



Comparative study of thermal inactivation kinetics of *Salmonella* spp. in peanut butter and peanut butter spread[☆]



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ABSTRACT

Peanut butter has been implicated in multi-state outbreaks of salmonellosis in recent years. Studies have shown that *Salmonella* exhibited increased thermal resistance in peanut butter. However, little is known about the effect of product formulation on the kinetics of survival of *Salmonella* during thermal treatment. Therefore, the objective of this research was to compare the thermal resistance of *Salmonella* in four commercially available peanut butter and spread products, and evaluate the effect of product formulation on the survival of this pathogen during heating.

Four peanut butter and spread samples, including Omega 3 (A), regular fat (B), reduced sugar (C), and reduced fat (D), inoculated with a 6-strain cocktail of *Salmonella* spp., were heated at 70, 75, 80, 85, and 90 °C. Experimental results showed that the highest thermal resistance of *Salmonella* was found in the samples with reduced fat, while the least in the samples with Omega 3 formulation. No significant difference in the bacterial thermal resistance was observed in the regular fat and reduced sugar formulations. The Weibull survival model was used to describe the survival curves. Results showed that the average exponent (shape factor) of the model ranged from 0.38 to 0.662, suggesting progressively decreased rate of inactivation during heating. The scale (rate) coefficients of the model increased linearly with temperature. The calculated minimum lethal temperature for *Salmonella* was 54.8, 59.8, 59.5, and 63.9 °C in samples A, B, C, and D, respectively. No tail effect was observed. The results of this study suggest that proper formulation of peanut butter and spread may enhance thermal inactivation of *Salmonella*.

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1. Introduction

In the United States, *Salmonella* accounts for an estimated 1,027,561 cases of foodborne illness, causing 19,336 hospitalizations and 378 deaths annually (CDC, 2011). While the outbreaks of salmonellosis are more commonly associated with the consumption of animal products (such as poultry, meat, and eggs) and fresh produce, several serious outbreaks of *Salmonella* infections have been linked to low water activity and high fat foods such as chocolate (Werber et al., 2005), peanut butter, and peanut butter-related products in recent years. While the first documented outbreak of

peanut butter-related salmonellosis was reported in 1996 (Burnett, Gehm, Weissinger, & Beuchat, 2000), there have been at least 3 recorded outbreaks of salmonellosis involving peanut butter contaminated with *Salmonella* in the U.S. since 2006. In late 2006 to early 2007, *Salmonella* Tennessee from a leaking roof of a processing plant caused 628 infections in 47 states (CDC, 2007). Between 2008 and 2009, an outbreak of salmonellosis involving *Salmonella* Typhimurium in peanut butter and peanut butter-containing products occurred, leading to 714 cases of infection and 9 deaths in 46 states (CDC, 2009). The latest multi-state outbreak associated with peanut butter was caused by *Salmonella* Bredeney, in which a total of 42 people were infected and 28% of the ill persons were hospitalized (CDC, 2012). Peanut butter has been identified as a new food vehicle for salmonellosis in the U.S. (Sheth et al., 2011). Once contaminated, *Salmonella* can survive in peanut butter and peanut butter spread during storage (Burnett et al., 2000; Park, Oh, & Kang, 2008).

In the U.S., peanut butter is consumed by approximately 90% of the households, with a total spending of \$800 million per year

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(National Peanut Board, 2014). In response to the recurring *Salmonella* outbreaks related to peanut butter and other peanut butter-containing products, the U.S. Food and Drug Administration (FDA) issued guidance for the industry, recommending at least a 5-log reduction in *Salmonella* for peanut and peanut-derived products (FDA, 2009). Although some emerging technologies, such as high pressure (Grasso, Somerville, Balasubramaniam, & Lee, 2010) and irradiation (Ban & Kang, 2014; El-Rawas et al., 2012), have been reported for use to control *Salmonella* in peanut butter, the scale-up feasibility and efficacy of these technologies remains uncertain and needs further examination. Thermal processing is still one of the most common and effective methods that can be used to inactivate spoilage and pathogenic microorganisms in foods, including peanut butter.

Heat treatment has been explored to inactivate *Salmonella* in peanut butter. However, it has been demonstrated that the thermal resistance of *Salmonella* is significantly higher in peanut butter than in other foods. Ma et al. (2009) investigated the thermal resistance of three strains of *Salmonella* Tennessee previously associated with an outbreak and other *Salmonella* strains in peanut butter. This study reported that the outbreak-associated *Salmonella* strains were more heat resistant and heating at 90 °C for >30 min was needed to achieve a 5-log reduction of *Salmonella* in highly contaminated peanut butter products. Shachar and Yaron (2006) also reported that *Salmonella* withstood heating at 90 °C and only 3.2 log reductions were observed in peanut butter. However, no significant difference was observed in the thermal resistance among *Salmonella enterica* serovars Agona, Enteritidis, and Typhimurium in artificially inoculated peanut butter. Keller et al. (2012) studied the effect of growth media on the thermal resistance of *Salmonella* Tennessee and Oranienburg in peanut butter and suggested that thermal death curves obtained from sessile cultures exhibited greater linearity than those from planktonic cells. He, Guo, Yang, Tortorello, and Zhang (2011) evaluated the survival and heat resistance of *Salmonella* and *Escherichia coli* O157:H7 in peanut butters with different formulations at two temperatures (70 and 90 °C) and reported the survival and heat resistance of the bacteria were significantly affected by the product formulation. This study also reported that the bacteria survived better, but were less heat-resistant in peanut butter with higher carbohydrate contents.

Various factors may affect the thermal resistance and survival of *Salmonella* in peanut butter during thermal inactivation. Few studies have systematically investigated the combined effect of temperature and product composition on the survival of *Salmonella* in peanut butter. Therefore, the main objective of this research was to compare the thermal inactivation kinetics of *Salmonella* spp. in commercially available peanut butter products, and evaluate the effect of composition in peanut butter on the survival of this pathogen during heating.

2. Materials and methods

2.1. Peanut butter and peanut butter spread

Four commercially processed peanut butter products with different formulations (fat, carbohydrate, protein, and sodium, Table 1) were purchased from a local grocery store. These products differed mainly in fat, carbohydrate, and protein contents. Three of the products (A, B, and C) selected for study contained approximately 50% fat, while product D contained only 33% fat. Product A contained extra Omega-3 fatty acids. Product B was labeled by the manufacturer as regular peanut butter. Product C was labeled as a reduced sugar product, while the last one, Product D, was a reduced fat formulation. Products A, B, and C, containing at least 90%

Table 1

Formulations of four commercially available peanut butter and peanut butter spread. The relative contents of each product were calculated from nutrient labels.

| Product code | Ingredient content (w%) | | | | |
|-------------------|-------------------------|--------------------|---------|--------|-------|
| | Total fat | Total carbohydrate | Protein | Sodium | Other |
| Omega-3 (A) | 48.5% | 24.2% (9.1%) | 21.2% | 0.5% | 5.6% |
| Regular (B) | 50.0% | 21.9% (9.4%) | 25.0% | 0.5% | 2.7% |
| Reduced sugar (C) | 53.1% | 18.8% (6.3%) | 25.0% | 0.2% | 2.9% |
| Reduced fat (D) | 33.3% | 41.7% (11.1%) | 19.4% | 0.6% | 5.0% |

peanuts, were categorized as peanut butter, according to 21CFR164.150 (FDA, 2013a). Product D contained 60% peanuts. Therefore, it was a peanut butter spread, according to 21CFR102.23 (FDA, 2013b).

2.2. Bacteria strains and preparation of inoculum

Six strains of *Salmonella*, including S. Thompson120, S. Newport H1073, S. Typhimurium TD104, S. Copenhagen 8457, S. Montevideo, and S. Heidelberg, were obtained from the microbiological culture collection of the Eastern Regional Research Center (ERRC), USDA Agricultural Research Service (ARS), located at Wyndmoor, PA. Each strain of the *Salmonella* cultures was induced to resist rifampicin (100 mg/L) by successively inoculating and transferring the cultures in brain heart infusion broth (BHI broth, BD/Difco Laboratories, Sparks, MD) containing 25, 50, 75, and 100 mg/L of rifampicin (Sigma, R 3501-5G, Sigma–Aldrich Co., MO). The bacterial cultures were incubated individually at 37 °C overnight on an orbital shaker (~100 rpm). Once the antibiotic resistance was induced and stabilized, each culture was streaked onto Tryptic Soy agar (TSA, BD/Difco Laboratories) plates supplemented with 100 mg/L rifampicin (TSA/R). To maintain the viability of the cells, the rifampicin-resistant *Salmonella* cultures were regularly propagated and maintained on TSA/R plates and stored in a refrigerator maintained at 8 °C. Using the rifampicin-resistant strains of *Salmonella* allowed recovery of the bacteria after heat treatments without using a selective medium, which may damage or kill thermally injured cells.

The working cultures were prepared by inoculating the rifampicin-resistant stock cultures individually into 10 mL BHI broth supplemented with 100 mg/L rifampicin. The bacterial cultures were incubated at 37 °C on an orbital shaker (~100 rpm) for approximately 19–20 h, harvested by centrifugation (2400 g, 15 min, at 4 °C), washed once with 10 mL 0.1% peptone water (PW, BD/Difco Laboratories), re-centrifuged, decanted, and re-suspended in 1.5 mL corn oil or 0.5 mL PW, and then combined to form a 9 mL oil suspension or 3 mL PW suspension of bacterial cocktail. In the preliminary experiment to determine the effect of culture preparation on the survival of *Salmonella*, both oil and PW suspensions of the bacterial cultures were used to inoculate samples. In the subsequent experiments, however, only the oil suspension was used. The final concentration of the cocktail was approximately 10^{9.0} colony-forming unit (CFU) per mL.

2.3. Sample preparation and inoculation

During inoculation, peanut butter and spread samples (1.00 ± 0.05 g each) were aseptically weighted into Whirl-Pak (7 oz/207 mL, Nasco-Fort Atkinson, WI) bags. Each sample was individually inoculated with 30 µL oil suspension or 10 µL PW suspension (Product B only) of the bacterial cocktail. The inoculated sample bags were gently massaged by hand for at least 3 min, and then flattened with a round bottle to a thin layer (<0.5 mm). To ensure uniform heating, the bags were vacuumed to evacuate the

air and then sealed when the internal pressure reached 2.0 kPa. The samples with PW suspensions were used in the preliminary study, while the ones with oil suspensions were used in all thermal inactivation studies. The uninoculated samples were used as negative controls. The bacterial concentration was ca. 7.0–7.7 log CFU/g in the inoculated samples.

2.4. Thermal inactivation

The inoculated samples sealed in Whirl-Pak bags were loosely placed in a plastic rack and fully immersed in a circulating water bath (Neslab RTE17, Thermo Fisher Scientific, Newington, NH) maintained at 70, 75, 80, 85, or 90 °C. The come-up time to reach the treatment temperatures was previously determined to be approximately 6 s (data not shown). During the preliminary study to determine the effect of sample inoculation on thermal inactivation of *Salmonella*, the heating experiments were conducted using Product B (regular peanut butter) at 70 °C with both oil and PW suspensions as inoculum.

In all heating experiments, samples were removed from the water bath at different time intervals (0.5–100 min), depending on temperature. After heating, the samples were immediately plunged into an iced water bath. All heating experiments were repeated at least three times on separate dates.

2.5. Determination of bacterial counts

Each heat-treated and control sample was aseptically opened, to which 9 mL of PW was added. Each sample was placed in a mini stomacher (Model BagMixer 100W, Interscience Co., France) and stomached twice at high speed with 3 min on each side. After stomaching, the liquid portion (0.1 mL) was withdrawn and plated, either directly or after serial tenfold dilutions, onto TSA/R plates in duplicate. When thermal treatment resulted in low bacterial counts, the surviving bacteria were recovered by pouring 1 mL undiluted liquid portion directly onto TSA/R plates. The plates were incubated at 37 °C for 24 h. The bacterial colonies, all rifampicin-resistant *Salmonella* recovered from TSA/R plates, were counted, averaged, and converted to the logarithms (base 10) of CFU per gram of peanut butter/spread (log CFU/g).

2.6. Kinetic analysis

The survival curves of *Salmonella* were obtained by plotting the log-reductions of bacterial counts against the heat treatment time at each temperature. All survival curves were obviously nonlinear and upwardly concave. Therefore, the Weibull survival model (equation (1)) was adopted for describing the thermal inactivation kinetics of *Salmonella* spp. in peanut butter and spread. A nonlinear regression analysis procedure in NCSS 2007 (Hintze, 2007) was used to analyze the survival data and fit the inactivation curves to the following equation:

$$\log(N_t) - \log(N_0) = -bt^n \quad (1)$$

In equation (1), t is the thermal treatment time (min); N_t and N_0 are the real time and initial *Salmonella* counts (CFU/g), respectively. The coefficients b and n are the parameters of the equation, with b being the scale (rate) parameter and n the shape parameter, respectively. The analysis of variance (ANOVA) for the effect of temperature and product formulation on n was performed using R (<http://www.r-project.org/>) and Package “agricolae”. The Tukey’s test with α at a 0.05 level was used to compare the means of each treatment. A factor with a p value of <0.05 was considered statistically significant in ANOVA.

2.7. Determination of water activity

The water activity (A_w) of peanut butter and spread samples was measured using a water activity meter (Dew Point Water Activity Meter Series 4, AquaLab, Pullman, WA).

3. Results

3.1. Effect of culture preparation on survival of *Salmonella* spp. in regular peanut butter

The measured water activity was 0.463, 0.405, 0.361, and 0.474 in Products A, B, C, and D, respectively. The water activity of corn oil used to prepare the bacterial oil suspensions in this study was measured as 0.405. This value was very close to the datum (0.403) reported by AquaLab (2014). In regular peanut (Product B), the water activity was 0.437 when inoculated with PW suspensions, representing a 7.9% increase in water activity. When inoculated with oil suspensions of bacteria, the water activity in Product B was only 0.409, suggesting the oil suspensions did not alter the water activity of the samples.

A preliminary study was conducted to evaluate the effect of culture preparation on the survival of *Salmonella* spp. in regular peanut butter (Product B). With initial inoculums of ca. 7.0–7.5 log CFU/g, the samples were heated at 70 °C. Fig. 1 shows the survival of *Salmonella* in the peanut butter inoculated with oil and PW bacterial suspensions. Both curves in Fig. 1 show that the populations of *Salmonella* exhibited a sharp decline in the first 10 min, and then continued to decrease at a lower rate in the later thermal process. While the population of *Salmonella* in the sample inoculated with PW suspensions was reduced, on average, by 2.14, 2.53, 2.95, and 3.19 log CFU/g after 2.5, 5, 7.5, and 10 min of heating, *Salmonella* in the samples inoculated with the oil suspensions was reduced by only 1.03, 1.25, 1.80, and 2.01 log CFU/g, respectively. When the heating time was increased to 50 min, an average of 5.86 log-reductions of *Salmonella* was observed in the samples inoculated with PW suspensions. In the samples inoculated with the oil suspensions, however, greater than 100 min was required to achieve the same reductions of *Salmonella*. This observation suggested that *Salmonella* exhibited greater thermal resistance in the samples inoculated the oil suspensions than in the ones inoculated with PW suspensions. Therefore, the samples inoculated with the oil

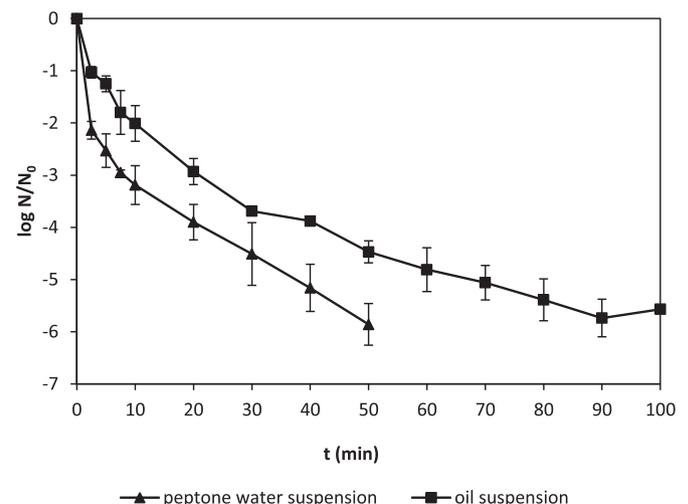


Fig. 1. Effect of culture preparation on thermal resistance of *Salmonella* spp. in peanut butter (regular, B) at 70 °C.

suspensions of the bacterial cocktail were used in the subsequent thermal inactivation studies.

3.2. Thermal inactivation of *Salmonella* in peanut butter and spread

In this part of study, the initial inoculation levels of *Salmonella* were ca. 7.2–7.7 log CFU/g (with oil suspensions). Similar to the survival curves observed previously in the preliminary study, all survival curves were upwardly concaved (Figs. 2–6). The bacterial concentrations in the inoculated samples started to decline rapidly during the initial stage of heating, and continued to decrease at a lower rate as heating progressed. Among all four samples, it is evident, by directly judging from the survival curves (Figs. 2–6), that *Salmonella* cells in reduced fat peanut butter (Product D) were more resistant to heat than the other three samples used in this study, as the cells survived better in this product. *Salmonella* in Product A with an elevated level of Omega 3 fatty acids, however, were least resistant to heat among all samples. The thermal resistance of *Salmonella* in regular and reduced sugar peanut butter samples (Products B and C) was similar, lower than that in Product D, but higher than that in Product A.

3.3. Data analysis and mathematical modeling

Since all the survival curves of *Salmonella* obtained in the present study were upwardly concaved, the curves were analyzed using the Weibull survival model, and the results are listed in Table 2. In the Weibull model, the shape of the survival curves is determined by the exponent (n) of the model. In all the survival curves obtained in this study, the shape factor n was all below 1. According to the results of ANOVA, the shape factor n was not significantly affected by temperature ($p = 0.796$), but was significantly affected by the products ($p < 2.0 \times 10^{-16}$) and the interaction between the heating temperature and product types ($p = 0.047$). Overall, there was no significant difference in the means of the shape factors between Product B and Product C (regular and reduced sugar peanut butters). However, the mean shape factor was the highest in Product D, smaller in Products B and C, and the smallest in Product A. Table 2 also lists the raw data of the scale factor b for each product under each temperature. Judging from the raw b data in Table 2, it appears that the b values increase with temperature within each product. Within each temperature, the

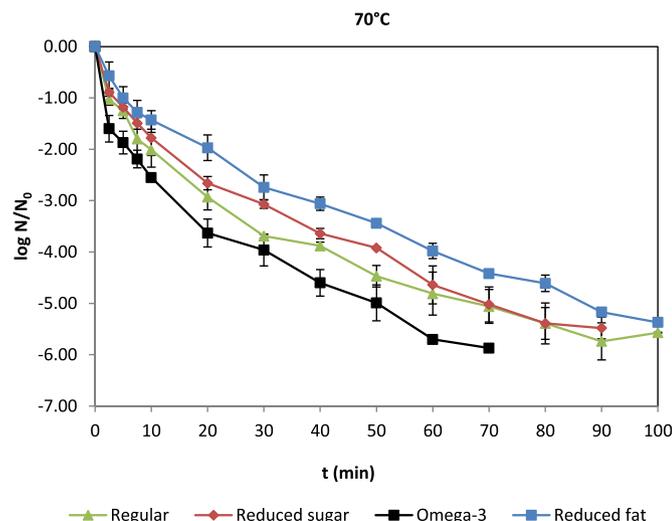


Fig. 2. Thermal inactivation of *Salmonella* spp. in peanut butter and peanut butter spread at 70 °C.

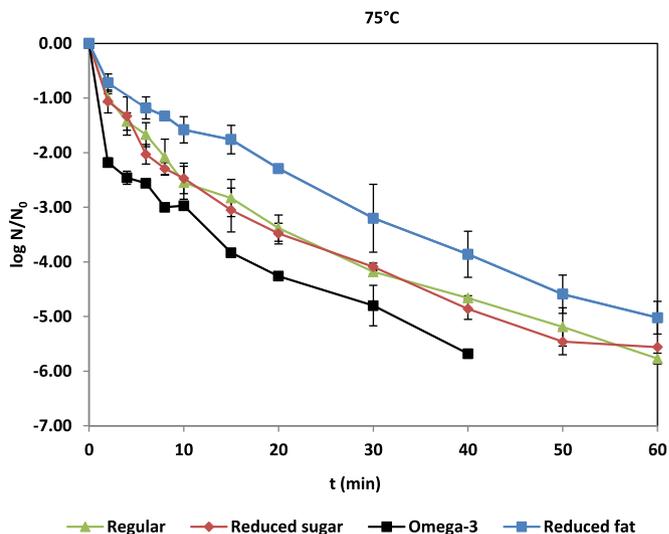


Fig. 3. Thermal inactivation of *Salmonella* spp. in peanut butter and peanut butter spread at 75 °C.

scale factors were the highest with Product A, smaller with Products B and C, and smallest with Product D, which is a reverse order of the thermal resistance of *Salmonella* in peanut butter and spread (highest with Product D, followed by Products B and C, and smallest with Product A).

To further evaluate the effect of temperature on the rate of thermal inactivation of *Salmonella* in each product, each survival curve was reanalyzed with the mean shape factor for each product. Fig. 7 illustrates the effect of temperature on the scale factor of the Weibull survival model in each product. It is clear that the shape factor (b) increases linearly with heating temperature. Therefore, a linear model (equation (2)) was used to correlate b and temperature for each product. The coefficients for equation (2) of each product are reported in Fig. 7. The R^2 of equation (2) ranged from 0.894 to 0.963, indicating that the linear model can be used to describe the effect of temperature on the scale factor in the Weibull survival model. In combination with equation (2), the Weibull model can be used to calculate the time needed to achieve a 5-log reduction of *Salmonella* in peanut butter and spread (Fig. 8). Again, it is easy to judge from Fig. 8 that the *Salmonella* inoculated to

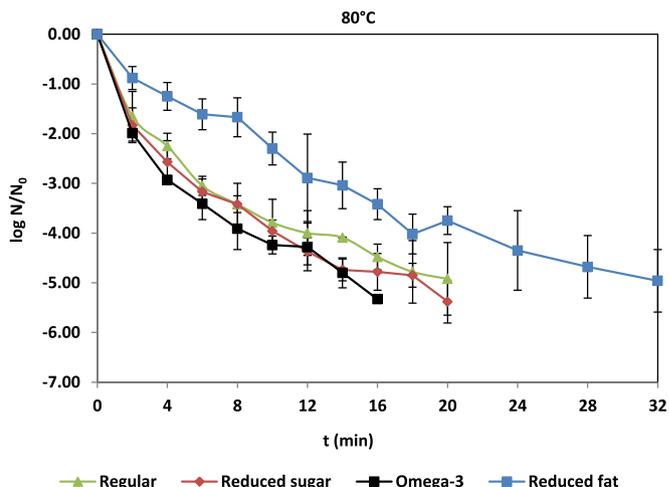


Fig. 4. Thermal inactivation of *Salmonella* spp. in peanut butter and peanut butter spread at 80 °C.

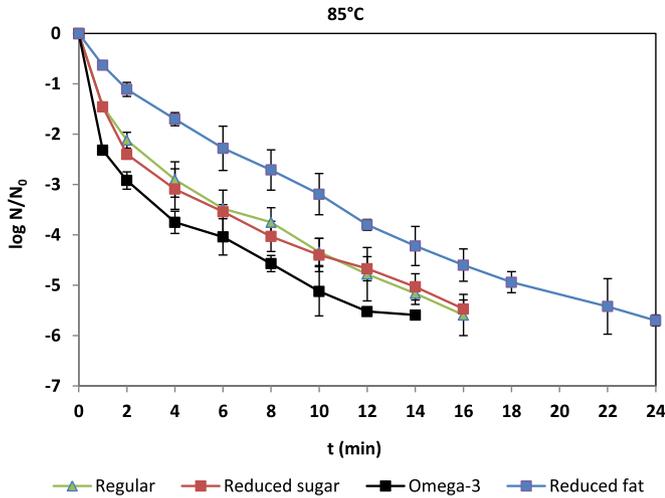


Fig. 5. Thermal inactivation of *Salmonella* spp. in peanut butter and peanut butter spread at 85 °C.

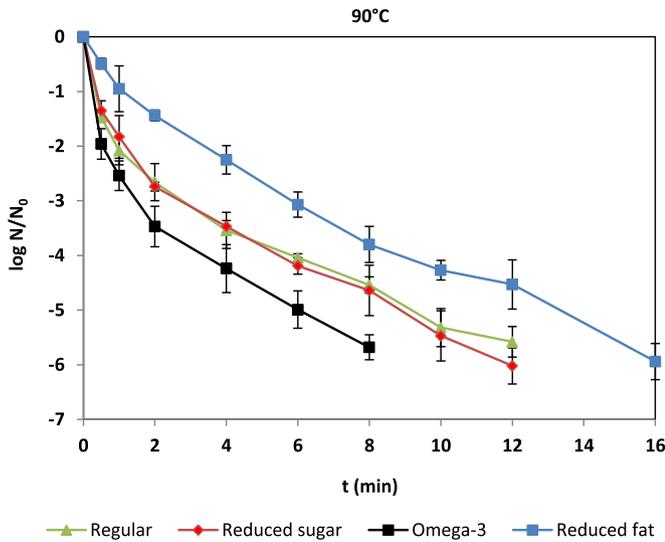


Fig. 6. Thermal inactivation of *Salmonella* spp. in peanut butter and peanut butter spread at 90 °C.

Product A showed the least resistance to heat, and the cells in the reduced fat product (D) exhibited the highest resistance among the four samples. The thermal resistance of *Salmonella* in regular and reduced sugar products (B and C) was similar, which was higher than that in Product A, but higher than that in Product D. According to equation (2) with $b = 0$ and the coefficients in Fig. 7, the

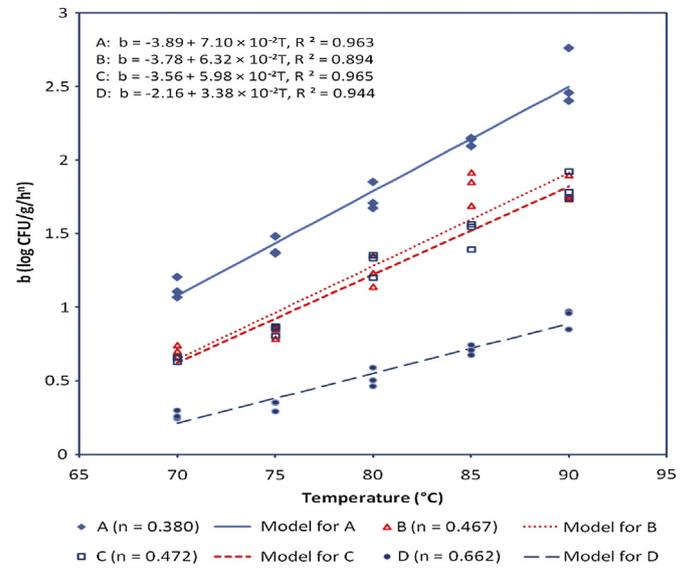


Fig. 7. Effect of heating temperature on the scale factor of the Weibull survival model for each product.

minimum lethal temperature for *Salmonella* was 54.8, 59.8, 59.5, and 63.9 °C in Products A, B, C, and D, respectively.

$$b = b_0 + kT \tag{2}$$

4. Discussion

Peanut butter is a product with very high fat contents and low water activity, both of which can provide protective effect towards *Salmonella* during thermal treatment. As a result, the *Salmonella* cells inoculated to peanut butter and spread samples could survive higher heating temperatures and longer times than those found in high moisture foods (GMA, 2009). This study shows that the inoculation method affected the results of kinetic data derived from thermal inactivation studies. In the preliminary study, the *Salmonella* cells in regular peanut butter (B) inoculated with PW suspension showed lower thermal resistance than those inoculated with oil suspension. The main reason attributing to the observed lower thermal resistance of *Salmonella* in the samples inoculated with PW suspension was probably due to the increased moisture surrounding the bacterial cells, as the water activity in these samples were higher (7.9%) than that in the samples inoculated with the oil suspensions. This observation could be also caused by poor mixing between the bacterial suspension and the peanut butter sample. Since peanut butter is basically an oil-based emulsion, the bacterial cells in PW suspension might not have completely mixed with the oil-rich matrix in the sample, creating localized high

Table 2
Mean coefficients for the Weibull survival model (mean and standard deviation) for each product and temperature.

| Temp (°C) | b | | | | n | | | |
|----------------|---------------|---------------|---------------|---------------|--------------------|--------------------|--------------------|--------------------|
| | A | B | C | D | A | B | C | D |
| 70 | 1.018 (0.190) | 0.728 (0.115) | 0.523 (0.093) | 0.338 (0.142) | 0.414 (0.041) | 0.460 (0.034) | 0.534 (0.052) | 0.621 (0.081) |
| 75 | 1.487 (0.065) | 0.746 (0.109) | 0.798 (0.145) | 0.355 (0.074) | 0.354 (0.015) | 0.504 (0.033) | 0.492 (0.049) | 0.649 (0.032) |
| 80 | 1.582 (0.101) | 1.289 (0.123) | 1.423 (0.247) | 0.496 (0.134) | 0.421 (0.030) | 0.454 (0.004) | 0.443 (0.042) | 0.683 (0.065) |
| 85 | 2.278 (0.193) | 1.452 (0.125) | 1.657 (0.191) | 0.677 (0.154) | 0.349 (0.046) | 0.482 (0.015) | 0.428 (0.034) | 0.688 (0.075) |
| 90 | 2.591 (0.293) | 1.925 (0.231) | 1.851 (0.131) | 0.917 (0.167) | 0.368 (0.024) | 0.432 (0.044) | 0.466 (0.030) | 0.673 (0.058) |
| Mean* (n = 15) | | | | | 0.380 ^c | 0.467 ^b | 0.472 ^b | 0.662 ^a |

* means with the same superscript are not statistically different at $\alpha = 0.05$.

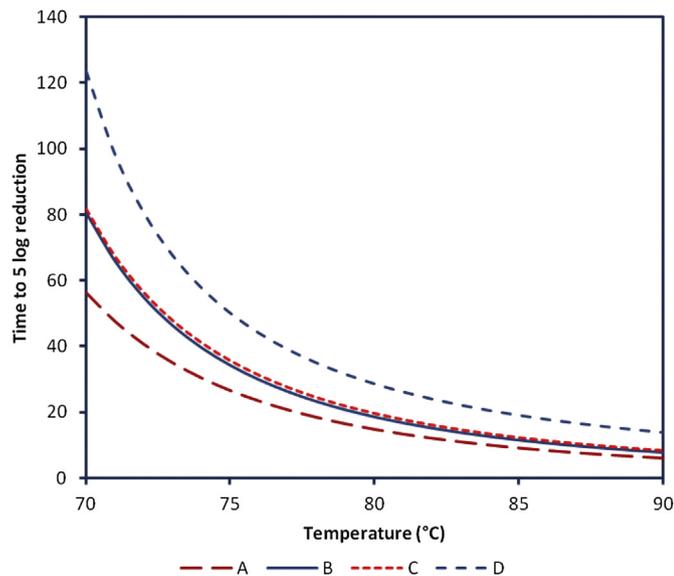


Fig. 8. Time to achieve a 5-log reduction of *Salmonella* at each temperature for each product.

moisture pockets. According to He et al. (2013), the thermal resistance of *S. enterica* was significantly reduced in peanut butter samples with increased water activity. Therefore, PW or water suspensions of *Salmonella* could not be used to inoculate peanut samples during thermal inactivation studies. The *Salmonella* cells in the oil suspension, however, could mix well with the oil-rich matrix. Therefore, the bacteria were protected by the high fat and low water activity environment in the peanut butter. As a result, the thermal inactivation data derived from the samples inoculated with oil suspensions might be more accurate than that derived from samples inoculated with PW suspensions.

The thermal resistance of *Salmonella* in reduced fat peanut (Product D) was higher than that in the other three samples. In the reduced-fat formulation, the product contained 33.3% fat, which was lower than that in the other three products. This product also contained significantly higher amount of carbohydrate (41.7%), in contrast to <24% carbohydrate in other products. Product D also contained corn syrup. However, the water activity of Product D was higher than that of Products B and C. The higher water activity should have reduced the thermal resistance of *Salmonella* in Product D. The elevated levels of total carbohydrate may have provided additional protective effects to *Salmonella*, since the simple sugars added to the product may partially dehydrate the bacterial cells, thus increasing the thermal resistance of *Salmonella*.

Since the water activity of Product A (Omega-3) was 0.463, it was not surprising to observe that the *Salmonella* cells in Product A was more sensitive to heat than those in Products B and C. However, the water activity of Product A was similar to Product D, which exhibited the highest thermal resistance among all samples tested in this study. This observation suggested that the water activity was probably not the only factor affecting the thermal resistance of *Salmonella* in peanut butter. The exact reason behind this observation is not clear, but it could be attributed to the composition of the fatty acids in the products. The higher water activity and Omega-3 fatty acids in Product A may be the main reason why the highest reduction of *Salmonella* spp. observed under the same heating conditions.

The survival curves reported in Shachar and Yaron (2006) showed significant tail effect and a significant portion of *Salmonella* survived after extended heating. The severe tail effect was not

observed in this study, suggesting that it is possible to eliminate *Salmonella* in peanut butter and spread.

Although all survival curves of *Salmonella* in peanut butter reported in the literature were analyzed with the Weibull model, the survival curves were also analyzed using the first order inactivation kinetics. Therefore, the D-values of *Salmonella* in peanut butter are also reported in the literature. For example, the D-values of *Salmonella* (overnight cultures) in peanut butter ranged from 2.33 to 2.55 min at 90 °C in the study reported in He et al. (2011). He et al. (2013) reported the D-values of *Salmonella* were affected by formulation, serotype, and water activity, and the D-values of *Salmonella* in peanut samples ($A_w = 0.4$) at 90 °C range from 1.35 to 2.64 min. With similar A_w (~ 0.4), the average D-value of *Salmonella* was 2.25/0.19 min (mean/standard deviation, $n = 3$) in regular peanut butter (B) and 2.69/0.23 min in reduced fat peanut butter spread, respectively. Therefore, the D-values in comparable products obtained in this study were within the range of the D-values reported in the literature.

5. Conclusions

In summary, this study observed that the *Salmonella* in reduced fat peanut butter spread exhibited significantly higher thermal resistance than that in other peanut butter products. On the other hand, the Omega 3 formulation proved to provide the least protective effect to *Salmonella*. This study suggests that proper formulation of peanut butter may enhance thermal inactivation of *Salmonella* in peanut butter. The kinetic parameters and models developed in this study can be used to guide thermal inactivation of *Salmonella* in peanut butter and peanut butter spread products.

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