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A mathematical model to predict ripening degree of *kimchi*, a Korean fermented vegetable for meeting consumer preference and controlling shelf life on real time basis

Chalalai Jaisan, Dong Sun Lee*

Department of Food Science and Biotechnology, Kyungnam University, 7 Kyungnamdaehak-ro, Masanhappo-gu, Changwon, 51767 South Korea

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ABSTRACT

Because microbial activity continues during packaged storage and marketing of *kimchi*, a Korean lactic acid fermented vegetable, there is a need to indicate the ripening degree represented in acidity on real-time basis, meeting the consumers' preference. Mathematical prediction model of acidity change applicable to dynamic temperature conditions was established using literature data. Huang's model was used to describe it against time providing its lag time and rate of increase for any temperatures of 5–20 °C. The solution of Huang's differential equation using Arrhenius relationship in their temperature dependence could estimate the acidity under dynamic temperature conditions. A set of comprehensively applicable model parameters was formulated from collective data analysis as a basis for generalized application and might be tuned for particular individual case of *kimchi*. The developed model may be useful to determine consumption time and shelf life under the dynamic product distribution channel by providing real-time indication of ripening state of *kimchi*.

1. Introduction

Kimchi, a Korean lactic acid fermentation food is packaged and marketed without pasteurization, which makes the bacterial growth and acid production continue through the supply chain. Because of this on-going process of fermentation after packaging, the products which consumers get at the point of purchase in the market may be variable in the degree of their ripening state depending on the their distribution history. Even though their shelf life is usually about 60 days under chilled temperatures, the state of ripening at the point of purchase or consumption may differ with their temperature and time experienced in the supply chain. In order to indicate the ripening state of *kimchi*, there have been attempts to use intelligent labels or sensors which are attached on the package and give the color change or signal in their response to the time/temperature exposure (Hong & Park, 2000; Hong & Park, 1999). These innovative tools may serve the function to indicate the ripening degree on real-time basis, meeting the consumers' preference. Matching the devices' response to the *kimchi* fermentation kinetics is an essential requirement for successful indication of the product's ripening state.

For application of innovative intelligent packaging tools in *kimchi* packaging and marketing, the predictive model of *kimchi* ripening workable under dynamic temperature conditions is required. Usually pH and acidity changes occurring along with fermentation are quality attribute showing the ripening state of *kimchi*. The optimum ripening state of *kimchi* is around at pH 4.2 with 0.6–0.8% of total acidity (Cheigh & Park, 1994; Mheen & Kwon, 1984). Acidity increase is more consistent in fermentation progress with time, while pH change is often affected by the buffering capacity of the ingredients. Thus acidity is more commonly used index of *kimchi* ripening than pH, and modeling its change may work for estimating its ripening.

There have been a few attempts to model the acidity change of *kimchi* to a limited extent (Lee, Cho, & Pyun, 1991; Lee & Lee, 1993). The published models described the acidity increase by simple equation with the parameters depending on the temperature and salt content. While those models are useful to predict the shelf life by presenting the temperature dependence of acidity change, their applicability to predicting the acidity change on real time basis is limited due to their inappropriately rigid and/or too much simple format in describing the change of acidity with time.

* Corresponding author.
E-mail address: dongsun@kyungnam.ac.kr (D.S. Lee).

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Therefore this study aims 1) to develop a simple convenient model able to estimate the acidity of *kimchi* under dynamic temperature conditions and 2) to provide the representative model parameters from comprehensive literature data.

2. Theory and methods

2.1. Huang's model to describe ripening of kimchi

Originally Huang's model has been developed for describing and predicting microbial growth on food (Huang, 2011) and also extended to the other quality change such as oxidation (Zhu, Lee, & Yam, 2012). Huang's model was shown to be used well for predicting the microbial growth on the perishable food under dynamic temperature conditions with its simplicity and convenience (Lee, 2014a). Therefore this model has a potential to be applied for estimating the acidity change of *kimchi* under fluctuating temperature conditions. Acidity change in *kimchi* ripening is known or reported to result from lactic acid bacterial growth and have a pattern similar to that of microbial growth consisting of initial lag, constant growth and stationary phases (Ku, Kang, & Kim, 1988; Lee et al., 1991; Shin, Kim, Han, Lim, & Park, 1996), presenting the potential applicability of Huang's model to the acidity change.

For the constant temperature conditions, Huang's equation was adopted for describing the change of total acidity which results from lactic acid bacterial growth:

$$TA = TA_o + TA_{max} - \ln\{\exp(TA_o) + [\exp(TA_{max}) - \exp(TA_o)] \cdot \exp(-\mu_{max}B)\} \quad (1)$$

where $B = t + \frac{1}{25}\ln\left(\frac{1+\exp[-25(t-\lambda)]}{1+\exp(25\lambda)}\right)$, TA is total acidity (%), t is time (d), TA_o is initial total acidity (%), TA_{max} is maximum total acidity (%), λ is lag time (d) and μ_{max} is maximum acidity production or increase rate (d^{-1}). λ may be simply assumed as initial time period before start of acidity increase, and μ_{max} may be inverse of time to increase the acidity by 1% at maximum rate.

While Eq. (1) describes the acidity change under constant temperature condition, it can be expressed in differential form of Eq. (2) which is suitable for any instant temperature condition (Huang, 2011):

$$\frac{d(TA)}{dt} = \frac{\mu_{max}\left(1 - \frac{\exp(TA)}{\exp(TA_{max})}\right)}{1 + \exp[-25(t-\lambda)]} \quad (2)$$

While Eq. (1) in integrated form is used for description of acidity change at constant temperature, Eq. (2) has advantage to give instantaneous acidity change rate at any temperature, which is useful for handling dynamic temperature conditions.

In order to apply Eq. (2) to the dynamic temperature conditions, the parameters, λ and μ_{max} need to be represented or expressed in appropriate relationship of temperature dependence. Two forms of Huang's model in Eqs. (1) and (2) can be used interactively to describe or simulate the acidity change of *kimchi* under constant or dynamic temperature conditions. In order to confirm the validity of Eqs. (1) and (2), literatures reporting the acidity changes both under constant temperature conditions and under dynamic temperature conditions were looked for. From the many research papers and reports, the work by Lim (2013) was selected for this study because it contained the data set most consistent and suitable.

2.2. Temperature dependence of kimchi ripening and its estimation under dynamic temperature conditions

As mentioned above, for applying Eq. (2) to dynamic temperature conditions, λ and μ_{max} at any instant need to be defined as function of temperature. Even though the square root equation or other type of equation is often used for describing the temperature dependence of microbial lag time or growth rate in predictive microbiology (Baranyi, Robinson, Kaloti, & Mackey, 1995; Huang, 2011), Arrhenius equation commonly used for shelf life modeling and time-temperature integrator in packaged foods seems better suitable for this study considering informational treatment of *kimchi* ripening on real-time in intelligent packaging (Koutsoumanis & Nychas, 2000; Singh, 2000; Taoukis, Koutsoumanis, & Nychas, 1999). Thus ($1/\lambda$) and μ_{max} were described as function of temperature according to Arrhenius equation relationship:

$$\frac{1}{\lambda} = \left(\frac{1}{\lambda_o}\right)\exp\left(\frac{-E_{a,\lambda}}{RT}\right) \quad (3)$$

$$\mu_{max} = \mu_{max,o}\exp\left(\frac{-E_{a,\mu}}{RT}\right) \quad (4)$$

where λ and μ_{max} are the lag time and maximum acidity increase rate at temperature T (K), respectively; ($1/\lambda_o$) and $\mu_{max,o}$ are the pre-exponential constant for ($1/\lambda$) and μ_{max}, respectively; $E_{a,\lambda}$ and $E_{a,\mu}$ are the respective activation energies for ($1/\lambda$) and μ_{max} (J mol^{-1}); R is universal gas constant (8.314 J K^{-1} mol^{-1}).

Arrhenius relationships of Eqs. (3) and (4) were substituted to Eq. (2) for estimation of acidity change under the dynamic temperature conditions, which was compared to the experimental data in the literature (Lim, 2013). Both bias factor (*BF*) and accuracy factor (*AF*) calculated, respectively by Eqs. (5) and (6), were used to check the degree of estimation.

$$BF = \exp\left(\frac{\sum \ln(TA_p/TA_e)}{n}\right) \quad (5)$$

$$AF = \exp\left(\frac{\sum |\ln(TA_p/TA_e)|}{n}\right) \quad (6)$$

where TA_p is the predicted acidity (%), TA_e is the experimentally observed acidity (%) and n is number of data.

The root-mean-square error (*RMSE*) values were also determined to see the quality of estimation by the model:

$$RMSE = \exp\left(\sqrt{\frac{\sum (TA_p - TA_e)^2}{n}}\right) \quad (7)$$

As a final step, the extension of the model was tried for its wider application. Literatures reporting acidity increase of *kimchi* were

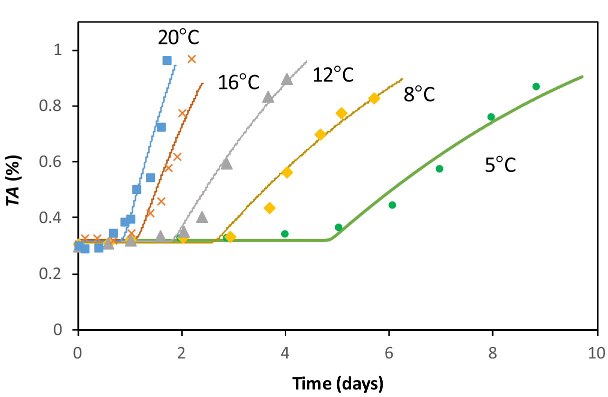

Fig. 1. *Kimchi* ripening data at constant temperature conditions as reported by Lim (2013). Solid lines are fitting by Eq. (1).