Inactivation of \textit{Salmonella} on Pecan Nutmeats by Hot Air Treatment and Oil Roasting

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ABSTRACT

Studies were done to determine the effectiveness of hot air drying, dry roasting, and oil roasting in killing \textit{Salmonella} on pecan nutmeats. Pecan halves and pieces were inoculated by immersion in a five-serotype suspension of \textit{Salmonella} or by surface application of powdered chalk containing the pathogen. Hot air treatment of low-moisture (2.8 to 4.1\%) and high-moisture (10.5 to 11.2\%) immersion-inoculated nutmeats (initial population, 6.18 to 7.16 log CFU/g) at 120°C for 20 min reduced the number of \textit{Salmonella} by 1.18 to 1.26 and 1.89 to 2.04 log CFU/g, respectively. However, regardless of the moisture content, hot air treatment of pecan halves containing 0.77 log CFU/g at 120°C for 20 min failed to eliminate \textit{Salmonella}. Reductions were >7 log CFU/g when dry pieces were dry roasted at 160°C for 15 min. Treatment of halves at 140°C for 20 min, 150°C for 15 min, or 170°C for 10 min reduced \textit{Salmonella} by 5 log CFU/g. The pathogen was slightly more heat resistant in immersion-inoculated nutmeats than on surface-inoculated nutmeats. Exposure of immersion-inoculated pieces to peanut oil at 127°C for 1.5 min or 132°C for 1.0 min reduced the number of \textit{Salmonella} by 5 log CFU/g. Treatment of halves at 138°C for 2.0 min reduced \textit{Salmonella} by 5 log CFU/g; treatment at 132°C for 2.5 to 4.0 min did not always achieve this reduction. Hot air treatment cannot be relied upon to reduce \textit{Salmonella} by 5 log CFU/g of raw pecan nutmeats without changing sensory qualities. Treatment temperatures and times typically used to oil roast nutmeats appear to be sufficient to reduce \textit{Salmonella} by 5 log CFU/g.

\textit{Salmonella} is known to have exceptional heat resistance when cells are embedded in food matrices with low water activity (\(a_w\)). Average decimal reduction times at 90°C (\(D_{90°C}\)-values) for \textit{Salmonella} serotypes Anatum, Senftenberg, and Typhimurium in milk chocolate have been reported to range from 11 to 75 min (3, 17). \textit{Salmonella} was reduced by only 3 log CFU/g during conching of 72\% chocolate at 75°C for 22 h (20). Thermal tolerance of \textit{Salmonella} Typhimurium and \textit{Salmonella} Alachua has been reported to increase with an increase in percent solids in milk (14). The \(D_{75-77°C}\)-value for \textit{Salmonella} Weltevreden increased from about 30 min in wheat flour at about \(a_w\) 0.57 to 150 min in flour at about \(a_w\) 0.26 (1). \(D_{49°C}\)-values for eight \textit{Salmonella} serotypes in corn flour ranged from 18 to 594 min (40). Habituation of \textit{Salmonella} to reduced \(a_w\) induces increased heat tolerance (30).

Outbreaks of salmonellosis implicating peanuts (27), a peanut snack (24, 36), peanut butter (10, 11, 34), and almonds (9, 21, 32) as vehicles of \textit{Salmonella} have raised interest in better understanding thermal tolerance characteristics of the pathogen in nuts and nut products. Heat inactivation of a three-serotype mixture of \textit{Salmonella} in peanut butter used to produce a peanut butter–coated snack associated in an outbreak of salmonellosis has been studied. Even by heating peanut butter at 90°C for 50 min, only a 3.2-log CFU/g reduction was observed (35). A study using a three-strain mixture of \textit{Salmonella} Tennessee isolated from peanut butter associated with an outbreak revealed that older cells were more resistant than young cells in peanut butter (\(a_w\), 0.45) heated at 90°C for up to 50 min (29). The minimum time to obtain a 7-log reduction at 90°C was significantly greater for \textit{Salmonella} Tennessee isolated from peanut butter than for clinical isolates of \textit{Salmonella} Tennessee from sporadic cases or for other serotypes.

Several studies have focused on determining thermal resistance of \textit{Salmonella} Enteritidis on almond kernels. A 5.47-log CFU/g reduction was achieved by dry heat treatment of almonds at 149°C for 16 min (12). Dry heat treatment of almonds inoculated with a four-strain mixture of \textit{Salmonella} Enteritidis at 55 or 60°C for 4 days resulted in a maximum inactivation of 1.30 log CFU/g (2). Treatment at 60°C for 4 days followed by catalytic infrared (IR) heat treatment for 70 s reduced the population by an additional 1.0 log. Exposure of almond kernels to IR heat for 30, 35, and 45 s followed by cooling at room temperature yielded reductions in \textit{Salmonella} Enteritidis of 0.63, 1.03, and 1.51 log CFU/g, respectively (8). Holding kernels at warm temperatures for 60 min after IR treatment resulted in a >7.5-log reduction. Pretreatment of almonds with water, citric acid, or lactic acid before dry roasting provides a means to increase antimicrobial efficacy (25). Increased relative humidity of hot air used to treat almonds enhances the rate of inactivation of \textit{Salmonella} Enteritidis (22). Steam

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from raw peanuts: Enteritidis, strain ATCC BAA-1045, from raw almonds; Oranienburg, strain 1839, from pecans; Sundsvall, strain 1659, from pecans; and Tennessee, strain K4643, clinical isolate from a patient in an outbreak of salmonellosis associated with consumption of peanut butter.

Preparation of immersion inoculum. Salmonellae were grown at 37 °C for 24 h in tryptic soy broth (TSB; Becton, Dickinson and Company [BD], Sparks, MD) supplemented with nalidixic acid (50 μg/ml) (TSBN). One milliliter of culture of each serotype was spread on the surface of TSAN (TSBN supplemented with agar [15 g/liter], 60 ml per plate) in large petri plates (150 by 15 mm). Four to eight plates were prepared, depending on the amount of inoculum needed for each experiment. Plates were incubated at 37 °C for 24 to 26 h. Cells were grown on an agar medium rather than in broth because at least one of the serotypes (Salmonella Enteritidis) used in the study appears to have increased resistance to drying on almonds when cells for inoculum are grown on TSA rather than in TSB (37). To harvest cells, 5 to 6 ml of sterile 0.1% peptone water was deposited on the lawn that had developed on the surface of each plate and cells were suspended in the peptone by gently rubbing the lawn with a sterile glass rod. Cell suspensions harvested from plates inoculated with a given serotype were pooled and analyzed for populations of Salmonella (see procedure described below). Equal volumes (20 to 40 ml, depending on the experiment) of each serotype suspension were combined to give 100 to 200 ml of a five-serotype mixture. The population of Salmonella in this mixture was also determined. Undiluted cell suspensions were used to inoculate chalk that was subsequently dried and used to surface inoculate pecan nutmeats (see procedures described below). Suspensions diluted in sterile deionized water were used for immersion-inoculation studies within 1 h after preparation.

Procedure for immersion inoculation. Nutmeats (mammoth halves and medium pieces) were inoculated by immersing in diluted (10⁻² and 10⁻⁶) five-serotype suspensions of salmonellae prepared as described above. Nutmeats (1,400 g at 21 °C) were placed in bags fabricated from fiberglass insect screen (Pfiher, Inc., Tuscaloosa, AL), immersed in suspensions (21°C) at a 1:2 ratio (wt/vol), and gently agitated for 30 s. After removing from the suspension, nutmeats were drained, removed from bags, placed in an aluminum screen basket, dried at 30 °C in a forced-air convection oven for 23 ± 1 h, and deposited in a 1-qt (0.94-liter) Snap n’ Seal freezer bag (Kroger Co., Cincinnati, OH) (25 g/bag). Bags containing nutmeats for each replicate trial were placed in a 1-gal (3.79-liter) Snap n’ Seal freezer bag and stored at 4 °C for 3 to 5 weeks before being used in hot air convection heating and oil roasting experiments.

Preparation of surface inoculum. A five-serotype suspension of salmonellae was prepared as described above. Nontoxic white Crayola chalk (Code #51-0320, Binney and Smith, Easton, PA) was used as a carrier for salmonellae. Chalk sticks (200 g) were immersed in 200 ml of Salmonella suspension at 4 °C for 24 h. The suspension-saturated chalk was removed from the excess suspension, placed on an aluminum screen, and dried at 30°C for 24 h. The chalk was pulverized with a food processor (model 70590, type FP11, Hamilton Beach, Southern Pines, NC); particle size was subsequently reduced by using a mortar and pestle. The powdered inoculum was deposited in a glass bottle, sealed, and stored at 4°C until used to inoculate nutmeats. The moisture content and aₐw, as well as the number of Salmonella in powdered inoculum, were determined immediately before surface inoculating nutmeats.
Procedure for surface inoculation. Medium pecan pieces and mammoth halves (1,800 g at 21°C) were separately combined with 18 g of powdered chalk inoculum in a 1-gal (3.79-liter) Snap n’ Seal freezer bag (Kroger Co.) and gently tumbled for 2 min. Nutmeats were placed on a screen and gently shaken to remove nonadhering chalk inoculum from the nutmeats. Inoculated nutmeats (25-g samples) were placed in 1-qt (0.947-liter) Snap n’ Seal freezer bags and sealed. Bags containing samples for each replicate trial were placed in 1-gal freezer bags and stored at 4°C for 3 to 5 weeks before subjecting nutmeats to hot air convection heat treatments. A limited study was done to determine the efficacy of oil roasting in killing Salmonella. Moisture content, \(a_w\), and populations of Salmonella on the inoculated nutmeats were determined before and after storage.

Hot air treatment of immersion-inoculated nutmeats. Immersion-inoculated, dried nutmeats were removed from storage at 4°C and adjusted to 21°C over a 2- to 3-h period. Nutmeats with no moisture adjustment are referred to as dry. Wet nutmeats (21°C) were prepared by immersing 25 g in 50 ml of sterile deionized water in a 150-ml beaker for 30 s, with gentle agitation, followed by decanting the water, draining the nutmeats, and placing them on paper towels for 3 to 5 min. Wet nutmeats were subjected to heat treatment within 5 min after wetting. Reductions in the number of Salmonella caused by hot air treatment of dry nutmeats (2.8 to 4.1% nutmeat moisture; \(a_w\) 0.52 to 0.61) and wet nutmeats (10.5 to 11.2% nutmeat moisture; \(a_w\) 0.94 to 0.96) were determined.

Dry or wet nutmeats (25 g, dry weight basis) were arranged in a single layer in aluminum screen trays (ca. 11 cm in diameter by 2 cm in height) and placed in a forced-air Fisher Scientific Isotemp oven (control sensitivity, ±0.25°C; model 851F, Fisher Scientific, Dubuque, IA). Dry and wet nutmeats (25-g samples) were exposed to forced dry air at 60, 70, 80, 90, 100, 110, and 120°C for 0, 5, 10, 15, and 20 min. In addition, dry nutmeats were also treated at 130, 140, 150, 160, and 170°C for 0, 5, 10, 15, and 20 min. The lower temperature-time treatments are in the range of or exceed those used to dry nutmeats after shelling. The higher temperature-time treatments are in the range of or exceed dry roasting conditions.

Treatment temperatures were measured with two T-type thermocouples (Omega Engineering, Stamford, CT) placed approximately 1 cm above and below the single layer of 25-g sample and recorded on a Hotmox Temperature Recorder (DCC Corp., Pennsauken, NJ). Immediately after heat treatments, nutmeats were placed in a Stomacher 400 bag (Seward Medical Ltd., London, UK) containing 100 ml of cold (4°C) LBN and analyzed for presence and number of Salmonella (in CFU per gram) using the methods described below.

Hot air treatment of surface-inoculated nutmeats. Dry, surface-inoculated medium pecan pieces and mammoth halves were removed from storage at 4°C and adjusted to 21°C before exposing to heat in a forced-air oven as described above for immersion-inoculated nutmeats, with the exception that not all of the treatment temperature-time combinations were tested. For surface inoculation studies, 25-g samples of nutmeats were treated at 60, 90, 120, 130, 140, 150, 160, and 170°C for 0, 5, 10, 15, and 20 min. Samples were analyzed for the presence (by enrichment) and number of Salmonella (in CFU per gram) using the methods described below.

Oil roasting. The effectiveness of hot oil treatment in killing Salmonella on immersion-inoculated, dried, stored pecan pieces and halves was determined. Inoculated nutmeats were removed from storage at 4°C and adjusted to 21°C. Samples (25 g) were deposited in bags (9 by 20 cm) fabricated from fiberglass insect screen and immersed in hot peanut oil in a Neslab RTE 10 bath (Thermo Fisher Scientific, Newington, NH), which is stated by the manufacturer to have a temperature stability of ±0.01°C. In our study, the oil temperature fluctuated ±1°C from the target temperature. Single bags containing samples of nutmeats were immersed in peanut oil (Kroger Co.) at 110, 116, 121, 127, 132, and 138°C for 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 min. In a limited study, surface-inoculated pieces and mammoth halves were roasted for 1.0 and 1.5 min, respectively, at 127, 132, and 138°C. The bags were held, with gentle agitation, 6 to 7 cm below the surface of the oil, which was 13 cm deep. The temperature in this central location of the oil bath was measured and recorded as described above. Immediately after hot oil treatment, nutmeats (25-g samples) were deposited in Stomacher 400 bags containing 100 ml of cold (4°C) LBN and analyzed for presence and number of Salmonella.

Detection and enumeration of Salmonella. Stomacher 400 bags containing 25 g of treated nutmeats and 100 ml of LBN were pummeled for 1 min at normal speed. Duplicate samples of homogenates were spiral plated (WASP2, Microbiology International, Frederick, MD) or surface spread (quadruplicate 0.25-ml samples and duplicate 0.1-ml samples) on TSAN and Bismuth sulfite agar (BSA; BD) supplemented with nalidixic acid (50 \(\mu g/ml\) (BSAN). Samples (0.1 ml, in duplicate) of LBN and nutmeat homogenate serially diluted in sterile 0.1% peptone water were also surface plated on TSAN and BSAN. Bags containing the preenriched homogenate, as well as the TSAN plates on which samples had been applied, were incubated at 37°C for 24 h; BSA plates were incubated at 37°C for 48 h. Colonies formed on TSAN and BSAN that were presumptive positive for Salmonella were counted. If colonies presumptive for Salmonella did not develop on TSAN, the preenriched BSA was streaked on BSAN. Plates were incubated at 37°C for 48 h before examining for colonies presumptive for Salmonella. For samples anticipated to have low numbers of Salmonella, 1 ml of preenriched LBN homogenate was added to 10 ml of tetraionate broth (BD) and 0.1 ml was added to 10 ml of Rappaport-Vassiliadis broth (BD). Enrichment broths were incubated for 24 h at 37 and 42°C, respectively, before streaking on BSAN. Presumptive-positive colonies that formed on BSAN plates within 48 h at 37°C were randomly selected for confirmation. Cells from these colonies were subjected to confirmation tests using BBL Enterotube II (BD) or API 20E (bioMérieux Vitek, Hazelwood, MO) assays, and a Salmonella latex agglutination test (Oxoid, Basingstoke, UK). The detection limit for enumerating Salmonella by direct plating was 0.60 log CFU/g (4 CFU/g) of nutmeat. The detection limit by enrichment was 1 CFU/25 g of nutmeat.

Statistical analysis. All experiments were replicated three to six times. Values from duplicate or triplicate samples representing each test parameter combination in each replicate trial were analyzed with a general linear model on SAS software (version 9.1, SAS Institute, Cary, NC). The least significant difference test was used to determine significant differences (\(\alpha = 0.05\)) in mean values.

RESULTS AND DISCUSSION

Higher numbers of Salmonella were more often recovered from inoculated nutmeats when samples were spread on TSAN than on BSAN. In some instances, counts on TSAN were significantly higher (\(\alpha = 0.05\)). Only counts obtained from samples plated on TSAN are reported.
We observed in another study (7) that thermal resistance of Salmonella in or on in-shell pecans is affected by the method of inoculation and conditions to which pecans are exposed between the time of inoculation and treatment with hot water. Salmonella that survived drying and storage of nuts at 4°C for 3 to 5 weeks were more heat resistant than were cells on nuts that were not dried or stored after inoculation. An increase in heat tolerance of Salmonella after exposure to low-a_w environments has been reported by others (26, 30). In all studies reported here, immersion-inoculated nutmeats were dried after inoculation, and both immersion- and surface-inoculated nutmeats were stored at 4°C for 3 to 5 weeks before being used in hot air, dry roast, and oil roast experiments. These conditions mimicked those to which contaminated nutmeats may be exposed in the pecan industry.

Hot air treatment of immersion-inoculated nutmeats. Thermal inactivation curves for Salmonella in initially wet pecan pieces (11.2% moisture; a_w, 0.96) and halves (10.5% moisture; a_w, 0.94) and initially dry pieces (2.8% moisture; a_w, 0.52) and halves (4.1% moisture; a_w, 0.61) heated at 60 to 120°C for up to 20 min are shown in Figure 1. Initial populations were 7.16 and 6.18 log CFU/g of pieces and halves, respectively. Significant reductions (µ = 0.05) of 1.89 and 2.04 log CFU/g of wet pieces and halves, respectively, were obtained by heating nutmeats at 120°C for 20 min. Salmonella was more resistant in dry nutmeats; significant reductions in dry pieces and halves heated at 120°C for 20 min were 1.26 and 1.18 log CFU/g, respectively. Reductions (0.02 to 0.10 log CFU/g) in wet and dry halves heated for up to 20 min at 60°C were not significant (µ = 0.05), whereas heating wet and dry pieces for 20 min at 60°C resulted in significant reductions of 0.74 and 0.53 log CFU/g, respectively. A correlation between increased heat resistance of salmonellae and decreased a_w in chocolate (3), wheat flour (1), and eggs (31) has been reported. Others have cited this trend in reviews of the behavior of salmonellae in these and other low-moisture foods (13, 15, 18, 33).

Shown in Figure 2 are changes in the moisture content and a_w of immersion-inoculated pecan pieces and halves that were dried, stored at 4°C for 3 to 5 weeks, and wetted before exposure to hot air at 60 to 120°C for up to 20 min. The shaded area indicates a moisture content in a range (3.5 to 5.5%) generally desired in nutmeats stored at refrigerated or subfreezing temperatures. Regardless of the air temperature, the moisture content in wet pieces and halves was reduced to less than 5.5% within 10 and 15 min, respectively. The dashed line indicates the a_w (0.70) below which growth of molds on nutmeats does not occur or is greatly retarded. Subsequent to cracking and shelling pecans, hot air treatment for sufficient times to achieve desired moisture content or a_w of nutmeats (Fig. 2) is clearly not sufficient to kill large numbers of Salmonella (Fig. 1).

When dry immersion-inoculated pieces and halves were exposed to air temperatures of 60, 90, and 120°C for 5 to 20 min, the moisture content and a_w were significantly reduced (Fig. 3). Reductions of Salmonella in dry nutmeats were less than those in wet nutmeats exposed to the same treatment (Fig. 1). Heating wet or dry nutmeats at temperatures as low as 80°C resulted in darkening the color of kernel testa and an increased brittleness in texture. More severe temperature-time treatments caused changes in sensory qualities that were subjectively judged to compromise the overall acceptability of the nutmeats without substantially reducing Salmonella counts.

The next series of experiments was focused on determining the effectiveness of hot air in killing Salmonella initially at lower numbers on immersion-inoculated pecan pieces and halves. Shown in Table 1 are numbers of Salmonella recovered from wet and dry pieces initially.
containing the pathogen at populations of 2.09 and 1.20 log CFU/g, respectively. Treatment of nutmeats at 60 to 120 °C for up to 20 min failed to eliminate the pathogen, regardless of the initial moisture content or count.

Shown in Table 2 are the numbers of samples (of six analyzed) of wet and dry immersion-inoculated pecan halves that were positive for Salmonella after treatment with hot air at 60 to 120 °C for up to 20 min. The initial population was 0.77 log CFU/g. Regardless of the moisture content or treatment temperature-time combination, Salmonella was detected in at least one of six samples in six replicate trials. As observed in experiments using nutmeats with much higher counts (Fig. 1), the range of air temperature-time treatments typically used by commercial pecan shellers to dry nutmeats after shelling cannot be relied upon to eliminate Salmonella, even when the pathogen is present at low populations.

In an attempt to obtain greater reductions of Salmonella on immersion-inoculated nutmeats, the air temperature was increased to 130 to 170 °C, a range more typically used for dry roasting. Reductions resulting from treatments at these temperatures for up to 20 min are shown in Figure 4. Dashed lines indicate 4- and 5-log CFU/g reductions. The lowest limit of detection by direct plating was 0.60 log CFU/g (shaded area). An initial population of 7.62 log CFU/g of pieces (3.5% moisture; a_w, 0.63) was reduced by 2.89 log CFU/g when nutmeats were heated at 130 °C for 20 min and by >7 log CFU/g within 15 min when the air temperature was 160 or 170 °C. However, the pathogen was detected in 3 of 6 and 2 of 6 samples of pieces heated for 20 min at 160 and 170 °C, respectively (data not shown), indicating that these harsh treatments did not eliminate the pathogen. Treatment at 130 or 140 °C for 20 min failed to reduce Salmonella by 5 log CFU/g of pecan pieces.

**FIGURE 2.** Moisture content and a_w of initially wet (10.5 to 11.2% moisture) pecan pieces and halves exposed to hot air treatment at 60 to 120 °C for up to 20 min. The shaded area indicates the moisture content in a range generally desired in nutmeats stored at refrigerated or subfreezing temperatures. A maximum a_w of 0.70 (dashed line) prevents or greatly minimizes the growth of molds on nutmeats.

**FIGURE 3.** Moisture content and a_w of initially dry (2.8 to 4.1% moisture) pecan pieces and halves exposed to hot air treatment at 60, 90, and 120 °C for up to 20 min.
Table 1. Recovery of *Salmonella* from immersion-inoculated *Desirable* var. *pecan nutmeats* (medium pieces) after treatment in hot air for up to 20 min

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<th>Treatment temp (°C)</th>
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**Notes:**
- Values (log CFU per gram) in the same row that are not followed by the same letter are significantly different (\( p = 0.05 \)). Within the same moisture content, values (log CFU per gram) in the same column that are not followed by the same letter are significantly different.
- En, number of samples positive for *Salmonella* by enrichment.
- Re, number of samples positive for *Salmonella* by direct plating.
- Re, reduction (log CFU per gram) compared with initial population (0 min).

An initial population of 7.01 log CFU/g of halves (3.9% moisture; \( a_w \): 0.66) was reduced by 3.15 log CFU/g when treatment was at 130 °C for 20 min (Fig. 4). Treatment at 170 °C for 10 min, 150 or 160 °C for 15 min, or 140 °C for 20 min reduced the *Salmonella* count by \( >5 \) log CFU/g. As with pecan pieces, however, heating pecan halves at 160 or 170 °C for 20 min did not eliminate *Salmonella* in 5 of 6 and 2 of 6 samples, respectively, in six replicate trials.

Overall, thermal resistance of *Salmonella* appears to be slightly greater in dry halves than in dry pieces upon exposure to hot air treatments at 60 to 120 °C (Fig. 1) and 130 to 170 °C (Fig. 4). This may be attributable in part to the larger mass in halves compared to pieces, thereby presumably resulting in a reduced rate of heat penetration (particularly in the early seconds of heat treatment) into the internal high-fat (70 to 72%) tissues where some of the *Salmonella* may have infiltrated. The protection of microorganisms against thermal inactivation in high-fat matrices has been known for many years (19).

**Hot air treatment of surface-inoculated nutmeats.** Thermal inactivation curves for *Salmonella* on dry (3.9% moisture; \( a_w \): 0.66) surface-inoculated pecan pieces and halves exposed to hot air (60 to 170 °C) for up to 20 min are shown in Figure 5. Initial populations were 6.73 and 6.67 log CFU/g, respectively. *Salmonella* was reduced by 0.69 and 0.47 log CFU/g of pieces and halves, respectively, heated at 90 °C for 20 min. Significant reductions (\( p = 0.05 \)) of 2.36 log CFU/g of pieces and 2.43 log CFU/g of halves occurred when nutmeats were heated at 120 °C for 20 min. Heating at 130 °C for 20 min reduced *Salmonella* on pieces and halves by 3.00 and 3.30 log CFU/g, respectively. Treatment at 160 or 170 °C reduced populations by \( >6 \) log CFU/g within 15 min. *Salmonella* was recovered by enrichment (1 of 6 replicate samples) of pieces heated at 170 °C for 20 min but not in halves heated at 160 °C for 20 min or 170 °C for 15 or 20 min. A comparison of log reductions on dry surface-inoculated nutmeats (Fig. 5) with reductions on or in immersion-inoculated nutmeats (Figs. 1 and 4) reveals that, for nutmeats exposed to the same temperature-time combinations, overall, reductions of *Salmonella* were slightly greater on surface-inoculated nutmeats. This would be expected since some of the cells in immersion-inoculated nutmeats were likely to have infiltrated nutmeats, thereby affording protection against heat and, consequently, a slower rate of inactivation compared to cells on the surface of external tissues.

Higher reductions of *Salmonella* may be achievable by exposing pecan nutmeats to other treatments, either before or after hot air treatment. Bari et al. (2) reported that hot water treatment of almond kernels inoculated with *Salmonella* (5.73 log CFU/g) at 88 °C for 20 s, followed by IR heat treatment for 70 s, reduced the population to \( <1 \) log CFU/g. Holding almonds at 60 °C for 4 days resulted in a reduction of 1.30 log CFU/g; subsequent IR treatment for 70 s reduced the pathogen by an additional 1.23 log CFU/g. IR treatment of almond kernels followed by holding kernels at warm temperatures results in substantial reductions of *Salmonella* Enteritidis (8). The lethality of IR treatment was greatly

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**TABLE 1.** Recovery of *Salmonella* from immersion-inoculated *Desirable* var. *pecan nutmeats* (medium pieces) after hot air treatment. Values are shown only for the samples (one to six samples) from six replicate trials not giving counts by direct plating. A primary log reduction of 5 CFU/g would be considered significant. Values are shown only for the samples (one to six samples) from six replicate trials not giving counts by direct plating. A primary log reduction of 5 CFU/g would be considered significant.
influenced by the maximum surface temperature of kernels. Kim and Harris (25) found that pretreatment of almond kernels with citric or lactic acids decreased the number of Salmonella Enteritidis by approximately 1 log CFU/g, and additional reductions of 4.7 and 5.3 log CFU/g occurred when almonds were subsequently heated at 135°C for 40 min. Physical or chemical treatments in combination with hot air treatment may also prove to be more efficacious than hot air alone in killing Salmonella on pecan nutmeats.

### Table 2. Detection of Salmonella in immersion-inoculated Desirable var. pecan halves (mammoth halves) after treatment in hot air for up to 20 min

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注: Number of samples positive for Salmonella by enrichment of six 5-pecan (50-g) samples from six replicate trials. Initial population (0 min) in high-moisture (10.5%) pecan halves was <0.60 log CFU/g (<4 CFU/g); initial population in low-moisture (4.1%) halves was 0.77 log CFU/g (5.89 CFU/g). The limit of detection by enrichment was 1 CFU/50 g.
Oil roasting treatment of immersion-inoculated nutmeats. Immersion-inoculated, dried pecan pieces and halves stored at 4°C for 3 to 5 weeks were adjusted to 21°C before exposure to hot (110 to 138°C) oil for up to 4 min. Inactivation curves are shown in Figure 6. Less than a 5-log CFU/g reduction of Salmonella was obtained by oil roasting pieces at 110 to 121°C for 4.0 min. However, a 5-log reduction was obtained by heating pieces at 127°C for 1.5 min or at 132°C for 1.0 min. Four-log reductions were obtained in pieces roasted at 110 or 116°C for 2.5 min, 121°C for 1.5 min, or 127°C for 1.0 min. With the exception of treatment for 0.5 min, at the same temperature-time treatment combination, inactivation of Salmonella tended to be greater in pecan pieces than in halves. As with pieces, 5-log reductions of Salmonella did not occur in halves roasted at 110 to 121°C for 4.0 min. Treatment of halves at 132°C for 2.5 to 4.0 min did not always result in 5-log reductions. A 5-log reduction was obtained when halves were oil roasted at 138°C for 2.0 min. Four-log reductions were obtained in halves oil roasted at 110°C for 3.0 min, 121°C for 2.0 min, or 127°C for 1.5 min.

The rate of inactivation of Salmonella on pecan pieces and halves was rapid during the first 1.0 to 1.5 min of exposure to hot oil (Fig. 6). Slower inactivation rates were observed during longer exposure times. Upwardly concave inactivation curves for salmonellae also have been observed for oil-roasted almonds (16). Possible explanations for the rapid initial reductions were that loosely attached Salmonella cells were washed off almonds when they were placed in oil, the presence of a less protected and more sensitive outer layer of cells, and a rapid decrease in aw at the almond surface. The same factors may have contributed to more rapid reductions of Salmonella on pecan nutmeats during the first minute or so of exposure to hot oil compared with slower rates of reduction thereafter. Cells that survived initial exposure to hot oil were likely afforded protection against heat inactivation as a result of decreased moisture in subsurface nutmeat tissue where they may have infiltrated. Pronounced tailing of thermal inactivation curves also has been observed for Salmonella on peanut butter. Shachar and Yaron (35) reported a 2.5-log CFU/g reduction in peanut butter heated at 90°C for 5 min, followed by an additional 0.30-log reduction after 20 min. Ma et al. (29) observed that tailing of inactivation curves for Salmonella in peanut butter may be affected by serotype and strain.

Oil roasting treatment of surface-inoculated nutmeats. A limited study was done to determine the efficacy of oil roasting in killing Salmonella on surface-inoculated nutmeats. Dry (3.9% moisture; aw, 0.64) surface-inoculated nutmeats that had been stored at 4°C for 3 to 5 weeks were adjusted to 21°C and oil roasted at 127, 132, and 138°C. Reductions of Salmonella on pieces exposed to oil at these temperatures for 1.0 min were 4.67 to 4.91 log CFU/g; reductions on halves roasted for 1.5 min were 4.31 to 5.24 log CFU/g. These reductions are similar to those resulting from oil roasting immersion-inoculated nutmeats at the same temperature-time combinations (Fig. 6).

A comparison of our observations on thermal resistance of Salmonella on oil roasted pecan nutmeats to those reported by Du et al. (16) on almond kernels shows that the pathogen is inactivated at a somewhat slower rate on pecan nutmeats. A Weibull model was used in the almond study to predict 4- and 5-log reductions of Salmonella Enteritidis on almonds roasted in safflower oil at 127°C to be 0.74 and 1.3 min, respectively. Reductions of 2.9, 3.0, and 3.6 log CFU/g occurred within 30 s when almonds were oil roasted at 116, 121, and 127°C, respectively. This compares to reductions of 1.13, 1.21, and 1.38 log CFU/g of immersion-inoculated pecan pieces and 1.87, 1.85, and 2.07 log CFU/g of immersion-inoculated halves roasted in peanut oil at 116, 121, and 127°C, respectively, for 30 s. In the Du et al. (16) study, neither Salmonella Enteritidis nor Salmonella Senftenberg was recovered by enrichment of 1-g samples after almonds inoculated at 5 log CFU/g were exposed to oil at 127°C for 1.5 min. They concluded that standard oil roasting times and temperatures should result in much greater than a 5-log reduction. The same conclusion can be made for pecan nutmeats.

The observation that Salmonella is more resistant on pecan pieces than on halves upon exposure to hot oil at 110 to 138°C is contrary to observations that the pathogen is slightly more resistant on halves than on pieces exposed to
hot air at temperatures at 60 to 170°C. Differences in the rate of heat penetration resulting from exposure of nutmeats to hot air versus oil, coupled with differences in the surface/volume ratio of the two types of nutmeats and the extent of infiltration of cells into nutmeat tissue, are factors which may have contributed to these findings. Differences in moisture content of nutmeats used in hot air and oil roasting studies may also have affected the rate of inactivation of *Salmonella*. The moisture contents of dry and wet nutmeats used in the hot air study were 2.8 to 4.1% and 10.5 to 11.2%, respectively. The moisture content of nutmeats used in the oil roast study was 3.7 to 5.0%. The rate of inactivation of *Salmonella Enteritidis* on almond kernels exposed to hot oil has been shown to be influenced by the moisture content (23). It was reported that treatment of kernels containing 5.1 and 8.6% moisture in oil at 121°C for 1 min reduced *Salmonella* by 2.2 and 5.1 log CFU/g, respectively. Our studies on hot air treatment of pecan halves and pieces are in agreement with these observations in that the heat resistance of *Salmonella* was less in wet nutmeats than in dry nutmeats. The effectiveness of hot oil treatment in killing *Salmonella* on or in pecan nutmeats would also be expected to be influenced by moisture content.

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