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Modeling the survival of *Salmonella* spp. in chorizos

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Abstract

The survival of *Salmonella* spp. in chorizos has been studied under the effect of storage conditions; namely temperature (T=6, 25, 30 °C), air inflow velocity (F=0, 28.4 m/min), and initial water activity (a_{w0}=0.85, 0.90, 0.93, 0.95, 0.97). The pH was held at 5.0. A total of 20 survival curves were experimentally obtained at various combinations of operating conditions. The chorizos were stored under four conditions: in the refrigerator (Ref: T=6 °C, F=0 m/min), at room temperature (RT: T=25 °C, F=0 m/min), in the hood (Hd: T=25 °C, F=28.4 m/min), and in the incubator (Inc: T=30 °C, F=0 m/min). Semi-logarithmic plots of counts vs. time revealed nonlinear trends for all the survival curves, indicating that the first-order kinetics model (exponential distribution function) was not suitable. The Weibull cumulative distribution function, for which the exponential function is only a special case, was selected and used to model the survival curves. The Weibull model was fitted to the 20 curves and the model parameters (α and β) were determined. The fitted survival curves agreed with the experimental data with R^2=0.951, 0.969, 0.908, and 0.871 for the Ref, RT, Hd, and Inc curves, respectively. Regression models relating α and β to T, F, and a_{w0} resulted in R^2 values of 0.975 for α and 0.988 for β. The α and β models can be used to generate a survival curve for *Salmonella* in chorizos for a given set of operating conditions. Additionally, α and β can be used to determine the times needed to reduce the count by 1 or 2 logs (t_{1D} and t_{2D}). It is concluded that the Weibull cumulative distribution function offers a powerful model for describing microbial survival data. A comparison with the pathogen modeling program (PMP) revealed that the survival kinetics of *Salmonella* spp. in chorizos could not be adequately predicted using PMP which underestimated the t_{1D} and t_{2D}. The mean of the Weibull probability density function correlated strongly with t_{1D} and t_{2D}, and can serve as an alternative to the D-values normally used with first-order kinetic models. Parametric studies were conducted and sensitivity of survival to operating conditions was evaluated and discussed in the paper. The models derived herein provide a means for the development of a reliable risk assessment system for controlling *Salmonella* spp. in chorizos.

Keywords: Chorizos; *Salmonella* spp.; Regression models; Survival curves; Weibull distribution function

1. Introduction

Mexican-style chorizo sausages are similar to the Spanish-style chorizo except that a controlled fermentation process using starter cultures is seldom used to acidify the Mexican-style version. Producers rely on a spontaneous fermentation with indigenous flora (Kuri et al., 1995; Escartín et al., 1999) or the addition of vinegar (acetic acid; Escartín et al., 1999) to reduce the pH of the sausages. *Salmonella* is one of several pathogens that have been a concern in chorizos. Other pathogens include *Listeria monocytogenes* and *Escherichia coli* O157:H7.

Chorizo sausages have not been implicated in any reported foodborne illness in the United States to date. However, *Salmonella* was recovered from this ethnic commodity outside the U.S. Raw pork chorizos produced and sold in Mexico City were found to contain *Salmonella* spp. in 41% of refrigerated and 46% of non-refrigerated samples tested (Kuri et al., 1995). Chorizo sausages sampled from butcher shops, grocery stores and retail markets in Guadalajara and Querétaro, Mexico had an even higher incidence of *Salmonella* contamination at 88.3% and 78%, respectively (Escartín et al., 1999). These findings show that there is a potential for *Salmonella* survival in this product.

In California, Mexican-style chorizos are of concern as they are raw meat sausages that often include ingredients that cause

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the final product to appear cooked, whereby consumers may eat the raw sausage without prior, proper cooking. Additionally, there are no existing mandates (state or federal) to inspect raw sausage production at local retail or ethnic markets. The responsibility is left to local health authorities, and limited expertise is available relating to that commodity. Consequently, these products enter the consumer food chain uninspected.

To address the above concerns, we conducted a number of studies examining the survivabilities of bacterial foodborne pathogens including *Salmonella* spp. in chorizos, as affected by environmental conditions such as water activity, pH and storage conditions. Results of some of this work have already been published (Hew et al., 2005b). The purpose of the present study was to develop a mathematical model to describe the survival of *Salmonella* spp. in chorizo that has been prepared and stored under environmental conditions similar to those commonly used in ethnic manufacturing facilities. The model is based on data collected from an actual food system, chorizo, rather than experimentally inoculated laboratory media.

2. Materials and methods

2.1. Bacterial strains

A cocktail of five *Salmonella* serovars was prepared to inoculate the chorizo batter. *Salmonella enteritidis*, *Salmonella gamanara*, *Salmonella newport* and *Salmonella typhimurium* were obtained from the laboratory of Dr. Dean O. Cliver at the University of California, Davis (UCD), and *Salmonella montevideo* was obtained from the laboratory of Dr. Linda J. Harris at UCD. The cocktail was prepared by growing each strain individually in Brain Heart Infusion (BHI, BD-Difco, Sparks, MD, USA) broth supplemented with 100 ppm ampicillin (AMP) for 18±2 h at 37 °C under aerobic conditions (Hew et al., 2005b). The cultures used have a plasmid that codes for ampicillin resistance and allows the microorganisms to fluoresce under long wave UV light, allowing us to detect them more easily and alleviating the problem with background flora when culturing *Salmonella*. The 18-h cultures were centrifuged at 15,000×*g* and 4 °C for 10 min, and the pellets were resuspended in equivalent amounts of 0.1% peptone water (PW, BD-Difco). Equal volumes of the individual suspensions were mixed to give the final five-strain cocktails for addition to the chorizo batters.

2.2. Chorizo processing

Preparation methods of chorizo sausages were the same as those outlined by Hew et al. (2005a,b). Briefly, ground fresh non-cured pork shoulder butt was mixed with garlic powder (~1.62%, McCormick and Co, Inc., Hunt Valley, MD), guajillo chili pepper powder (~1.62%, Mojave Foods Corp., Los Angeles, CA), cumin (~0.43%), black pepper (~0.43%), and paprika (~0.86%, McCormick and Co, Inc.). Percentages of added spices were based on the initial weight of each batch of meat. Thereafter, acetic acid (vinegar, white, Heinz, Pittsburgh, PA) was added to reduce the final pH of the batter to 5.0. Enough table salt (sodium chloride, NaCl, Morton®, Chicago, IL) was added to each batch to yield a chorizo formulation with initial a_w of 0.85, 0.90, 0.93, 0.95, or 0.97 (13.3%, 9.5%, 6.0%, 4.4%, and 2.6% salt, based upon the initial weight of a batch of meat). Each chorizo batch was inoculated with the five-strain cocktail at a 1% level by weight. The initial inoculum level was fixed at approximately 6.2 log CFU/g. Chorizo links (average weight=122 g; average size=3×13 cm) were then individually prepared from each inoculated batch by stuffing the product into the pre-soaked natural pork casings (Oversea Casing Co., Seattle, WA). The 32 links per batch were randomly divided into four groups of eight, individually labeled, weighed, and mounted on hanging racks. Of the four groups per batch, two were stored at room temperature, 25–26 °C; one (labeled "Inc") was stored at elevated temperatures, 30–31 °C, in an incubator; and another group (labeled "Ref") was stored in a refrigerator at 6–8 °C (the refrigerator was set at 6 °C and most of the refrigerated samples were at that temperature with a few exceptions). Of the two groups stored at room temperature (~25 °C), one was labeled "Hd" and placed in a laminar flow hood (average inflow velocity was 28.4 m/min, down flow volume was 9.4 m^3/min, exhaust volume was 5.1 m^3/min), while the second was labeled "RT" and stored in a designated location in the laboratory workroom. A sufficient number of links was prepared per batch to account for all sampling times − 1, 2, 4, and 7 days per storage condition. At each sampling time, each selected sausage was weighed and tested for pH, a_w, and counts of *Salmonella* spp. Each formulation of sausages (which represented one of the five initial a_w) was prepared and tested twice. At each sampling time, two sausages were tested per treatment combination. Detailed descriptions of methods for determining pH, and a_w can be found in Hew et al. (2005a). Additionally, results relating to pH and a_w can be found in Hew et al. (2005b).

2.3. Microbiological analysis

On each sampling day, a 25-g sample per selected chorizo link was individually removed and aseptically transferred to a Whirl-Pak® bag (NASCO, Modesto, CA) containing 50 ml of PW. Samples in the bags were homogenized for 2 min using a Stomacher™ (Model # STO-400, Tekmar® Co., Cincinnati, OH). Serial dilutions were prepared from each sample, using 9-ml dilution blanks of PW. Counts of the transformed pathogen were determined by spread plating samples on BHI+AMP in duplicate using 0.1 ml of the initial and all subsequent dilutions. Each 0.1 ml of inoculum was distributed evenly over the surface of a BHI+AMP plate, using a sterile "hockey stick" (Cole-Palmer, Vernon Hills, IL). Plates were incubated at 37 °C for 24 h and enumerated; microbial counts were reported as CFU/g.

2.4. Model description and derivation

The survival curve for a microorganism is defined as the decline from the initial count (or log count) of the microor-

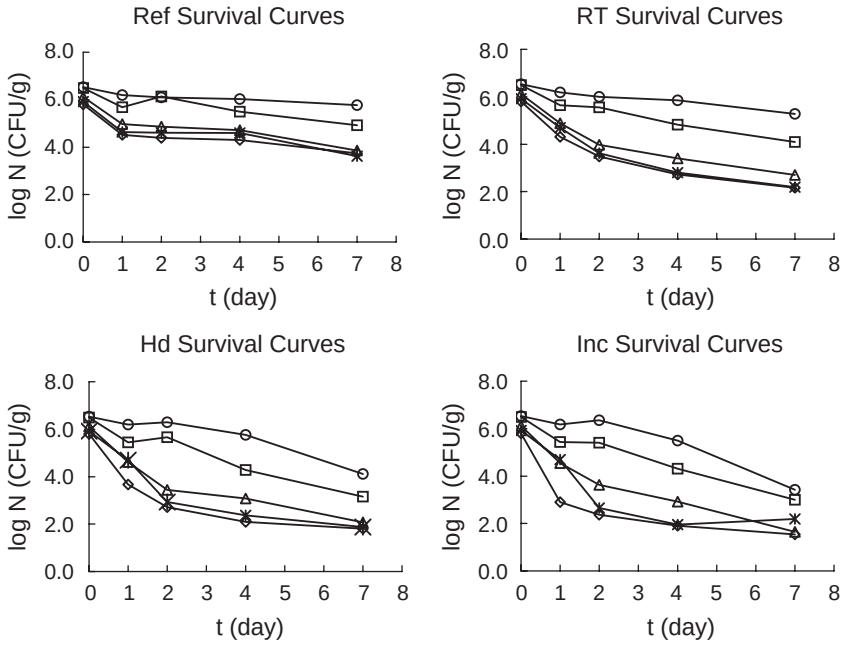

Fig. 1. The experimentally obtained survival curves for *Salmonella* spp. at four (T, F) conditions and five a_{w0} values. Ref: (6,0); RT: (25,0); Hd: (25,28.4), and Inc: (30,0). a_w: −◇−, 0.85; −∗−. 0.90; −△−, 0.93; −□−, 0.95; −○−, 0.97.

ganism with time as affected by one or more stressors (e.g., chemical or thermal). Unlike thermal inactivation of microorganisms using elevated temperatures, the reduction in count in this study is primarily attributed to reduction in the water activity as affected by drying of the tested chorizo sausages at relatively moderate temperatures (6−30 °C). The Weibull distribution function was used for modeling the survival curves of *Salmonella* spp. This distribution, which has been widely used in many industrial applications to describe the failure of industrial components with time, has recently been investigated by a number of researchers in the field of predictive microbiology (e.g. Cunha et al., 1998; Peleg and Cole, 1998; Fernandez et al., 1999; Hutchinson, 2000; Van Boekel, 2002). The probability density function and the corresponding cumulative distribution function of the Weibull distribution can be found in statistics and probability textbooks. The cumulative distribution function, $F(t)$, where t is time, is expressed as (Devore, 1991):

$$F(t;\alpha,\beta) = 1 - \exp[-(\beta t)^{\alpha}] \quad (1)$$

for $t \geq 0$, and $F(t;\alpha,\beta)=0$ elsewhere. The distribution parameter $\beta>0$ is a scale factor (units of reciprocal of time) and $\alpha>0$ is a shape parameter (unitless). If $F(t;\alpha,\beta)$ denotes the fraction of microorganisms that have died by time t, then the Weibull cumulative function describes this decline in the number of microorganisms. If the initial count of microorganisms is denoted by N_0 and the count at any time, t, is denoted by $N(t)$, then $F=1-[N(t)/N_0]$. Hence, the Weibull function for the fraction of microorganisms remaining may be written as:

$$N^*(t) = \exp[-(\beta t)^{\alpha}] \quad (2)$$

in which $N^*(t)=N(t)/N_0$; the proportion of microbial count at time t relative to the initial count. When $\alpha=1$, the Weibull function reduces to the first-order kinetic model $\ln(N^*)=-\beta t$, in which β refers to the rate constant. When $\alpha \leq 1$, the N^* vs. t curve is concaved-up, indicating a decreasing death rate with time. When $\alpha>1$, the survival curve is concaved downward with an initial shoulder indicating an increasing death rate with time. Similar curves, except without an initial shoulder for $\alpha>1$, will also result if log N^* is plotted against t. For the case with $\alpha=1$ (first-order model), the log N^* vs.

Table 1
Fitted α and β parameters of the 20 experimental survival curves

T (°C)	F[a]	a_{w0}[b]	α	β (day^{-1})
6	0	0.85	0.3203	18.815
		0.90	0.3198	17.499
		0.93	0.3193	16.203
		0.95	0.3073	2.944
		0.97	0.2962	0.547
25	0	0.85	0.3309	72.404
		0.90	0.3300	64.078
		0.93	0.3285	52.890
		0.95	0.3178	12.815
		0.97	0.3065	1.267
	28.4	0.85	0.3356	133.009
		0.90	0.3326	88.257
		0.93	0.3322	84.779
		0.95	0.3216	21.108
		0.97	0.3022	1.253
30	0	0.85	0.3383	186.990
		0.90	0.3361	90.997
		0.93	0.3329	92.365
		0.95	0.3232	26.149
		0.97	0.3116	1.607

[a] Air flow rate (m/min).
[b] Initial water activity.

t is represented by a straight line (i.e., constant death rate). Fig. 1 shows the log N^* vs. t experimental survival curves obtained for the *Salmonella* spp. tested in this study. It is evident that such curves are not linear, indicating the inadequacy of a first-order kinetic model to describe the data.

Both α and β can be determined by linear transformation of Eq. (2) (Hutchinson, 2000), although nonlinear least-squares regression can also be used. Taking twice the natural logarithm of both sides of Eq. (2) yields:

$$\ln[-\ln(N^*(t))] = \alpha\ln\beta + \alpha\ln t \tag{3}$$

where ln is the natural logarithm operator. Thus, given set of (t,N^*) data points representing the fraction of count at given times, the left-hand side of Eq. (3) is plotted against ln$t$, and a best-fit line is drawn through the data points, from which α=slope, and β=exp (intercept/α). In reliability engineering, such plots are known as hazard plots and commonly used as a test for judging the applicability of the Weibull model (Nelson, 1972).

The t_{1D} (or D-value) is the time corresponding to 90% (or 1 log) reduction from initial count. Thus, with $N^*=0.1$, t_{1D} can be determined from Eq. (3). Similarly, t_{2D} is the time required to reduce the count by 2 logs (99%). In general, for n logs reduction, t_{nD} is determined from:

$$t_{nD} = \frac{1}{\beta}\cdot(\ln 10^n)^{1/\alpha} \tag{4}$$

2.5. Summary of calculation procedure

1. For a given set of operating conditions, normalize N in each of the (t,N) pairs by dividing each value by the initial count N_0 to obtain a set of (t,N^*) pairs.
2. For each (t,N^*) data pair, compute ln$t$ and ln($-$lnN^*) according to Eq. (3). To avoid taking the natural logarithm of zero, either discard the initial-condition point (t,N^*)=(0,1) if enough data points are available, or replace the initial time of zero with a small number (e.g., 10^{-20} days=8.64×10^{-13} ms), and the initial N^* of 1 with 0.999999. These two values were used in this study. Practically, (t,N^*)=(0,1) should be

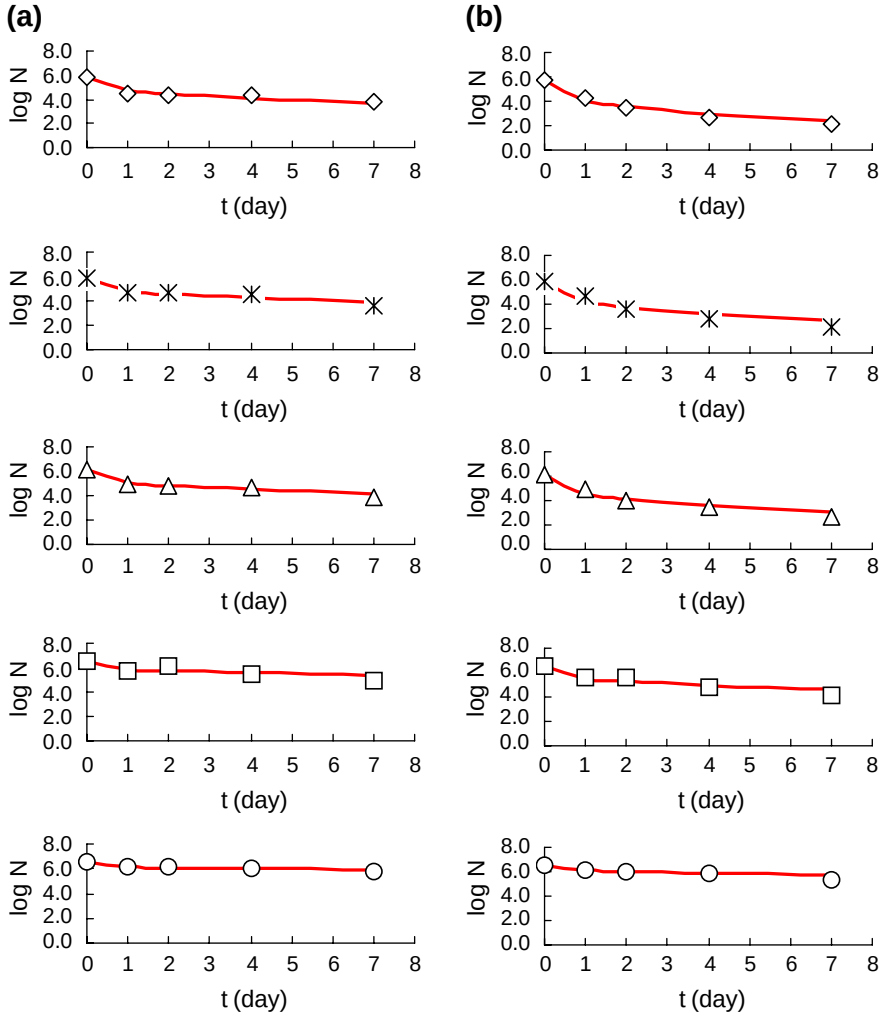

Fig. 2. Comparison between the predicted survival curve and the measured log N values. (a) Ref cases, (b) RT cases, (c) Hd cases, and (d) Inc cases. a_w: −◇−, 0.85; −∗−. 0.90; −△−, 0.93; −□−, 0.95; −○−, 0.97.

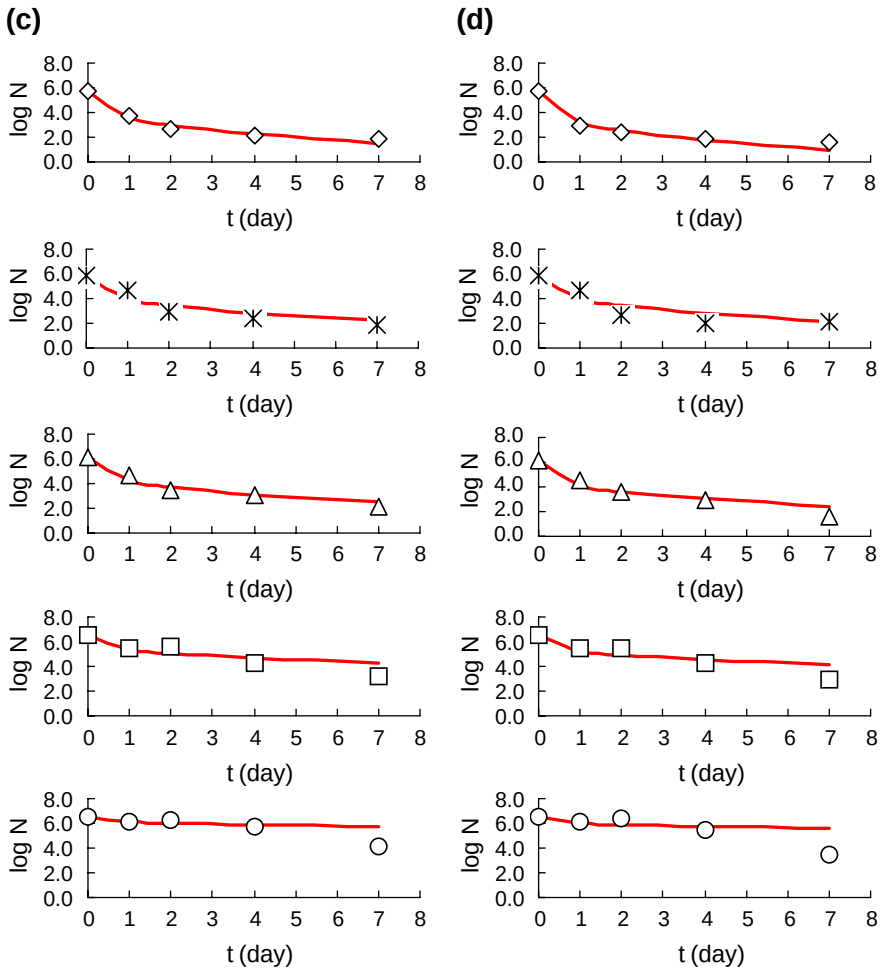

Fig. 2 (*continued*).

very close to (8.64×10^{-13} ms, 0.999999), considering the precision and sensitivity, at the present, of the methods conventionally used to measure time and count.

3. Using the transformed pairs, plot the ln$t$ on the x-axis and ln(−ln$N$*) on y-axis.
4. Fit a straight line to the plotted transformed data and calculate its slope (s) and intercept (i). Compute the Weibull's model parameters $\alpha = s$, and $\beta = \exp(i/\alpha)$.
5. Using α and β, determine t_{1D} and t_{2D} from Eq. (4).
6. For each experimental survival curve (known set of operating conditions such as a_{w0}, T, F), repeat 1–5.
7. Develop models (e.g., using multilinear regression) to describe the variation of α and β with the set of operating conditions. Such models will enable the determination, for any set of operating conditions, the α and β parameters necessary to compute survival kinetics (e.g., t_{1D}, t_{2D}) and plot the survival curves according to the Weibull model (Eq. (2)).

3. Results and discussion

3.1. Survival curves

The (T, F) conditions tested were: Ref(T,F) = (6,0), RT(T,F) = (25,0), Hd(T,F) = (25,28.4), and Inc(T,F) = (30,0) where T is in °C and F in m/min. With five a_{w0} values, a total of 20 experimental survival curves were obtained, as shown in Fig. 1. The Weibull's optimal values of the model parameters α and β were determined, and then were used to estimate the counts at the five measurement times (0, 1, 2, 4, and 7 days). The Weibull model linear transformation yielded almost perfect straight lines with R^2 ranging from 0.995 to 0.999, indicating that the data followed the Weibull distribution. The α and β of the Weibull model obtained for the 20 curves are summarized in Table 1. Fig. 2(a,b,c,d) shows comparison between the experimentally obtained survival curves and the estimated counterparts, for the four different storage conditions. The experimental survival curves agreed with the estimated counterparts with $R^2 = 0.951$ for the Ref data, 0.969 for the RT data, 0.908 for Hd data, and 0.871 for the Inc data. The reasonably high agreement between the experimental and estimated survival curves indicates the appropriateness of the Weibull distribution function to model the survival of *Salmonella* spp. in chorizos.

3.2. Response surface models

Since the Weibull function has been found to describe the variation of the number of *Salmonella* spp. survivors with time,

the next step was to develop models to enable the prediction of α and β for any known storage condition described by T, F, and a_{w0}. The relationship between each of the model parameters (α and β) and the set of operating conditions (T, F, a_{w0}) was determined using multiple linear stepwise regression analysis with the aid of EssentialRegression© (Werner et al., 2001). This software allows the user to use a number of transformations for the dependent variable including ln, square root, power, exponential, standardized, etc.

For the α parameter, the best prediction model was a third-degree model with interaction:

$$\alpha = b_0 + b_1 a_{w0}^3 + b_2 T^2 + b_3 a_{w0}^2 + b_4 a_{w0} \quad (5)$$

where the a_{w0} and T are the initial water activity and storage temperature, respectively, and b_0 through b_5 are the obtained model coefficients. The values of the various model coefficients along with their standard error of estimate (S.E.) and p-values are summarized in Table 2. Eq. (5) indicates that both the a_{w0} and storage temperature affect the α parameter, while the F was not a significant variable at 95% confidence level. Fig. 3a shows the agreement between α fitted from experimental data and α estimated by the model, which yielded an $R^2=0.975$.

For β, the best obtained regression model was a square-root β model with interaction which showed the influence of the T, F, and a_{w0}. The model is expressed as:

$$\sqrt{\beta} = b_0 + b_1 a_{w0}^3 + b_2 T^2 + b_3 a_{w0}^2 + b_4 a_{w0} T^2 + b_5 TF \quad (6)$$

where β is in day^{-1}. The model coefficients b_0 through b_6 and their standard errors and p-value are also given in Table 2. The model's $R^2=0.945$. Fig. 3b shows the agreement between the fitted and estimated $\beta^{1/2}$ values.

For both the α and β models, the plots of residuals (not shown in this paper) against the independent and predicted variables showed a random distribution, indicating the validity of the assumption of normal distribution of errors.

Because the above models are empirically based, it is important to limit their use within the ranges of operating conditions used in their development (i.e., $T=6-30$ °C, $F=0-28.4$ m/min, and $a_{w0}=0.85-0.97$).

Table 2
The coefficients, S.E., and p-values of the α and β models

Parameter model	Coefficient	Value	S.E.	p-value
α	b_0	32.24256	9.46168	0.003896
	b_1	−46.0525	12.54658	0.002272
	b_2	1.85E−05	1.55E−06	4.66E−09
	b_3	122.2954	34.30177	0.002819
	b_4	−108.233	31.2226	0.003453
$\beta^{1/2}$	b_0	−193.59	43.56	0.000555
	b_1	−556.36	115.01	0.000263
	b_2	0.07368	0.01646	0.000523
	b_3	745.36	157.34	0.000318
	b_4	−0.07417	0.01788	0.000983
	b_5	0.00153	0.000777	0.06903

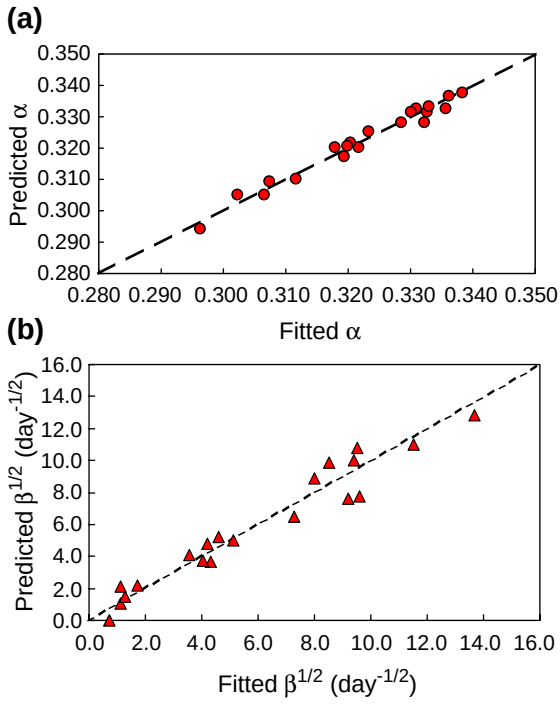

Fig. 3. Agreement between the fitted Weibull parameters and their respective modeled values: (a) α and (b) β parameters. ---- Equality line.

Once the α and β parameters are determined, the survival curve may be plotted and the survival times t_{1D} and t_{2D} can be determined using Eq. (4).

3.3. Effect of T, F, and a_{w0} on α and β

The effect of storage conditions (T, F) and a_{w0} on the Weibull shape parameter α is shown in Fig. 4. Note that F does not affect α (Eq. (5)). For the range of T and a_{w0} used in generating the experimental data, the parameter α remained below 1.0, indicating an initial shoulder-free survival curve. Additionally, α is much smaller than 1.0 indicating the high

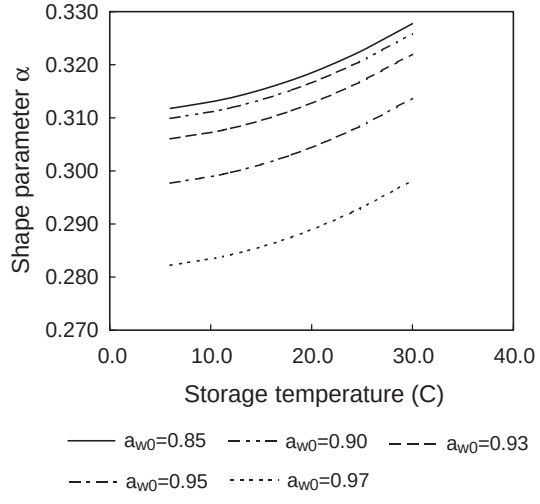

Fig. 4. Effect of storage temperature and initial water activity on Weibull parameter α.

deviation of the data from the first-order kinetic model. For a given T, α increases as a_{w0} decreases. Additionally, for a given a_{w0}, α increases with T, and the increase becomes faster as the temperature gets higher. An increase in α indicates a smaller relative count, N^*. Fig. 4 also shows that for drier chorizo formulation (lower a_{w0}), α becomes less sensitive to a_{w0}, compared to wetter formulations (higher a_{w0}). For instance, a decrease in a_{w0} from 0.95 to 0.85 would result in nearly the same amount of increase in α as it decreases from 0.97 to 0.95.

Fig. 5(a,b) shows the effect of a_{w0}, T, and F on Weibull's scale parameter β for two F values; namely $F=0$ and 28.4 m/min, the latter being that of the hood. The β is plotted on logarithmic scale as the values varied over 2 orders of magnitude, which yielded straight lines rather than curvilinear when plotted on linear scale. As seen from Fig. 5, β increases with T and decreases with a_{w0} (higher β indicates lower relative count, N^*). The F does not seem to have great influence on β; however, the variation lines tend to move up towards higher β as F increases. Additionally, the sensitivity of β to initial water activity increases by increasing storage temperature. As was seen with α, sensitivity of the β parameter was more pronounced with higher a_{w0} formulations.

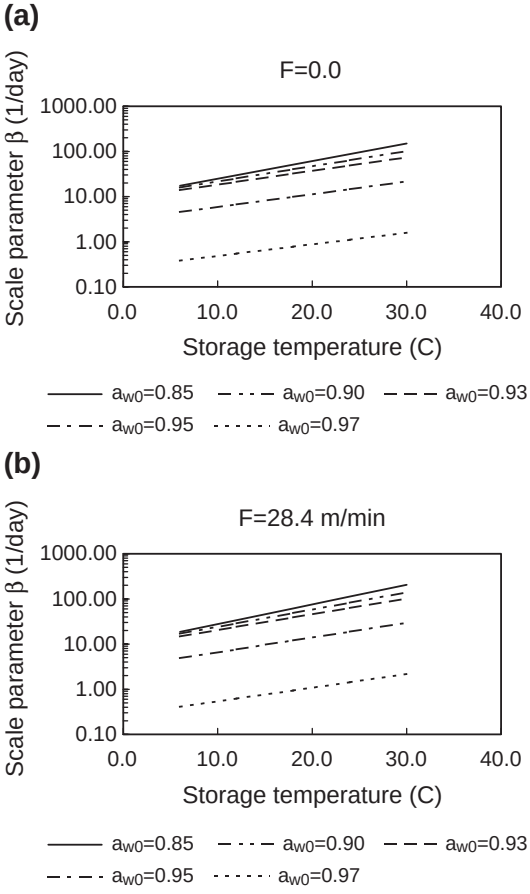

Fig. 5. Effect of storage temperature, air inflow velocity (F) and initial water activity on Weibull parameter β: (a) $F=0$ and (b) $F=28.4$ m/min.

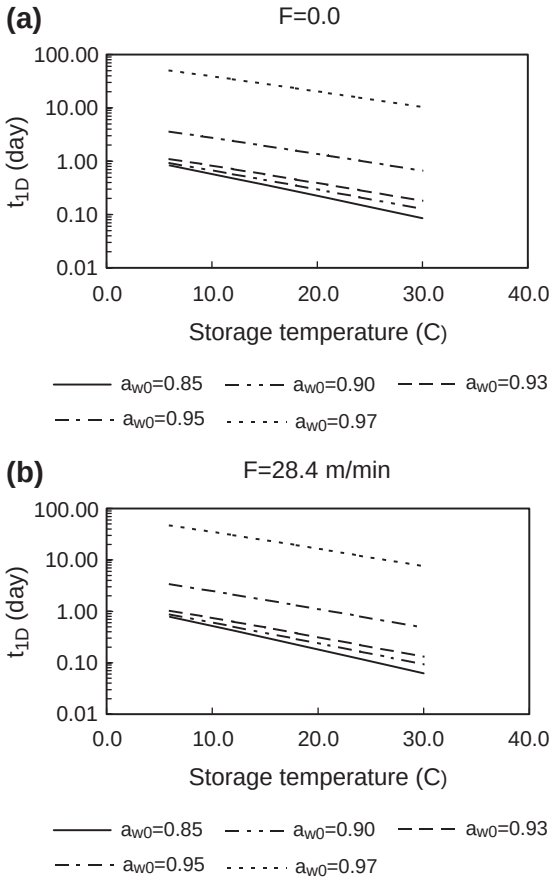

Fig. 6. Effect of storage temperature, air inflow velocity (F) and initial water activity on t_{1D}: (a) $F=0$ and (b) $F=28.4$ m/min.

3.4. Effect of T, F, and a_{w0} on t_{1D} and t_{2D}

Both t_{1D} and t_{2D} are affected by model parameters α and β as explained by Eq. (4), which in turn are affected by storage conditions and a_{w0}. Therefore, these times are affected by those operating conditions. Fig. 6(a,b) shows the variation in t_{1D} at two F values, plotted on semi-logarithmic plot, yielding straight lines (linear scale shows curvilinear variation). The t_{1D} decreases with increasing T, and increases with a_{w0}. As seen in Fig. 6, t_{1D} does not exceed 1 day for all formulations with a_{w0} below 0.93, regardless of F. Only when a_{w0} exceeds 0.95 does F affect, though slightly, the t_{1D}. For the $a_{w0}=0.97$ cases, the D-value ranges from 10 days (at $T=30$ °C) to as high as 50 days (at $T=6$ °C). Also, when a_{w0} increases from 0.95 to 0.97, the D-value increases by about 9 days at $T=30$ °C and by about 45 days at $T=6$ °C.

Similar trends were also observed with t_{2D}; however, the times were much larger. The variation of t_{2D} with T, a_{w0}, and F is shown in Fig. 7. For a_{w0} up to 0.93, the t_{2D} does not exceed 10 days regardless of T and F. For these formulations, only with storage temperature exceeding 30 °C does the t_{2D} get below 1 day. Increasing the a_{w0} from 0.95 to 0.97 would result in dramatic increase in t_{2D} by about 110 days at 30 °C and 460 days at 6 °C.

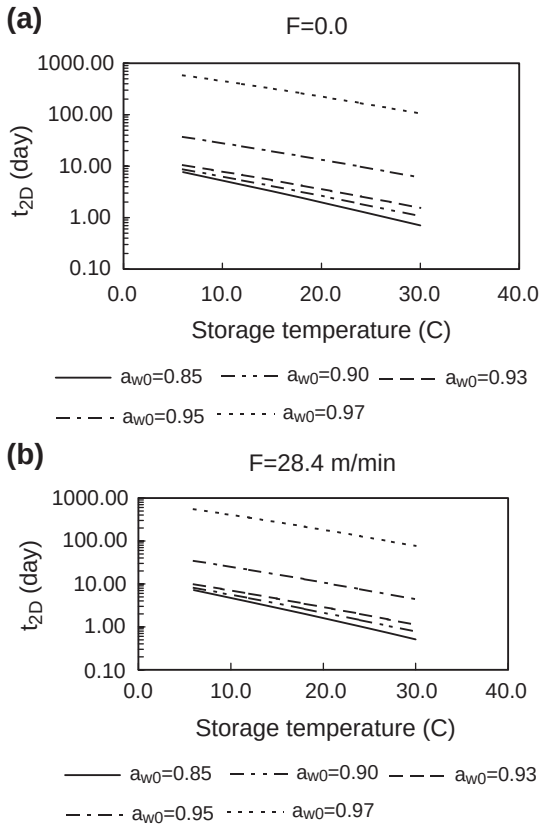

Fig. 7. Effect of storage temperature, air inflow velocity (F) and initial water activity on t_{2D}: (a) $F=0$ and (b) $F=28.4$ m/min.

3.5. Comparison with other studies

Van Boekel (2002) computed Weibull parameters for a large number of inactivation studies carried out by other researchers on various food products, laboratory media, and microorganisms. It is quite difficult to make direct comparison between the Weibull parameters obtained by Van Boekel (2002) and those calculated in this study because: (1) Chorizo (with its distinct formulation) was none of the products tested earlier. (2) A *Salmonella* cocktail was used in our chorizo study but one *Salmonella* serovar was examined in the other studies. The five-serotype cocktail was used to afford some genetic diversity. These were plasmid-transformed, ampicillin-resistant, fluorescent cultures. Such cultures have been used in several laboratories for many years, and no bias has yet been reported relative to non-transformed bacteria. (3) Thermal destruction was conducted at high temperature, normally above 50 °C in the studies cited, whereas in the current work, drying at temperatures of 30 °C and below was the primary mechanism for reducing the count. (4) There were differences in the durations of treatment. Furthermore, while the majority of the studies including that on *Salmonella* analyzed by Van Boekel (2002) involved egg yolk, milk, and lab media, one involved (plain) ground beef. For the ground beef study, van Boekel computed $\beta=41.1$, 800, and 4800 day^{-1} for $T=51.6$, 57.2, and 62.7 °C, respectively, and an α of ~1.0 (not affected by T). Notice that van Boekel's β is our α, and his α is the reciprocal of our β with conversion from minutes to days. Using our α and β models with $a_{w0}=0.85$ and $F=0$, the "extrapolated" values for β at these higher temperatures were computed as 997.0, 1448.2, and 2031.2 day^{-1}, respectively, and an average α of 0.38. As expected, both α and β obtained from the chorizo models differed from those determined for the ground beef, and the differences may be attributed to many reasons including: (1) microorganism itself, (2) extrapolation used in chorizo models, (3) different meat formulations (plain vs. spiced ground beef) and product type and (4) variable duration of treatment.

3.6. Comparison with pathogen modeling program

The t_{1D} and t_{2D} for a number of operating conditions (T, a_{w0}) predicted using Eq. (4) were compared to the respective values obtained using the Pathogen Modeling Program (PMP version 6.0). The PMP is based on microbial survival and growth data obtained using a broth system, not an actual food system as is the case with chorizos. Fig. 8 shows the agreement between the predicted t_{1D} and t_{2D} and those obtained using the PMP. As can be seen, for $a_{w0}\geq 0.95$, the PMP predicted a shorter time needed to reduce the count by one log (t_{1D}) than those predicted using the derived models. Also, the PMP underestimated the t_{2D} for all a_{w0} values tested. This suggests the inability of the PMP to predict accurate and safe survival kinetics for the food system studied in this research.

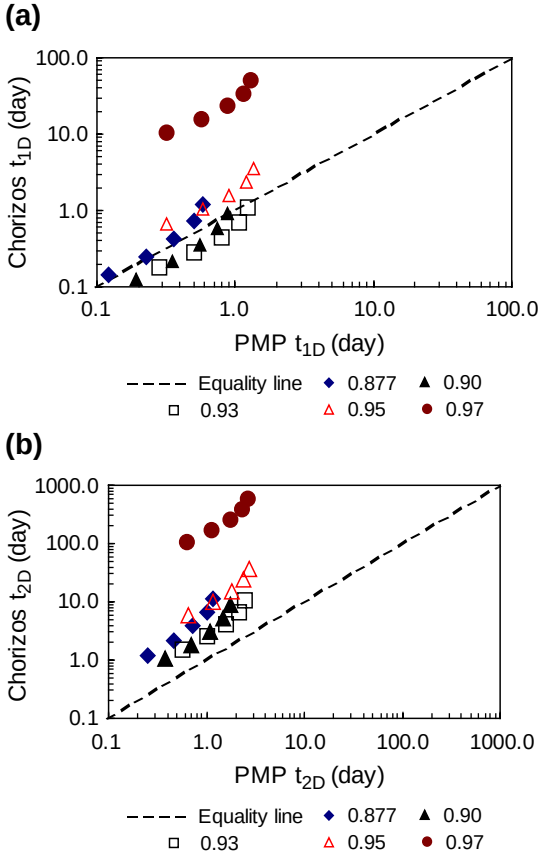

Fig. 8. Comparison between PMP-predicted t_{1D} and t_{2D} and prediction using the chorizos model.

4. Conclusions

The survival curves of *Salmonella* spp. in chorizos as affected by initial water activity and storage conditions did not follow a first-order reaction model. However, the Weibull cumulative distribution function was adequate to describe those survival curves in response to a_{w0}, T, and F. The Weibull two-parameter model offers a number of features such as: (i) it is a generalization of the exponential model and as such provides great flexibility in describing the survival data; (ii) its two empirical parameters (α and β) can be determined with simple linear transformation of the Weibull cumulative distribution function; and (iii) the simplicity of the model statement. Models relating the Weibull parameters to the operating conditions were developed, and the times to one- and two-log reductions in count (t_{1D} and t_{2D}) were derived from those parameters. The sensitivity of the Weibull model parameters to the operating conditions was assessed. The t_{1D} and t_{2D} determined using the PMP were found to be much lower than those actually determined for chorizos, especially for chorizo formulations with higher a_{w0}. The developed models can be used to simulate the survival curves and calculate the times for any desired reduction in count for all a_{w0}, T, and F not tested experimentally (but within the experimental ranges). It is to be noted, however, that there are (a_{w0}, T, F) combinations that would result in t_{1D} and t_{2D} exceeding the 7-day time period allowed in the experiments, for which the user is cautioned regarding the reliability of these extrapolated values. Finally, the derived models provide a useful tool for a better control over the manufacturing of chorizos, and can improve existing microbial risk assessment systems for this particular product.

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