Development and Validation of a Predictive Model for Foodborne Pathogens in Ready-to-Eat Pork as a Function of Temperature and a Mixture of Potassium Lactate and Sodium Diacetate

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ABSTRACT

We developed and validated secondary models that can predict growth parameters of Salmonella Typhimurium and Staphylococcus aureus in cooked-pressed ready-to-eat (RTE) pork as a function of concentrations (0 to 3%) of a commercial potassium lactate and sodium diacetate mixture (PL + SDA) and temperature (10 to 30°C). The primary growth data were fitted to a Gompertz equation to determine the lag time (LT) and growth rate (GR). At 10°C, the growth of Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork containing 2% and 3% PL + SDA was completely inhibited. The effects of temperature and concentration of PL + SDA on the growth kinetics of Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork were modeled by response surface analysis using polynomial models of the natural logarithm transformation of both LT and GR. Model performance was also evaluated by use of the prediction bias ($B_p$) and accuracy ($A_p$) factors, median relative error, and mean absolute relative error, as well as the acceptable prediction zone method. The results showed that LT and GR models of Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork are acceptable models. Thus, both the LT and GR growth models developed herein can be used for the development of tertiary models for Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork in the matrix of conditions described in the present study.

According to the Korea Food and Drug Administration (16), 227 foodborne disease outbreaks and 5,972 infected patients were reported in 2009 in Korea. Of these patients, 864 (14.47%) and 477 (7.99%) were infected with Staphylococcus aureus and Salmonella, respectively. Many outbreaks of foodborne disease have been attributed to the consumption of ready-to-eat (RTE) food in convenience stores (4). RTE meat products are commonly contaminated with Salmonella and S. aureus in Korea (16). Recently, vacuum-packaged and cooked-pressed RTE pork, called pyeonyuk, has been introduced in the convenience and retail store industry, and the products are often sold at room temperature in Korea. Since the cooked-pressed RTE pork in the market is not free from contamination with Salmonella or S. aureus (unpublished data), control measures for these pathogens are needed. The addition of 0.2% potassium sorbate (PS) is permitted to prevent bacterial growth in meat products in Korea (15). In a previous study (21), we investigated the antimicrobial effects of garlic, of a mixture of potassium lactate and sodium diacetate (PL + SDA), of e-polylysine, and of PS, alone or in combination, on the growth of foodborne pathogens and production of staphylococcal enterotoxin A in cooked-pressed RTE pork. PS at 0.2% was found to be insufficient to prevent the growth of Salmonella Typhimur-
especially RTE foods, which are often temperature abused at the retail market.

Potassium lactate (PL) and sodium diacetate (SDA) have been approved by the U.S. Food and Drug Administration (FDA) for use in RTE meat products (30), and combinations of these two antimicrobials (PL + SDA) can effectively inhibit the growth of Listeria monocytogenes on RTE meats during long-term refrigerated storage (19, 27, 28, 31). A 3% PL + SDA mixture was found to be the most effective antimicrobial agent for control of the growth of Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork stored at various temperatures (21), and at 10°C this level of PL + SDA showed an effect superior to that of PS and garlic extract for inhibition of the growth of Salmonella Typhimurium and S. aureus. In previous modeling studies, researchers have used lactate, diacetate, or a combination of these compounds as independent variables to predict the safety of various products, including cooked meat products (9, 18), bologna sausages (12), cured processed meat products (27), beef (13), frankfurter slurry (26), lightly preserved seafood (20), and air-dried raw sausages (5).

The objective of the present study was to develop predictive models that can predict growth parameters of Salmonella Typhimurium and S. aureus as a function of PL + SDA mixtures at various concentrations (0 to 3%) and storage temperatures (10 to 30°C) to determine the optimum conditions for controlling the growth of serovar Typhimurium and S. aureus in cooked-pressed RTE pork in convenience and retail stores in Korea.

MATERIALS AND METHODS

Bacterial culture. Strains of Salmonella Typhimurium (ATCC 13311) and Staphylococcus aureus producing enterotoxin A (ATCC 13565) were purchased from the Korean Culture Center of Microorganisms (Seoul, Korea) and maintained at −80°C in brain heart infusion broth and tryptic soy broth (Difco, BD, Sparks, MD) containing 20% glycerol, respectively. For each experiment, stock cultures of serovar Typhimurium and S. aureus were thawed at room temperature. Ten micro liters of thawed stock culture was inoculated into a 50-ml Erlenmeyer flask containing 10 ml of sterile brain heart infusion broth and tryptic soy broth, which was then sealed with a silicone cap and incubated at 35°C for 24 h on a rotary shaker (VS-8480SR, Vision, Korea) at 140 rpm. Viable cell counts of serovar Typhimurium and S. aureus ranged from 9.5 to 10.5 log CFU/ml. One milliliter of the stationary phase of start culture was transferred into 9 ml of 0.1% sterilized peptone water (Difco, BD), which was serially diluted before inoculation into the cooked-pressed RTE pork.

A commercially prepared blend of PL and SDA. A mixture of PL and SDA (PURASAL Opti. Form PD Plus; potassium-l-lactate, water, and sodium diacetate) was obtained from Purac America, Inc. (Lincolnshire, IL). PURASAL Opti. Form PD Plus is a 78% solution with a PL-to-SDA ratio of 14:1 (72.8% PL and 5.2% SDA).

Preparation of cooked-pressed RTE pork, inoculation, and enumeration. Fresh pork loin was purchased from a local supermarket in Seoul, Korea. The pork loin was boiled in water with 1% (0.73% PL and 0.05% SDA), 2% (1.46% PL and 0.10% SDA), and 3% (2.18% PL and 0.16% SDA) PL + SDA mixture for 60 min. The cooked pork was then pressed continuously with a heavy cutting board (2 kg) for 1 h, after which treatment the product can be called pyeonyuk (cooked-pressed RTE pork), a traditional pork dish in Korea. Next, 5 g of sliced pressed pork was aseptically weighed and placed in a sterile petri dish. Each thin slice of cooked-pressed RTE pork was then uniformly surface inoculated with 100 μl of the diluted starter culture of Salmonella Typhimurium and S. aureus by use of a sterile pipette to give a target population of approximately 2.5 to 3.5 log CFU/g for each pathogen, after which the samples were vacuum packed and stored at 10, 17, 24, and 30°C. At selected times after inoculation, a 100-μl aliquot was taken, diluted as appropriate, plated onto tryptic soy agar (TSA; Difco, BD) in duplicate, and incubated aerobically at 35°C for 24 h. The colonies on the TSA plates were then counted, and bacterial counts from duplicate plates were converted to log numbers.

Primary modeling. Growth curves representing the viable counts (log CFU per gram) of Salmonella Typhimurium and S. aureus were graphed as a function of time and then iteratively fit to the modified Gompertz model using GraphPad Prism V4.0 (GraphPad Software, San Diego, CA) to determine the lag time (LT), growth rate (GR), and maximum population density. The model used was as follows (11):

\[
Y_t = N_0 + C \times \exp\left[-\exp\left(\frac{2.718 \times GT/C}{C} \right) \right] \\
\times (\text{Lag} - t) + 1]
\]

where \(Y_t\) is the viable cell count (log CFU per gram), \(N_0\) is the initial log number of cells, \(C\) is the difference between the initial and final cell numbers, \(GR\) is the growth rate (log per hour), \(\text{Lag}\) is the lag time (LT) before growth, and \(t\) is sampling time. Each experiment was replicated twice. The goodness of fit of the data was evaluated based on the coefficient of determination (\(R^2\)), which was provided by GraphPad Prism. Results of growth parameters in primary models were analyzed by analysis of variance, and the means were separated using Duncan’s multiple range test at \(P = 0.05\) using the Statistical Analysis Systems SAS V 9.1 (SAS Institute Inc., Cary, NC).

Secondary modeling. Response surface equations as a function of temperature and the concentration of PL + SDA mixture were developed for LT and GR of Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork by multiple regressions using the SAS (V 9.1) General Linear Models Procedure:

\[
\ln y = a_0 + a_1 A + a_2 B + a_3 A \times B + a_4 A \\
\times A + a_5 B \times B + a_6 
\]

where \(\ln y\) is the natural logarithm of the modeled growth parameters (LT or GR), \(A\) is the temperature, \(B\) is the concentration of the PL + SDA mixture, \(a_0\) to \(a_6\) are regression coefficients, and \(\varepsilon\) is the random error.

Model performance. The goodness of fit of the data to each model was evaluated using the coefficient of determination (\(R^2\)), which was provided by GraphPad Prism. In addition, the relative error (RE) of each prediction case was calculated using the following equation (8):

\[
\text{RE for LT} (\%) = \left|\frac{\text{predicted} - \text{observed}}{\text{predicted}}\right| \times 100 \\
\text{RE for GR} (\%) = \left|\frac{\text{observed} - \text{predicted}}{\text{predicted}}\right| \times 100
\]

where an RE less than zero represented fail-safe predictions and an RE above zero represented fail-dangerous predictions. The median
RESULTS AND DISCUSSION

Development of a primary growth model for *Salmonella Typhimurium* and *S. aureus* in cooked-pressed RTE pork. LT and GR values of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork samples containing PL+SDA that were stored at 10, 17, 24, and 30°C are shown in Tables 1 and 2, respectively. Overall, the addition of PL+SDA to the cooked-pressed RTE pork delayed the growth of serovar Typhimurium and *S. aureus* by increasing the LT and decreasing the GR, and this effect was enhanced at lower storage temperatures.

At 10°C, addition of 1% PL+SDA significantly (*P < 0.05) extended the LT (163.97 h) and decreased the GR (0.019 log CFU/h) of *Salmonella Typhimurium* (Table 1). The growth of serovar Typhimurium in cooked-pressed RTE pork was completely inhibited by 2 and 3% PL+SDA mixture at 10°C. This finding agrees with the results of previous studies (2, 31). At 17, 24, and 30°C, the LTs of serovar Typhimurium in cooked-pressed RTE pork treated with 2 and 3% PL+SDA were significantly (*P < 0.05) extended. Conversely, the addition of a PL+SDA mixture had a significant effect on the GRs of serovar Typhimurium at 17, 24, and 30°C, regardless of concentration.

Table 2 shows the effectiveness of PL+SDA on the growth kinetics of *S. aureus* in cooked-pressed RTE pork. At 10°C, the addition of 1% PL+SDA led to a significant relative error (MRE) and the mean absolute relative error (MARE) were also used as the measures of model prediction bias and accuracy, respectively, and these were also quantified by calculating the bias factor (Bf) and the accuracy factor (Af) using the following equations (23, 24):

\[
B_f \text{ for } LT = 10^{\frac{\log\text{(predicted/observed)}}{n}}
\]

\[
A_f \text{ for } LT = 10^{\frac{\log\text{(observed/predicted)}}{n}}
\]

\[
B_f \text{ for } GR = 10^{\frac{\log\text{(observed/predicted)}}{n}}
\]

\[
A_f \text{ for } GR = 10^{\frac{\log\text{(predicted/observed)}}{n}}
\]

where \(n\) is the number of prediction cases used in the calculation. The mean values for \(B_f\) and \(A_f\) were used as overall measures of model prediction bias and accuracy, respectively. Different ratios were used for LT and GR so that \(B_f\) values of <1 represented fail-safe predictions and \(B_f\) values of >1 represented fail-dangerous predictions (1). \(B_f\) values consider whether prediction error is more in the fail-safe direction or not, while \(A_f\) values do not consider the direction of prediction error (23). In the acceptable prediction zone method for LT and GR, the percentage of RE (%RE) that is in an acceptable prediction zone (i.e., the ratio of the number of RE in the acceptable prediction zone to the total number of prediction cases) from −30% (fail-safe) to 15% (fail-dangerous) is calculated and used as a new measure of model performance. Different acceptable prediction zones are used for evaluating the performances of individual parameters because of differences between experimental errors associated with different kinetic parameters (GR, LT, and maximum population density); thus, the width of the acceptable prediction zone is most narrow for GR (−30 to 15%), intermediate for LT (−60 to 30%), and widest for maximum population density models (−80 to 40%). Models with a %RE of ≥70 are considered to provide predictions with acceptable bias and accuracy (22, 23).

### Table 1. Log time (LT) and growth rate (GR) of *Salmonella Typhimurium* in cooked-pressed RTE pork obtained using a modified Gompertz equation.\(^a\)

<table>
<thead>
<tr>
<th>Antimicrobial agent</th>
<th>10°C</th>
<th>17°C</th>
<th>24°C</th>
<th>30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1% PL+SDA</td>
<td>163.97</td>
<td>169.00</td>
<td>19.00</td>
<td>ND</td>
</tr>
<tr>
<td>2% PL+SDA</td>
<td>163.97</td>
<td>169.00</td>
<td>19.00</td>
<td>ND</td>
</tr>
<tr>
<td>3% PL+SDA</td>
<td>163.97</td>
<td>169.00</td>
<td>19.00</td>
<td>ND</td>
</tr>
</tbody>
</table>

\(^a\) Values are means ± standard deviations (*n* = 4). LT values are in hours, and GR values are in log per hour. Means within a column with different letters are significantly different (*P < 0.05*).
The growth of *S. aureus* was not observed in cooked-pressed RTE pork treated with 3% PL + SDA. These results indicate that treatment with 1% PL + SDA mixture can enhance the safety of RTE pork at refrigeration temperature. At 17, 24, and 30°C, the LTs of *S. aureus* in cooked-pressed RTE pork were significantly (*P < 0.05*) influenced by the concentrations of PL + SDA mixture. Even treatment with 1% PL + SDA led to a significant decrease (*P < 0.05*) in the GRs of *S. aureus* in cooked-pressed RTE pork at temperatures of up to 17°C, while 1% was not sufficient to decrease the GRs of *S. aureus* in cooked-pressed RTE pork at temperatures above room temperature. Because cooked-pressed RTE pork is often sold at room temperature in the retail market, at least 2% PL + SDA is recommended to ensure the safety of RTE pork products. As shown in Tables 1 and 2, the addition of PL + SDA to cooked-pressed RTE pork increased the LT of *Salmonella Typhimurium* more than that of *S. aureus* at all tested temperatures, and this effect was especially pronounced for 2% PL + SDA at 10°C.

### Development of secondary modeling and evaluation of model performance of *Salmonella Typhimurium* and *S. aureus* in cooked-pressed RTE pork.

The growth curves of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork were well fit to the modified Gompertz primary model (*R^2* > 0.94) in the present study (data not shown). Juneja et al. also reported (14) that the growth data of *Salmonella* in chicken at various isothermal conditions were fitted with three primary models. The modified Gompertz model provided the best fit for growth data, followed by the Baranyi model and then by the logistic model. The secondary models were developed to describe the primary model parameters, including natural logarithms (ln) of LT and GR as a function of PL + SDA mixture and storage temperature. Growth data in the primary model of the present study were subjected to response surface analysis using the SAS General Linear Model Procedures (1).

The resulting models and comparison of the best fit values for the LT and GR as indicated by *R^2* are shown in Table 3. The *R^2* values of the LT and GR were 0.966 and 0.974 for *Salmonella Typhimurium* and 0.973 and 0.974 for *S. aureus*, respectively, which indicates that the models predicted the growth of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork well. Figure 1 shows the surface response models for the effects of the PL + SDA mixture on the LT and GR of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork as a function of temperature. In the present study, the growth of serovar Typhimurium was not observed in cooked-pressed RTE pork treated with >2% PL + SDA, while at least 3% PL + SDA was required to completely eliminate the growth of *S. aureus* at 10°C. The data also indicate that serovar Typhimurium and *S. aureus* did not grow with the hurdle combination of refrigeration temperature and treatment with 3% PL + SDA. Therefore, these conditions were excluded.

#### TABLE 2. Log time (LT) and growth rate (GR) of *Staphylococcus aureus* in cooked-pressed RTE pork obtained using a modified Gompertz equation

<table>
<thead>
<tr>
<th>Antimicrobial agent</th>
<th>LT (h)</th>
<th>GR (h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>1% PL + SDA</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>2% PL + SDA</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>3% PL + SDA</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Values are mean ± standard deviations (*n* = 4). LT values are in hours, and GR values are in log per hour. Means within a column with different letters are significantly different (*P < 0.05*).
from development of the secondary growth models for serovar Typhimurium and S. aureus in cooked-pressed RTE pork in the present study.

Seman et al. (27) and Legan et al. (18) reported the growth of L. monocytogenes as a function of the SDA and PL in cured RTE processed meat products. Increased amounts of both SDA (0 to 0.2%) and PL (0.25 to 9.25%) resulted in significant reductions in the growth rate constants of L. monocytogenes. More recently, predictive modeling for the growth of L. monocytogenes in sausages (5) and broth (1) containing a combination of PL and SDA was introduced. Bang et al. (5) developed six polynomial models for the specific growth rate and LT of L. monocytogenes in air-dried raw sausages as a function of PS, PL, and PL + SDA, as well as storage temperature. At 4 and 10°C, the addition of 0.1 and 0.2% PS did not inhibit the growth of L. monocytogenes, while 2 and 4% PL + SDA inhibited the growth of L. monocytogenes in sausages. These results agreed well with the results reported by Min et al. (21), which indicated that the 0.2% PS did not affect the LT of Salmonella Typhimurium and S. aureus in cooked-pressed pork stored at 10°C. Abou-Zeid et al. (1) also reported quadratic and cubic polynomial models for specific growth rate and LT and provided acceptable predictions of L. monocytogenes Scott A growth in broth as a function of concentration (0 to 3%) of a commercial PL + SDA mixture, pH (5.5 to 7.0), and temperature (4 to 37°C). In their study, addition of 1% PL + SDA at a pH of 5.5 completely inhibited the growth of L. monocytogenes at 4 to 24°C. However, at a pH of 6, 3% PL + SDA (PURASAL Opti. Form 60% solution, containing 1.68% PL and 0.12% SDA) is required to completely inhibit the growth of L. monocytogenes at all tested temperatures (4 to 37°C), indicating that pH influences the antimicrobial effect of the PL + SDA mixture. In the present study, the addition of 2% (1.46% PL and 0.10% SDA) and 3% (2.18% PL and 0.16% SDA) PL + SDA mixture completely inhibited the growth of serovar Typhimurium and S. aureus in cooked-pressed RTE pork (pH 5.8 and 6.5) stored at 10°C. These results indicate that the antimicrobial effect of PL + SDA differs between pathogens; therefore, the target microorganisms to be controlled must be considered when determining the concentration of the PL + SDA mixture to use.

Oscar (23) suggested that an acceptable prediction zone method with an RE plot can overcome the limitation of model performance of bias factor (Bp) and accuracy factor (Ap) and provided a complete evaluation of model performance. The bias factor assesses whether the model is fail-safe, whereas the accuracy factor indicates by how much, on average, the prediction differs from the observed data. Ideally, predictive models would have an Ap of 1.00, but typically, the accuracy factor will increase by 0.10 to 0.15 for every variable in the model (24). The prediction Bp and Ap factors are the most widely used measures of performance of predictive models for food pathogens. However, Bp and Ap have limitations that can produce inaccurate assessments of model performance. This is because Bp and Ap are based on average values and prediction cases involving no growth are excluded from calculation of Bp and Ap, which can result in an overestimation of model performance (3, 8). Evaluating model performance using only Bp and Ap for Salmonella Typhimurium and S. aureus models revealed a limitation, since no growth conditions were excluded in the present study, where the growths of serovar Typhimurium and S. aureus were not observed in cooked-pressed RTE pork.

### TABLE 3. Response surface models for effects of temperature and potassium lactate (PL) and sodium diacetate (SDA) concentration (0 to 3%) on lag time (LT) and growth rate (GR) of Salmonella Typhimurium and S. aureus in cooked-pressed RTE pork

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SE</th>
<th>P value</th>
<th>Intercept</th>
<th>Estimate</th>
<th>SE</th>
<th>P value</th>
<th>ln LT of serovar Typhimurium</th>
<th>ln GR of serovar Typhimurium</th>
<th>ln LT of S. aureus</th>
<th>ln GR of S. aureus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>7.7668</td>
<td>0.6475</td>
<td>&lt;0.0001</td>
<td>-0.1831</td>
<td>0.1895</td>
<td>0.3622</td>
<td>8.0460</td>
<td>0.6603</td>
<td>&lt;0.0001</td>
<td>0.1312</td>
<td>0.1920</td>
</tr>
<tr>
<td>T</td>
<td>-0.4074</td>
<td>0.0704</td>
<td>0.0004</td>
<td>0.0172</td>
<td>0.0206</td>
<td>0.4282</td>
<td>-0.5380</td>
<td>0.0690</td>
<td>&lt;0.0001</td>
<td>-0.0322</td>
<td>0.0201</td>
</tr>
<tr>
<td>A</td>
<td>0.5026</td>
<td>0.2986</td>
<td>0.1309</td>
<td>-0.0231</td>
<td>0.0874</td>
<td>0.7978</td>
<td>0.9381</td>
<td>0.2866</td>
<td>0.0096</td>
<td>0.0972</td>
<td>0.0833</td>
</tr>
<tr>
<td>T x A</td>
<td>0.0016</td>
<td>0.0107</td>
<td>0.0072</td>
<td>-0.0046</td>
<td>0.0031</td>
<td>0.1798</td>
<td>-0.0002</td>
<td>0.0104</td>
<td>0.9857</td>
<td>-0.0080</td>
<td>0.0030</td>
</tr>
<tr>
<td>T x T</td>
<td>0.0063</td>
<td>0.0018</td>
<td>0.3951</td>
<td>0.0009</td>
<td>0.0005</td>
<td>0.1229</td>
<td>0.0095</td>
<td>0.0017</td>
<td>0.0004</td>
<td>0.0023</td>
<td>0.0005</td>
</tr>
<tr>
<td>A x A</td>
<td>-0.0601</td>
<td>0.0669</td>
<td>0.8854</td>
<td>0.0126</td>
<td>0.0196</td>
<td>0.5376</td>
<td>-0.0885</td>
<td>0.0755</td>
<td>0.2715</td>
<td>-0.0076</td>
<td>0.0220</td>
</tr>
<tr>
<td>R²</td>
<td>0.966</td>
<td>0.974</td>
<td></td>
<td>0.973</td>
<td>0.974</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* T: temperature; A: PL + SDA.
treated with 2 and 3% PL+SDA or 3% PL+SDA at 10°C, respectively.

Therefore, in the present study, we used the acceptable prediction zone method in combination with RE plot along with the $B_f$, $A_f$, MRE, and MARE to evaluate the ability of the predictive model to describe the experimental data adequately. For the LT models of *Salmonella* Typhimurium and *S. aureus* in cooked-pressed RTE pork, $B_f$ values of 1.00 and 1.01 were obtained, respectively (Table 4). Especially, the $B_f$ value for the LT model of serovar Typhimurium was 1.00, a value that indicates no average bias. The $A_f$ values for the LT of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork models were 1.06 and 1.10, respectively. $B_f$ values of 1.04 and 0.98 were obtained for the GR models of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork, respectively. The $A_f$ values for the GR models of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork were 1.20 and 1.17, respectively. Overall, the $B_f$ and $A_f$ values for both the LT and GR models of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork were close to 1, indicating that these models accurately predicted their growth. In addition, for the LT models for serovar Typhimurium and *S. aureus*, the MRE was −0.03 and −0.02, while the MARE was 0.06 and 0.09, respectively (Table 4). For the GR models for serovar Typhimurium and *S. aureus*, the MRE was −0.03 and −0.05, while the MARE was 0.23 and 0.16, respectively.

The %RE parameter described by Oscar (23) was also used to evaluate the performance of model prediction, and the %RE values of the LT and GR models of *Salmonella* Typhimurium and *S. aureus* in cooked-pressed RTE pork in the present study are shown in Table 4. The %RE that fell in an acceptable prediction zone from an RE of −0.3 (fail-safe) to 0.15 (fail-dangerous) was calculated and used as a new measure of model performance (23). The acceptable prediction zone was wider in the fail-safe direction because greater prediction error can be tolerated in the fail-safe direction when using models to predict food safety (25). The %REs for developed LT and GR models were in the range of 85.71 to 100% in the current study. For the LT and GR models of serovar Typhimurium, the %RE was 100 and 85.71, respectively, while it was 100 and 86.67 for the LT and GR models, respectively, of *S. aureus*. Overall, %RE was higher in the present study, indicating that the LT model showed a more accurate prediction than the GR model (Table 4). Although the $B_f$ values for the GR model of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork models were close to 1, the %REs for the GR models were lower than those of the LT models in the current study. Figure 2 shows the RE plot of the LT and GR models of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork. The fitted values are in the acceptable range, indicating that the developed models provide an acceptable prediction of the growth of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork in the present study. Most RE for LT and GR models of serovar Typhimurium and *S. aureus* were less than zero, which indicated fail-safe predictions. All REs for the LT models of serovar Typhimurium and *S. aureus* were inside the acceptable prediction zone (Fig. 2A and 2C) for %RE of 100. On the other hand, the GR model of serovar Typhimurium had a $B_f$ of 1.04, an $A_f$ of 1.20, and %RE of 85.71. One prediction case for the GR model of serovar Typhimurium was outside the acceptable prediction zone (Fig. 2B). Likewise, the GR model of *S. aureus* had a $B_f$ of 0.98, an $A_f$ of 1.17, and a %RE of 86.67. The GR model of *S. aureus* made fail-safe predictions, but only one RE was outside the acceptable prediction zone, which was very close to the upper boundary (Fig. 2D). These results indicate that %RE was able to detect a performance problem for GR models, which was not detected by $B_f$ and $A_f$. Overall, results indicate that the predictions of the LT models of serovar Typhimurium and *S. aureus* in cooked-pressed RTE pork were better than those provided by the GR models in the present study.

In summary, the growth of *Salmonella* Typhimurium and *S. aureus* in cooked-pressed RTE pork containing PL+SDA was delayed via an increased LT and decreased GR. This was especially true at 10°C, when the growth of serovar Typhimurium and *S. aureus* in cooked-pressed pork was completely inhibited by the addition of 2 or 3% PL+SDA. These results indicated that the PL+SDA

<table>
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<tr>
<th>Pathogen</th>
<th>Growth parameter</th>
<th>Prediction bias</th>
<th>Prediction accuracy</th>
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<tr>
<td></td>
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<td>$B_f$</td>
<td>MRE</td>
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<tr>
<td><em>Salmonella</em></td>
<td>LT</td>
<td>1.00</td>
<td>−0.03</td>
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<tr>
<td>Typhimurium</td>
<td>GR</td>
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<tr>
<td><em>S. aureus</em></td>
<td>LT</td>
<td>1.01</td>
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<td></td>
<td>GR</td>
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mixture has a control effect against both gram-negative and gram-positive pathogens, suggesting that PL + SDA can be expected to greatly enhance the safety of refrigerated RTE pork meats. The present results also indicated that treatment with at least 2% PL + SDA (1.46% PL and 0.10% SDA) is recommended to ensure the safety of RTE pork products. The LT and GR models provided acceptable predictions of the growth of serovar Typhimurium and S. aureus in cooked-pressed RTE pork in the matrix of conditions described in the present study and can be used as a tool to estimate the impact of food formulation containing PL + SDA (0 to 3%) and temperature (10 to 30°C) on the growth of serovar Typhimurium and S. aureus in cooked-pressed RTE pork sold in convenience stores. The models will be incorporated into the tertiary model for use in the food industry. In addition, the models developed in this study require further evaluation for model performance at temperatures outside the current model boundaries for extrapolation.

REFERENCES


