol, and syringol were purchased from MilliporeSigma.

### Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS Version 9.3 (SAS Institute Inc., Cary, NC). Processing characteristics, proximate analysis, and fatty acid composition utilized an incomplete block design with fixed effects of Belly half and Treatment with random effects of Replication and Belly number. The TBARS, GCMS, and sensory analysis were analyzed as a split plot with repeated measures, whole plot factor was Treatment with the sub-plot factor of Storage Day. Random effects included Replication and Belly number within Replication. The covariance structure for the repeated measures was heterogeneous compound symmetry. The results from GCMS were log transformed in order to have equal variance to detect difference in means. The log transformed data and the standard errors

**Table 2.** Processing characteristics and proximate composition of anterior and posterior belly halves

Item	Belly half		SEM	P-value
	Anterior	Posterior		
Initial belly weight, kg	2.76	2.82	0.093	0.41
Initial brine injection <sup>1</sup> , %	16.8	17.3	0.730	0.58
Retained brine <sup>2</sup> , %	11.8	12.3	0.475	0.37
Chilled bacon weight, kg	2.84	2.87	0.107	0.64
Product yield <sup>3</sup> , %	102.5	101.6	0.562	0.06
Fat, %	40.3	33.5	1.63	0.01
Moisture, %	41.1	47.6	1.32	0.01
Protein, %	12.7	15.2	0.426	0.01

<sup>1</sup>Initial brine injection = weight immediately after injection – initial weight / initial weight × 100.

<sup>2</sup>Retained brine = belly weight after equilibration – initial weight / initial weight × 100.

<sup>3</sup>Product yield = chilled bacon weight after cooking / initial weight × 100.

were back transformed using the delta method to report values as ppm. A paired *t*-test was utilized to separate mean differences between treatments with a Tukey-Kramer adjustment for all pairwise comparisons and the denominator degrees of freedom were adjusted with Kenward-Roger adjustment. Means were determined to be significantly different at an  $\alpha$ -level of  $P < 0.05$ .

## Results

### Bacon processing characteristics

The CON brine had a significantly higher ( $P < 0.01$ ) pH compared to the NSS brine (Table 1). In contrast, there were no differences ( $P > 0.05$ ) between treatments for initial belly weight, initial brine injection percentage, retained brine percentage, or chilled bacon weight. Product yield percentage was higher ( $P < 0.01$ ) for CON compared with NSS. Further, there were no differences ( $P > 0.05$ ) for initial weight, initial brine injection percentage, retained brine percentage, chilled bacon weight, or product yield percentage between anterior and posterior belly halves (Table 2).

### Fat, moisture, and protein analysis

Fat, moisture, or protein percentages were not different ( $P > 0.10$ ) between treatments. However, there were Belly half main effects for all 3 measures with anterior belly sections being fatter, having less moisture and less protein compared to posterior belly sections ( $P < 0.01$ ; Table 2).

**Table 3.** Fatty acid composition of anterior and posterior belly halves<sup>1</sup>

Fatty acid, %	Belly half		SEM	P-value
	Anterior	Posterior		
Capric acid (C10:0)	0.25	0.83	0.69	0.42
Myristic acid (C14:0)	0.95	0.85	0.10	0.33
Pentadecylic acid (C15:0)	0.29	0.22	0.08	0.42
Palmitic acid (C16:0)	16.44	16.31	1.01	0.90
Palmitoleic acid (C16:1)	1.53	1.65	0.18	0.50
Margaric acid (C17:0)	1.32	2.08	0.90	0.41
Stearic acid (C18:0)	12.56	13.18	1.18	0.61
Oleic acid (C18:1n9c)	38.37	37.01	2.45	0.59
Vaccenic acid (C18:1n7)	0.89	0.80	0.54	0.86
Linoleic acid (C18:2n6t)	0.02 <sup>b</sup>	0.44 <sup>a</sup>	0.01	0.01
Linoleic acid (C18:2n6)	18.09	15.88	1.08	0.06
$\alpha$ -Linolenic acid (C18:3n6)	0.27 <sup>a</sup>	0.06 <sup>b</sup>	0.08	0.02
$\alpha$ -Linolenic acid (C18:3n3)	0.44	1.39	1.11	0.42
Eicosadienoic acid (C20:2)	0.41	0.32	0.14	0.52
Arachidonic acid (C20:4n6)	0.81	0.88	0.23	0.75
Total SFA <sup>2</sup>	32.16	33.56	1.80	0.45
Total MUFA <sup>3</sup>	41.72	40.95	1.42	0.60
Total PUFA <sup>4</sup>	20.12	20.31	0.71	0.21
Iodine value, g/100 g <sup>5</sup>	68.85	67.03	1.13	0.13

<sup>a,b</sup>Values in the same row with different superscripts differ significantly.

<sup>1</sup>There were no Belly half  $\times$  Treatment interactions or Treatment main effects for all individual fatty acids ( $P > 0.16$ ).

<sup>2</sup>Total saturated fatty acids = [(C10:0) + (C12:0) + (C14:0) + (C15:0) + (C16:0) + (C17:0) + (C18:0) + (C20:0) + (C22:0)], where the parentheses indicate concentration.

<sup>3</sup>Total monounsaturated fatty acids = [(C14:1) + (C16:1) + (C17:1) + (C18:1n9c) + (C18:1n7) + (C20:1) + (C22:1n9)], where the parentheses indicate concentration.

<sup>4</sup>Total polyunsaturated fatty acids = [(C18:2n6t) + (C18:2n6c) + (C18:3n6) + (C18:3n3) + (C20:2) + (C20:3n3) + (C20:4n6)], where the parentheses indicate concentration.

<sup>5</sup>Calculated as IV = [(C16:1)  $\times$  0.95 + (C18:1)  $\times$  0.86 + (C18:2)  $\times$  1.732 + (C18:3)  $\times$  2.616 + (C20:1)  $\times$  0.785 + (C22:1)  $\times$  0.723], where the parentheses indicate concentration, (AOCS, 1998).

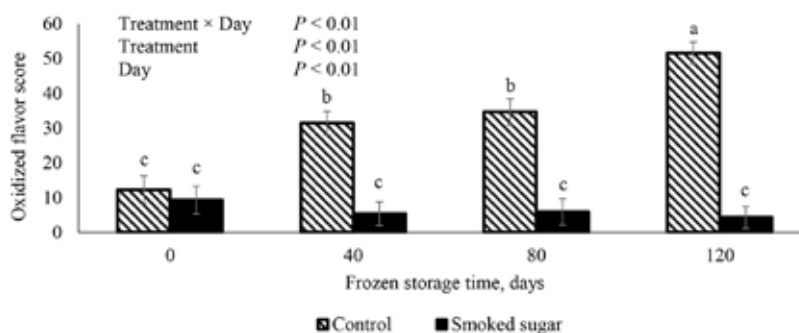
## Fatty acid analysis

Individual fatty acids were not different ( $P > 0.16$ ; Table 3) for bacon slices between treatments. Also, belly half did not influence ( $P > 0.06$ ) most individual fatty acids reported in the study, except for linoleic acid (C18:2n6t) and  $\alpha$ -linolenic acid (C18:3n6;  $P < 0.02$ ). The posterior belly half had a higher ( $P = 0.01$ ) Linoleic acid percentage and lower ( $P = 0.02$ )  $\alpha$ -linolenic acid percentage compared to the anterior half. Total saturated, monounsaturated, and polyunsaturated fatty acid percentages along with calculated IV ( $P = 0.13$ ) were not different for bacon slices between Treatment or Belly half.

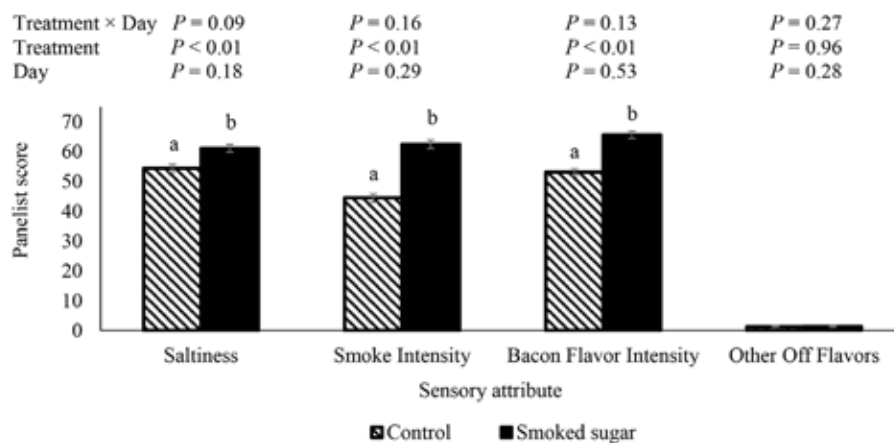
## Sensory evaluation

There was a Treatment  $\times$  Day interaction ( $P < 0.01$ ) for sensory panel oxidized flavor intensity scores (Figure 1). On d 0 of frozen storage, oxidized flavor intensity scores did not differ ( $P = 0.47$ ) between CON and NSS bacon; however, on all other storage days CON bacon exhibited higher oxidized flavor intensity scores compared to NSS bacon ( $P < 0.01$ ). Additionally, oxidized flavor scores increased for CON as time increased ( $P < 0.01$ ) from d 0 through d 120. In contrast, oxidized flavor intensity scores did not increase ( $P < 0.01$ ) for NSS from d 0 through d 120.

Trained panelists scored NSS bacon samples higher ( $P < 0.01$ ) for saltiness and smoke intensity as well as bacon flavor intensity compared with CON samples (Figure 2). Conversely, there was no treatment effect ( $P = 0.95$ ) in the intensity of other off-flavors detected by sensory panelists. Descriptors for other off-flavors included barnyard, boar odor, burnt, and piggy.



**Figure 1.** Panelist scores for oxidized flavor intensity for foodservice bacon stored aerobically frozen for 0 to 120 d. Half bellies were pumped with a 12% brine solution containing none (Control) or added (Smoked sugar) naturally smoked sugar. Trained sensory panelists evaluated oxidized flavor on a continuous line scale; 0 = no oxidized flavor and 100 = extremely intense oxidized flavor. <sup>a-c</sup>Means within a storage day with different superscripts are significantly different ( $P < 0.05$ ).



**Figure 2.** Panelist scores for saltiness, smoke intensity, bacon flavor intensity, and other off-flavors for foodservice bacon stored aerobically frozen for 0 to 120 d. Half bellies were pumped with a 12% brine solution containing none (Control) or added (Smoked sugar) naturally smoked sugar. Trained sensory panelists evaluated saltiness, smoke intensity, bacon flavor intensity, and other off-flavors on a continuous line scale; 0 = extremely not salty, extremely not smoky, extremely bland, none present and 100 = extremely salty, extremely smoky, extremely intense, extremely intense. <sup>a,b</sup>Means within the same attribute with different superscripts are significantly different ( $P < 0.05$ ).

### Thiobarbituric acid reactive substances analysis

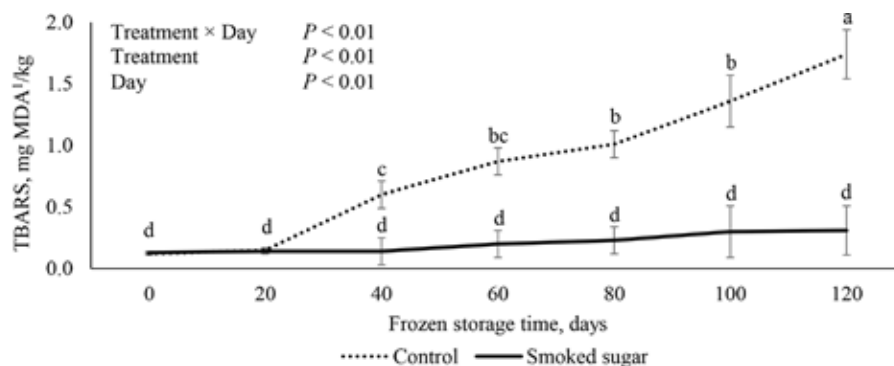
Similar to the results reported for sensory analysis, there was a Treatment × Day interaction ( $P < 0.01$ ) for TBARS values (Figure 3). On d 0 and 20 of frozen storage, CON and NSS bacon TBARS values did not differ ( $P > 0.99$ ). At all other days of frozen storage, CON bacon displayed higher TBARS values than NSS bacon ( $P < 0.01$ ). Furthermore, TBARS values increased ( $P < 0.01$ ) from d 0 through d 120 for CON but were not different ( $P > 0.05$ ) from d 0 to d 120 for NSS.

### Volatile analysis

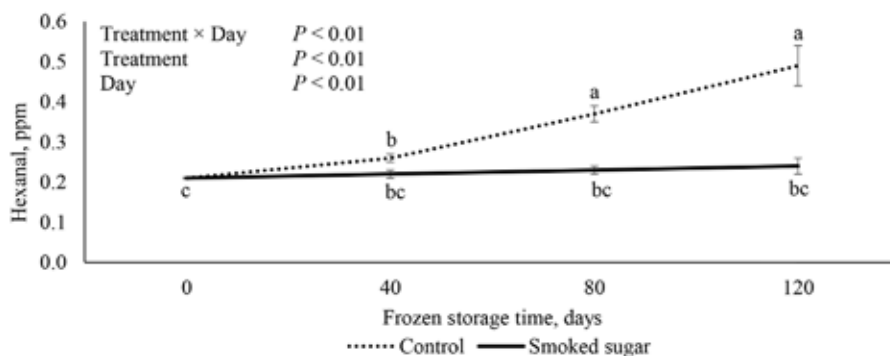
There were Treatment × Day interactions for hexanal (Figure 4) and heptanal (Figure 5) concentra-

tions ( $P < 0.01$ ). Similar to both sensory and TBARS data, on d 0 CON and NSS bacon did not differ ( $P = 0.57$ ) in hexanal concentration. On the remaining d of frozen storage, NSS bacon had lower concentrations of hexanal compared to CON bacon ( $P < 0.01$ ). Additionally, hexanal concentration increased from d 0 through d 120 for CON but did not increase for NSS. On d 0, 40, and 120 of frozen storage, heptanal concentrations did not differ between CON and NSS bacon ( $P > 0.29$ ). On d 80 of frozen storage, heptanal concentration was higher ( $P = 0.0016$ ) for CON bacon compared to NSS bacon. There was no Treatment × Day interaction or Treatment or Day main effect for nonanal concentration for CON and NSS treated bacon ( $P > 0.05$ ).

Finally, there were no Treatment × Day interactions or Day main effects for creosol and syringol con-



**Figure 3.** Thiobarbituric acid reactive substances (TBARS) values for foodservice bacon stored aerobically frozen for 0 to 120 d. Half bellies were pumped with a 12% brine solution containing none (Control) or added (Smoked sugar) naturally smoked sugar. <sup>a-d</sup>Means within a storage time with different superscripts are significantly different ( $P < 0.05$ ). The interaction of Treatment × Day was significant at ( $P < 0.05$ ). <sup>1</sup>MDA = malondialdehyde.



**Figure 4.** Mean hexanal content for foodservice bacon stored aerobically frozen for 0 to 120 d. Half bellies were pumped with a 12% brine solution containing none (Control) or added (Smoked sugar) naturally smoked sugar. <sup>a-c</sup>Means within a storage time with different superscripts are significantly different ( $P < 0.05$ ).

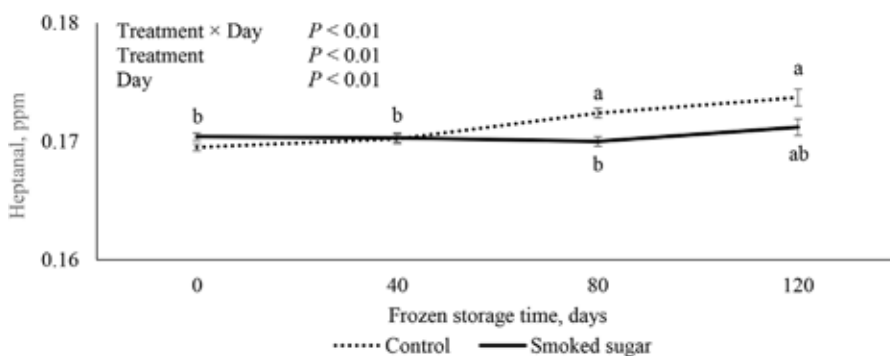
tent ( $P > 0.07$ ); however, there were Treatment main effects ( $P < 0.01$ ; Table 4). Bacon formulated with NSS exhibited higher concentrations of creosol and syringol compared to CON bacon ( $P < 0.01$ ).

## Discussion

Adding NSS to the curing brine effectively lowered brine pH by almost 1 full unit compared to CON. This was anticipated as smoke preparations often contain significant acid content. Montazeri et al. (2013) reported that commercially available liquid smoke products contained titratable acetic acid levels from 0.7 to 10.3% with pH values ranging from 2.3 to 5.7. As expected, this drop in pH had a negative effect on water holding capacity and resulted in a lower product yield compared with CON. Bacon by United States Department of Agriculture (USDA) regulation is limited in added moisture to what is inherently contained in the raw belly (USDA, 1984). Therefore, regula-

tory restrictions on added water by USDA in bacon manufacturing coupled with the minimal changes to all other processing characteristics measured would suggest that processors could effectively use NSS for economical bacon production with little concern.

In order to limit the biological variation between bellies, this experiment was conducted with single bellies split in half to yield an anterior and posterior section so that a paired *t*-test statistical model could be used to decrease variation between experimental units. This approach was used because it is widely accepted that the population of commercial bellies can be highly variable in fat quality because of variations in swine diets (Browne et al., 2013). Further, it has been shown that compositional differences exist within a single belly depending on sampling location as Trusell et al. (2011) reported that bellies exhibited highly variable lean and fat content from dorsal to ventral and cranial to caudal belly locations. As a result, we should expect that differences exist in proximate composition between anterior and posterior belly sections as was the case in this



**Figure 5.** Mean heptanal content for foodservice bacon stored aerobically frozen for 0 to 120 d. Half bellies were pumped with a 12% brine solution containing none (Control) or added (Smoked sugar) naturally smoked sugar. <sup>a,b</sup>Means within a storage time with different superscripts are significantly different ( $P < 0.05$ ).



study. In addition, it might be expected that differences in proximate composition between the anterior and posterior sections could affect processing characteristics such as injection percentage or product yield. However, no differences were reported for any processing characteristic measured due to belly section used. More importantly, this approach yielded belly pieces that had only minor differences in FA concentration between anterior and posterior sections with similar iodine values even though there were differences in proximate composition. The homogeneity of FA within the belly combined with similar processing characteristics from anterior and posterior sections shown in this study suggest that splitting bellies in half is a viable experimental design if researchers are concerned about the impact of raw material variation on bacon research.

Calculated iodine values for the collected bellies were 68.85 for anterior sections and 67.03 for posterior belly sections, which was lower than recently reported data by Lowell et al. (2017) and Lowe et al. (2014). Lowell et al. (2017) reported a mean iodine value range of 73.30 to 75.61 while Lowe et al. (2014) shown a mean iodine value range of 73.44 to 79.66 for raw bellies used for bacon manufacture. Differences in iodine value between studies may be due to diets fed (Browne et al., 2013) or may be explained in part by sampling location. Both Lowell et al. (2017) and Lowe et al. (2014) sampled from the dorsal edge of the anterior portion of the belly while these data were a composite of slices taken from the entire belly section. Trusell et al. (2011) reported that the dorsal portion of the anterior belly end to have the highest iodine value of the entire belly. Given the differences in sampling location, it is highly likely that the bellies from this study are comparable in fat quality compared with the belly populations from both the Lowell et al. (2017) and Lowe et al. (2014) studies.

It is well known that smoking meat products is a means of preservation. The lignin component of hardwoods is responsible for the production of phenolic compounds, which contributes to the antioxidant properties of smoke (Rozum, 2009). There have been multiple studies on the phenol composition of liquid smoke products (Knowles et al., 1975; Simon et al., 2005; Montazeri et al., 2013) as well as the antioxidant potential of smoke products (Wendorff, 1981). Few studies have examined trained sensory evaluation for smoke products as a potential antioxidant for foodservice bacon. However, it is known that the inclusion of phenolic antioxidants into meat products will inhibit the formation of off-flavors. For example, cooked frozen pork sausage treated with 2,500 ppm of rosemary extract exhibited lower trained sensory scores for warmed-over

**Table 4.** Mean creosol and syringol concentrations for foodservice bacon stored aerobically frozen for 0–120 d<sup>1</sup>

Phenolic compound, ppm	Brine treatment		SEM	P-value
	Control	Smoked sugar		
Creosol	1.52	2.14	0.22	0.01
Syringol	47.2	67.8	6.35	0.01

<sup>1</sup>Phenolic smoke compounds. Half bellies were pumped with a 12% brine solution containing none (Control) or added naturally smoked sugar (Smoked sugar).

flavor compared to cooked sausage formulated with less than 1,500 ppm of rosemary extract (Sebranek et al., 2005). Trained sensory evaluation showed oxidized flavor increased throughout extended frozen storage for CON bacon but not NSS bacon which demonstrates that smoked sugar is effective at limiting oxidation in frozen, food service bacon. Also, our results confirm results from Lowe et al. (2014) who found conventionally produced foodservice bacon stored frozen for 90 d at –33°C exhibited increased trained panelists' off-flavor scores as storage time increased.

A method of measuring lipid oxidation in meat products has historically been TBARS measurement. The TBARS values for bacon in the present study closely resemble previous work from Lowell et al. (2017) which documented a significant increase in TBARS values for aerobically packaged foodservice bacon during a 90 d frozen storage period formulated without an antioxidant. Therefore, this study demonstrated that bacon injected with NSS should have greater lipid stability when stored frozen in an aerobic environment for an extended period.

In addition to TBARS value, Shahidi et al. (1987) reported hexanal was also an effective indicator of lipid oxidation, while Yu et al. (2008) was able to identify heptanal as a product of lipid oxidation in bacon. Shahidi et al. (1987) found the concentration of hexanal was highly correlated with TBARS values, as well as sensory acceptability scores in cooked ground pork. Additionally, Ahn et al. (1999) reported hexanal concentration was highly correlated to TBARS values in cooked sausage. In the current study, CON bacon increased in hexanal and heptanal concentration during storage, while NSS bacon concentrations remained relatively unchanged. These measures further demonstrate that bacon will oxidize in a frozen environment that utilizes aerobic packaging and that adding NSS to a brine will help protect lipids from oxidation.

The antioxidant ability of NSS to inhibit lipid oxidation was most likely due to increased concentrations of phenolic compounds present. Phenolic compounds

have been quantified by many researchers (Guillén and Manzanos, 1999; Montazeri et al., 2013) in smoke and liquid smoke products. Montazeri et al. (2013) identified and quantified volatile as well as semi-volatile compounds within liquid smoke and the greatest concentrations of compounds were classified as phenolic. Phenolic compounds are active in scavenging for free radicals, thus inhibiting lipid oxidation. The GCMS was able to identify the phenolic compounds creosol and syringol in both treatments since both were manufactured using a traditional smokehouse schedule where wood chips were burned to produce smoke. However, greater concentrations of creosol and syringol were found in the NSS treatment, and was most likely a part of the reason for limited production of off-flavor compounds and lipid degradation products seen in the NSS treatment. It is also very likely that the placement of the phenolic compounds via injection into the interior portion of the belly was equally important in stabilizing lipids in the NSS treatment as the CON would only have a surface treatment of smoke provided by the smokehouse.

The trained sensory data show the addition of NSS into the brine formulation served as an effective antioxidant without negatively affecting other flavor attributes typically found in bacon. Saltiness, smoke intensity, and bacon flavor were greater for bacon processed with NSS. Smoke and smoke derived products are known for imparting flavor onto meat products. Cellulose, hemicellulose, and lignin contribute to smoke flavor; however, phenols are responsible for the common pungent flavor of smoke. Other phenolic descriptors include sharp, dry or charred wood, and sweet/fruity (Rozum, 2009). Further, these results indicate that the addition of NSS to a curing brine may present additional benefits to flavor development in sliced bacon.

## Conclusion

The inclusion of naturally smoked sugar into bacon formulations successfully inhibited lipid oxidation when bacon slices were stored aerobically and subjected to extended periods of frozen storage. The ability of naturally smoked sugar to function as an antioxidant was confirmed with both subjective sensory evaluations along with multiple objective measurements of lipid degradation products. Also, aerobically packaged frozen bacon formulated without the addition of phenolic antioxidants such as those present in naturally smoked sugar had significant challenges in lipid stability as frozen storage length increased. Meat

processors manufacturing sliced bacon intended for aerobic, frozen storage should seriously consider the use of technologies aimed at improving lipid stability in their products or risk decreased purchasing of bacon products by consumers at foodservice establishments.

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