A New Secondary Model Developed for the Growth Rate of *Escherichia coli* O157:H7 in Broth

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Abstract This study was attempted to develop a new exponential sum model to describe the effect of temperature on growth rate (GR) of *Escherichia coli* O157:H7 in broth. The growth rates of *E. coli* O157:H7 at different storage temperatures (4, 10, 15, 20, 25, 30, and 35°C) estimated by fitting with the modified Gompertz model were used to develop secondary models such as square root model, Ratkowsky model and exponential sum model. Measures of coefficient of determination (R^2), root mean square error (RMSE) and the sum of squares due to error (SSE) were employed to compare the performances of these three secondary models. Based on these criteria, the developed exponential sum model showed the better goodness-of-fit and performance.

Keywords *Escherichia coli* O157:H7 · Predictive microbiology · Exponential sum model · Broth

Introduction

Predictive models are essential tools to describe the relationship between the quantitative evolution of microbial populations and different influencing surrounding environmental factors in predictive microbiology area [1]. However, different models can show different performances

when fitted with various experimental data, which is the main reason why the previous models are continuously improved and modified in later publications. In this study, exponential sum model was newly developed for growth rate (GR) of *E. coli* O157:H7 in broth, and compared the performance of the new model with other typical secondary models such as square root model and Ratkowsky model. Furthermore, the reliability and accuracy of exponential sum model were also validated.

Materials and Methods

Two strains (932 and 933) of *E. coli* O157:H7 were used in this study. Inoculum with a level of 7 log CFU/ml was prepared using the same method described in our previous study [2]. Then, after inoculation the inoculated broth was stored in 4, 10, 15, 20, 25, 30, and 35°C, respectively, and the growth kinetic was checked at certain sampling interval. Bacterial numbers (cfu/g) were transformed into log10 for statistical analysis. The growth parameters were estimated by fitting the data into the modified Gompertz model. Square root model (Eq. 1), Ratkowsky model (Eq. 2), and exponential sum model (Eq. 3) were used to establish secondary models for GR of *E. coli* O157:H7 by non-linear regression in Matlab environment (version 7.0).

$$\sqrt{\mu} = a(T - T_{\min}) \quad (1)$$

$$\mu = a(T - T_{\min})^2(1 - \exp(b(T - T_{\max}))) \quad (2)$$

$$\mu = ae^{bT} + ce^{dT} \quad (3)$$

where μ is the growth rate (log cfu/h), T is the temperature (°C), $T_{\min}$ and $T_{\max}$ are the minimum and maximum temperature (°C) required for growth, a , b , c , and d are the regression constants.

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Fig. 1 Growth curves of *E. coli* O157:H7 fitted into the modified Gompertz model in broth at different temperatures (4, 10, 15, 20, 25, 30, and 35°C). The dotted curves are upper and lower prediction limits at a 95% confidence level

The performances of different secondary models were compared by coefficient of determination (R^2), root mean square error (RMSE, Eq. 4) and the sum of squares due to error (SSE).

$$\text{RMSE} = \sqrt{\frac{\sum (\mu_{\text{observed}} - \mu_{\text{predicted}})^2}{n}} \quad (4)$$

Fig. 2 Square root model (full line), Ratkowsky model (slight dotted line), and exponential sum model (heavy dotted line) obtained from nonlinear regression analysis using Matlab 7.0 software

Table 1 Coefficient of determination (R^2), root mean square error (RMSE), and the sum of squares due to error (SSE) obtained for square root model, Ratkowski model and exponential sum model, respectively

	R^2	MSE	SSE
$GR = 0.00025 \times (T + 8.805)^2$	0.9687	0.0327	0.0053
$GR = 0.00083 \times (T - 3.35)^2 \times (1 - \exp(0.1253 \times (T - 40.68)))$	0.9717	0.0319	0.0048
$GR = 0.7965 \times \exp(0.1339T) - 0.7683 \times \exp(0.1348T)$	0.9827	0.0313	0.0030

where n is the number of observations, μ_{observed} is the observed value, and $\mu_{\text{predicted}}$ is the predicted value.

Results and Discussion

The growth data of *E. coli* O157:H7 in broth collected from different temperatures were fitted into the modified Gompertz model (showed in Fig. 1), and then square root model, Ratkowski model and exponential sum model were developed for the growth rates obtained from the primary model using non-linear regression in the environment of Matlab 7.0. All the curves fitted by different models are presented in Fig. 2, respectively, which illustrate the non-linear relationship between the growth rate and homologous growth temperature.

In order to compare the performances of different secondary models, three criterion factors such as R^2 , RMSE, and SSE were employed (Table 1). The R^2 is normally

regarded as an overall measure of the prediction calculated by developed model, and the closer to one indicates that the better performance the model has. The RMSE is also a very important factor which used to offer a measurement standard of the goodness-of-fit of a model to the data used to produce it [3]. High RMSE value demonstrates an unacceptable prediction. Besides, SSE also namely the residual sum of squares, measures the variation not explained by regression predictors [4]. Generally, it is the sum of the squared differences between the predicted and observed values of the response variable. Karaca et al. [5] suggested in his publication that the smaller the SSE, the better the approximating function fits the data. As presented in Table 1, it can be observed obviously that the exponential sum model leads higher R^2 , lower RMSE, and SSE values than the other two. Therefore, the results indicate that the exponential sum model has the best performance of all selected models in this study.

In this study, the exponential sum model is a relatively simple model and its coefficients can be estimated easily by nonlinear regression. In addition, as we proved, the models developed have strong fitting capacity with the growth rates of microbes based on growth data of *E. coli* O157:H7. Consequently, we believe that the exponential sum model has the potential for widespread application in predictive microbiology and that it is capable of providing an excellent description of target experimental data or reliable predictions of the growth of target pathogens. Nonetheless, we can observe that exponential sum model can not describe the growth kinetic well at low temperatures (less than 10°C) from the Fig. 2, it still needs further modification in the future study.

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