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Predictive modeling for monitoring egg freshness during variable temperature storage conditions

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ABSTRACT The overall aim of this research was to develop egg freshness prediction models in terms of selected quality indices. Six experiments (4 constant temperatures and 2 variable temperatures) were carried out on hen eggs for a total period of 10, 21, 26, 13, and 105 d at storage temperatures of 30, 20, 20 to 10, 30 to 10, and 5 and 10°C, to observe trends in the relative weight loss (RWL), Haugh unit (HU), yolk index (YI), albumin index (AI), yolk pH, and albumin pH. The results showed that there was an increasing trend in the RWL and a decreasing trend in the YI, AI, and HU for all temperature conditions. The changes in the yolk and albumin pH were not uniform. The data from the constant temperature conditions were used to determine the coefficients of the egg quality prediction models, which consisted of the primary model controlling the change rate of the quality indicator at a temperature condition in differential equation form, and the secondary model controlling the change rate with temperature, which was in quadratic polynomial form. The models were applied to the data from the fluctuating temperature conditions, and the zeroth, third, and eighth order kinetic models described the stepwise change in the RWL, HU, and YI, respectively. The accuracy and bias factor values for the RWL, HU, and YI were 1.116 and 0.940, 1.028 and 1.001, and 1.038 and 0.966, respectively. It can be concluded that the models can be used to predict egg freshness in terms of the RWL, HU, and YI at any temperature condition with in the range of 5 to 30°C during storage.

Key words: egg freshness, Haugh unit, prediction model, kinetic order, variable temperature

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INTRODUCTION

Eggs are an inexpensive yet, very nutritious food. Eggs have various uses and contain many essential nutrients, as they support life during embryonic growth (Scott and Silversides, 2001), and are one of the most nutritious and complete foods known to man (Dudusola, 2009). Eggs are one of the main sources of protein, iron, phosphate, amino acids, and fatty acids (Tabidi, 2011).

Eggs are perishable and can rapidly undergo weight loss and interior quality deterioration during storage, causing a major economic loss to the poultry industry (Freeland-Graves and Peckman, 1987; Stadelman and Cotterill, 1995; Caner, 2005; No et al., 2005). Eggs deteriorate in internal quality with time, depending on the shell and the internal contents of the egg (Adeogun and Amole, 2004). Environmental factors, such as the temperature and humidity of storage, as well as the gaseous environment and storage time, are the major contributing factors in the post-lay changes in egg quality (Sekeroglu et al., 2008; Akyurek and Okur, 2009; Chung and Lee, 2014). The principle degrading factors are high storage temperature and dehydration (Tabidi, 2011). The rate at which these changes occur during storage also depends on hen age and strain (Scott and Silversides, 2000; Silversides and Scott, 2001).

Freshness, which is the characteristic most commonly related to egg quality, declines after laying mainly in a time- and temperature-dependent manner (Karoui et al., 2006). This quality decay is associated with chemical, nutritional, functional, and hygienic changes. Because egg quality varies with time as a function of storage temperature, freshness cannot only be defined by an egg's age. Freshness degradation occurs in eggs with an increase in storage time. The research results by Jin

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et al. (2011) reported that egg weight loss, the albumen pH, and the Haugh unit are parameters that are greatly influenced by the storage temperature and time.

Effective control of the distribution of eggs is vital to their commercial viability. Eggs are exposed throughout the distribution to effective temperatures that deviate significantly from the recommended range. Application of an optimized quality and safety assurance system for the safe distribution of eggs would require continuous monitoring and the control of storage conditions, from collection to consumption (Karoui et al., 2006). Shell eggs with the same d of storage could appear qualitatively different to the consumer in terms of freshness if stored with different conditions. The research result by Jo et al. (2011), for instance, reported that the combination of chitosan coating and dry ice significantly inhibited a Haugh unit decrease during storage at 23°C.

Important changes occur in eggs during storage, leading to loss of quality. Predicting these changes is critical to monitoring egg quality and freshness. Knowledge of the various property descriptors that are encountered in an egg immediately after laying must be known, as must the changes in the properties that take place over time. This information can be gained by performing controlled storage experiments that extend from the time after laying. Loss in freshness can, thus, be monitored; once the dynamics and the rate of various changes that occur have been measured, the next step is to attempt to develop a model to determine the freshness of unknown commercial shell eggs in terms of selected quality indices. To achieve this aim, it is useful to combine several measurements obtained from using different methodologies and to develop models to predict quality changes during expected storage life.

To date, most egg prediction models have intended to predict egg freshness in terms of storage d at constant temperature conditions. Studies carried out in order to set up techniques for prediction of the d of storage and the assessment of the egg freshness parameters include the furosine analysis (Hidalgo et al., 2006), the biogenic amine concentrations analysis (Ramos et al., 2009), the dielectric properties analyses (Ragni et al., 2006), the use of an electronic nose-based system (Dutta et al., 2003; Yongwei et al., 2009), the use of FT-NIR spectroscopy (Giunchi et al., 2008), the use of visible near-infrared transmission and low-resolution proton nuclear magnetic resonance spectroscopy combined (Kemps et al., 2007), the assessment of viscosity measurements on the albumen (Kemps et al., 2010), and the use of *S*-ovalbumin as an indicator (Huang et al., 2012). Note that these previous studies made use of isothermal experiments to estimate model parameters, which may result in parameter estimates unable to reproduce non-isothermal conditions. Therefore, models that can predict egg freshness in terms of selected quality indices both at constant and variable temperature conditions are needed.

The objective of this study was to establish models for the prediction of egg freshness in terms of selected quality indices that could be used during distribution under variable storage temperature conditions.

Table 1. Overview of storage conditions.

Storage set-point temperature (°C)		Measured relative humidity range (%)
Isothermal	5	75 to 87
	10	78 to 88
	20	35 to 45
	30	25 to 35
Variable	10 to 20	5 to 75
	10 to 30	30 to 70

MATERIALS AND METHODS

Experimental Materials and Storage

Freshly laid special class unfertilized egg samples were obtained directly from Ireefarm Egg Company, Seoul, and the storage experiments were conducted at the Korea Food Research Institute. Samples were stored in their commercial packaging (cartons, each containing 10 egg specimens) in temperature-controlled storage chambers set at 5 °C, 10 °C, 20 °C, and 30 °C (constant temperature conditions) and at 10 to 20 °C and 10 to 30 °C (variable temperature conditions). The 2 variable temperature profiles used were set at 10 to 20 °C (isothermal steps per repeated temperature cycle: 24 h at 10 °C, 24 h at 20 °C) and 10 to 30 °C (isothermal steps per repeated temperature cycle: 24 h at 10 °C, 24 h at 30 °C). The specific time-temperature scenario for each variable profile was applied in temperature programmable storage chambers. Experiments under fluctuating temperature conditions were performed to validate the quality prediction models developed using isothermal conditions. The given temperature profiles were chosen considering the harshest possible temperature range of egg distribution. The temperature was constantly monitored using electronic, programmable, miniature data loggers (HL-1D/TL-1D, Rotronic Measurement Solutions, Bassersdorf, Swiss) in the storage chambers. Data loggers were placed inside the storage chambers as well as attached to the egg surface and egg core to monitor the storage air, egg surface, and egg core temperature. Relative humidity data loggers also were placed in each storage chamber to monitor the humidity during the storage periods, while the relative humidity was not controlled in the experiments. The temperature and relative humidity (**RH**) data were recorded every 10 min throughout the storage periods. The storage conditions are shown in Table 1. Although the difference in the relative humidity levels among test cases might affect the egg freshness, the impact was not considered in the study due to the difficulty of controlling it, and it is usually not controlled in the real distribution process. In many of storage studies, temperature is controlled but relative humidity is not. There are practical difficulties in maintaining relative humidity in large storage rooms within a narrow range and also maintaining the same relative humidity at different temperatures.

Sampling Procedure

Six experiments (4 at constant and 2 at variable temperatures) were carried out on hen eggs for a total period of 10 d at 30 °C, 21 d at 20 °C, 26 d at 10 to 20 °C, 13 d at 10 to 30 °C, and 98 d at 5 °C as well as 10 °C storage temperatures to observe the variation in the weight loss rate, the Haugh unit (**HU**), the yolk index, the albumin index, the yolk pH, and the albumin pH. The egg quality indices were measured every 1, 3, 2, 1, and 7 d for the 30 °C, 20 °C, 10 to 20 °C, 10 to 30 °C, and 5 °C as well as 10 °C storage samples, respectively.

During each sampling time, 2 egg cartons (each containing 10 eggs) were randomly selected. One carton was used for the albumen index, the yolk index, and the Haugh unit; another carton was used for the pH measurements (albumen and yolk). For the weight loss rate, on the initial d of the storage experiment, 3 packs (each containing 10 eggs) were randomly selected and individual eggs were labeled 1 through 30. The eggs were identified and labeled by pasting masking tape with an appropriate identification tag around the sharp end of the egg.

Weight Loss The weight (in grams) was established by individually weighting each labeled egg each d using an analytical balance (Carter, 1975). The egg weight was measured using a digital scale with a sensitivity of 0.1 g. This was achieved by placing the egg on a plastic holder on the flat surface of the scale ensuring that the scale was set to 0.0 g prior to the measurement. The weight loss percentage was calculated in relation to the d zero egg weight (g). The difference between the d zero egg weight and the weight after each time point was expressed as a percentage of the d zero egg weight.

Yolk Index, Albumen Index, and Haugh Unit Eggs were cracked onto a flat transparent glass surface using a spatula to obtain various internal parameter measurements.

The yolk index was estimated from the ratio of the yolk height to the yolk width. The height and diameter of the yolk were measured using a digimatic indicator (ID-C1050XB, Mitutoyo Co., Kawasaki-shi, Japan) and digimatic caliper (CD-15CPX, Mitutoyo Co., Kawasaki-shi, Japan), respectively. The measured values were expressed as the mean length and the mean breadth. The yolk index was calculated from the resulting mean values using Eq. (1) (Funk, 1948):

$$\text{Yolk index} = \text{yolk height(mm)}/\text{yolk diameter(mm)} \tag{1}$$

Similarly, the height and diameter of the thick albumen were measured using a digimatic indicator and digimatic caliper, respectively. The long and short axes at 90° were measured and expressed as the mean values. The albumen index was calculated from the resulting mean values using Eq. (2) (Heiman and Carver, 1936):

$$\text{Albumen index} = \text{thick albumen height(mm)}/\text{thick albumen diameter(mm)} \tag{2}$$

The Haugh unit was determined from the egg weight and albumen height of a broken egg spread on a horizontal plate using Eq. (3) (Haugh, 1937):

$$HU = 100\log(H + 7.51 - 1.7W^{0.37}) \tag{3}$$

where H is the albumen height (mm), and W is the weight of egg when tested (g).

pH Measurement After separating the yolk and albumen, each egg was placed in a beaker and homogenized; pH values of the albumen and yolk were measured using a pH meter (TA-70, DKK-TOA Corporation, Tokyo, Japan). The pH meter was calibrated using buffer solutions at pH 4 and 7 prior to measurements. Measurements were performed on 3 replicates, and average values are reported.

Statistical Analysis

The obtained data were subjected to statistical analysis using the statistical analysis system (SAS, 2008). Mean comparisons were performed by applying Fisher's least significant difference (**LSD**) test (at $P < 0.05$). The R program for Windows was used to fit the experimental data to polynomial equations to obtain the coefficients of the equations (R Development Core Team, 2011).

The comparison between the observed and predicted values of freshness indices of the eggs stored under constant and variable temperature conditions was based on the bias and accuracy factors (Ross, 1996). The accuracy and bias factors provide an indication of the average deviation between the model predictions and observed results (Ross, 1996), and their closeness to a value of one is an effective and practical measure of predictive model validity. To evaluate the prediction error of each model, these statistical characteristic indices (bias factor [$\mathbf{B_f}$] and accuracy factor [$\mathbf{A_f}$]) were employed:

$$B_f = 10^{\frac{\sum \log(C_{\text{predicted}}/C_{\text{observed}})}{n}} \tag{4}$$

$$A_f = 10^{\frac{\sum \left|\log(C_{\text{predicted}}/C_{\text{observed}})\right|}{n}} \tag{5}$$

where c_{observed} is the value of each datum experimentally observed, $c_{\text{predicted}}$ is the value predicted at the same

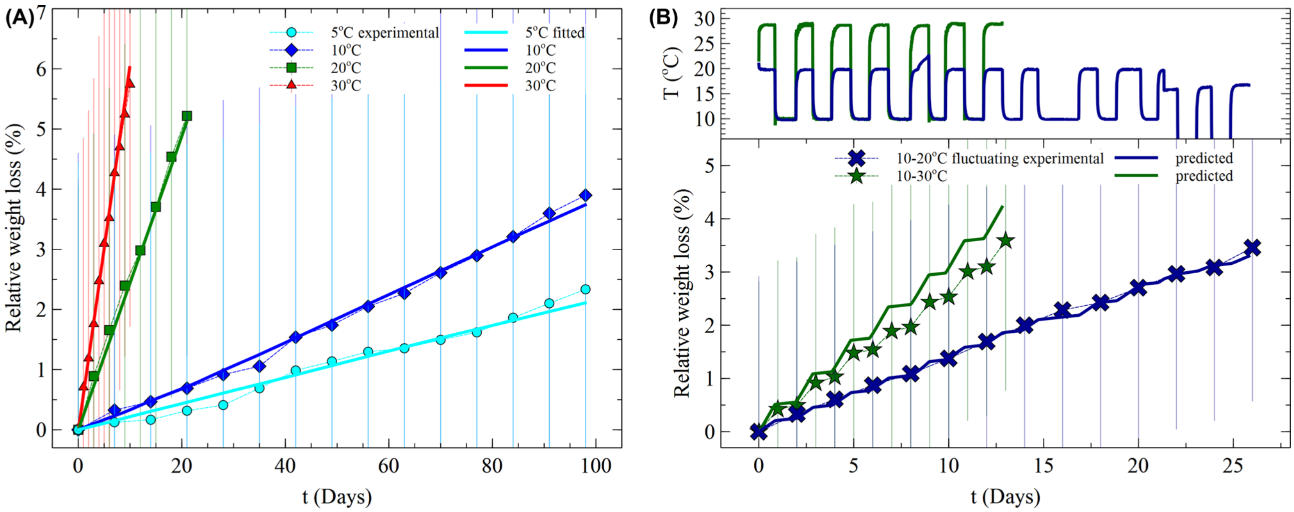

Figure 1. Comparison of experimental observations (symbols) and model predictions (dashed lines) of relative weight loss rate of eggs under (A) constant and (B) variable temperature conditions.

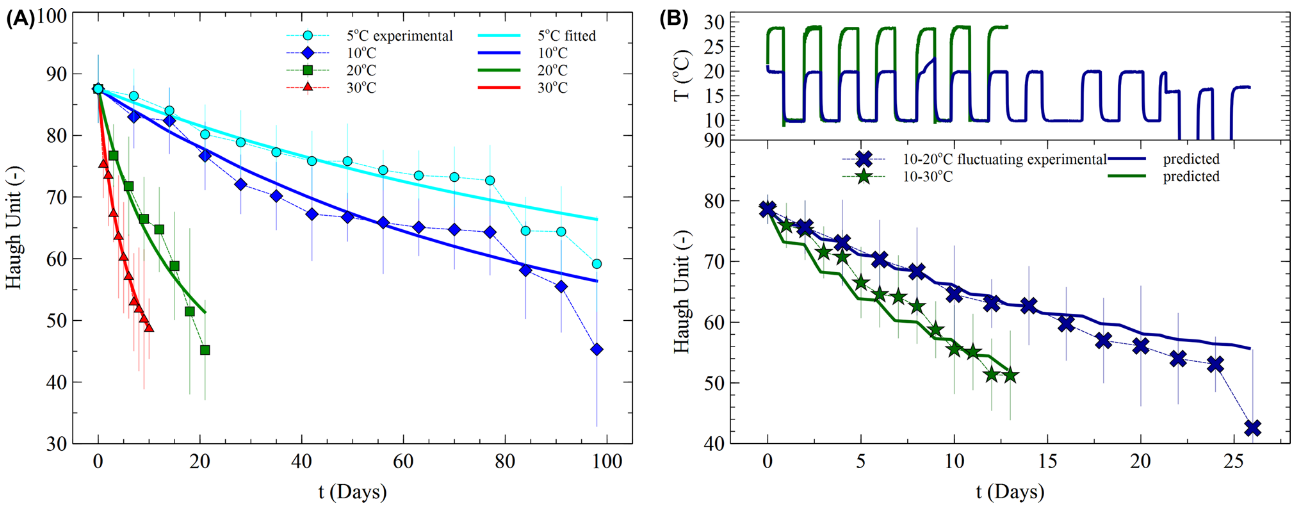

Figure 2. Comparison of experimental observations (symbols) and model predictions (dashed lines) of Haugh unit change of eggs under (A) constant and (B) variable temperature conditions.

time the data were observed, and n is the number of observations.

RESULTS AND DISCUSSION

Egg Quality Changes During Storage Periods

The storage time and temperature significantly ($P < 0.05$) affected almost all of the egg quality parameters investigated in the present study.

The relative weight loss of the eggs increased as the storage time increased at all temperatures and when the storage temperature increased, and the loss of egg weight dramatically increased as the storage time increased. In our study, the egg weight losses were significantly different compared with the various storage temperatures, as shown in Figure 1(A) and (B). On the seventh day of storage, for example, eggs from the 30° C storage group had a 4.27% loss in weight, whereas eggs from the 5 °C storage group had a 0.12% loss. At the end of all of the storage experiments, the egg weight loss rate was 5.74% on the 10th d, 5.22% on the 24th d, 3.21% on the 84th d, 1.86% on the 84th d, 3.46% on the 26th d, and 3.59% on the 13th d of storage for the 30, 20, 10, 5, 20 to 10, and 30 to 10 °C groups, respectively. Similar results were reported by Okeudo et al. (2005), Samli et al. (2005), Akyurek and Okur (2009), Jin et al. (2011), Akter et al. (2014) and Chung and Lee (2014). Normally, eggs stored for longer periods of time lose more of their initial weight due to the evaporation of water and, to a much lesser extent, the loss of CO_2, ammonia, nitrogen, and hydrogen sulfide gas from the albumen (Haugh, 1937; Obanu and Mpieri, 1984; Scott and Silversides, 2000).

The Haugh unit values decreased with an increase in the storage time at all storage temperatures and a greater decrease in the Haugh unit values was found at higher temperatures (20, 30, 20 to 10, and 30 to 10°C) compared with the lower temperatures (5 and 10 °C),

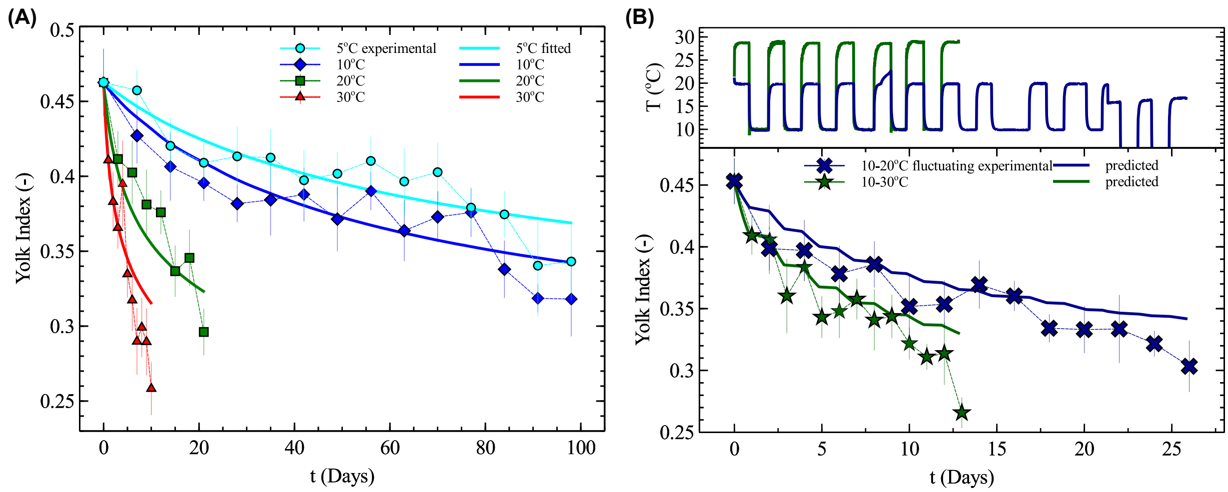

Figure 3. Comparison of experimental observations (symbols) and model predictions (dashed lines) of yolk index change of eggs under (A) constant and (B) variable temperature conditions.

as shown in Figure 2(A) and (B). The Haugh unit reduction occurs due to the decrease in the thick albumen height, because during egg storage, the albumen becomes thinner and loses CO_2, which allows the electrostatic complex between the lysozyme and ovomucin to rupture, which helps increase the pH of eggs (Scott and Silversides, 2000). These results are in agreement with those of Samli et al. (2005), Akyurek and Okur (2009), and Akter et al. (2014) who reported a significant ($P \leq 0.05$) decrease in the HU due to storage time and temperature.

The HU decreased from 87.57 to 64.51 at 5°C during 84 d of storage, whereas in the 20 and 30°C storage groups, this decline was further extended to 45.2 at 21 d of storage and 48.66 for 10 d of storage, respectively. This finding implies that the deterioration of the egg quality increased in a storage time- and temperature-dependent manner. Therefore, one should bear in mind that the deterioration of internal egg quality is a function of storage time and temperature. Similar results also were demonstrated by other researchers: The HU was significantly ($P \leq 0.05$) affected by storage time (Jin et al., 2011; Tayeb, 2012; Tebesi et al., 2012). Chung and Lee (2014) also reported that a higher storage temperature lowered the Haugh unit.

Dramatic deteriorations also were observed in the yolk index due to the storage time and temperature, as shown in Figure 3(A) and (B). After eggs are laid, water moves from the albumen to the yolk due to differences in osmotic pressure, and this may change the yolk index and may cause weakening of the vitelline membrane (Akter et al., 2014). At 20°C, the yolk index decreased from 0.47 to 0.3, at 30°C from 0.47 to 0.26, and at 30 to 10°C from 0.45 to 0.27 after 21, 10, and 13 d of storage, respectively. In contrast, at 10°C, the yolk index decreased from 0.47 to 0.34 and at 5°C from 0.47 to 0.37 after 84 d of storage. These results are in line with the works of Tayeb (2012) and Samli et al. (2005), who reported a decrease in the yolk index due to the storage time and temperature. Jin et al. (2011) and

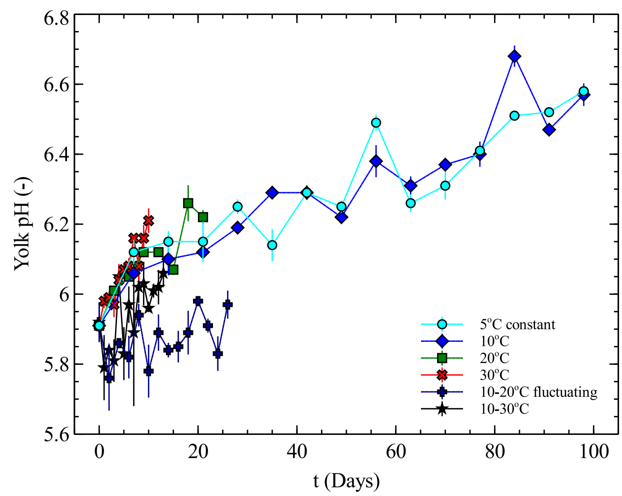

Figure 4. Changes in the yolk pH of egg during storage period at 5°C, 10°C, 20°C, 30°C, 20 to 10°C, and 30 to 10°C (mean ± SD, n = 3).

Tebesi et al. (2012) also reported that the yolk index was significantly ($P \leq 0.05$) affected by storage time.

At the beginning of the storage period, the albumen index was similar among all the storage temperatures; subsequently, we observed a decreasing trend, which was sharpest for eggs stored at higher temperatures (20, 30 and 3 to 10 °C). At the end of the experiments, the albumen index values were 0.03 on 10th d, 0.02 on 21st d, 0.05 on 84th d, 0.06 on 84th d, and 0.03 on 13th d for the 30 °C, 20 °C, 10 °C, 5 °C, and 30 to 10 °C storage groups, respectively. These results are in agreement with those of Akyurek and Okur (2009), Jin et al. (2011), Tayeb (2012), and Tebesi et al. (2012), who found that a similar decrease in the albumen index was observed in eggs depending on the storage temperature and time.

As shown in Figure 4, overall increases in the pH of the yolk were observed at the end of all the storage experiments, especially for the isothermal storage conditions. However, the trend was not uniform for all storage experiments. This is in line with the work of Akyurek and Okur (2009), who reported that most of the increase in the yolk pH occurred during the first 3 d of storage at 20°C and 4°C, with a greater increase at 20°C than 4°C.

During the initial storage d, increases in the albumen pH were observed for all storage conditions. Here, similar to the yolk pH, the trend was not uniform during all storage periods.

Overall increases in the albumen pH were observed at the end of all storage experiments. This may be related to the deterioration of the albumen quality or the Haugh unit. The deterioration in the albumen quality is the consequence of moisture evaporation and carbon dioxide loss, which leads to an increase in the pH and concomitant structural change in the albumen protein (Akter et al., 2014; Chung and Lee, 2014).

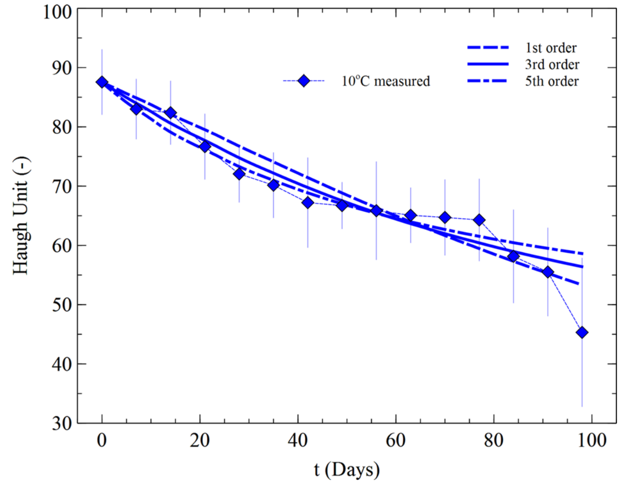

Figure 5. Comparison of the effect of model kinetic order on the fitted lines for Haugh unit.

Egg Freshness Quality Prediction Models

Currently, measurements of the relative weight loss, the Haugh unit, and the yolk index are used most frequently in commercial practice. The Haugh unit is generally considered to be a good indicator to evaluate egg quality (Dudusola, 2009), and the measurement of the Haugh unit is the most used method (Silversides and Scott, 2001). Additionally, highly significant changes were observed for these common egg quality indices for all storage conditions considered in the current study. Conversely, trends in yolk and albumen pH were not uniform. Therefore, the relative weight loss rate, the Haugh unit, and the yolk index were considered to be feasible indicators to develop egg freshness quality prediction models in the current study. The data from the constant (at 5, 10, 20, and 30°C) temperature conditions were used to determine the coefficients of the egg quality prediction models, which consisted of the primary model controlling the quality indicator change rate at a temperature condition in the form of a differential equation, and the secondary model that considered the variation of the change rate with temperature in a quadratic polynomial form. The developed models were applied to predict the change in the indicators under fluctuating temperature conditions, and the model performance was analyzed. The optimum set of model coefficients was determined from the iterative process to minimize the sum of the squared deviations of the indicators between the fittings and the experimental observations using the DEoptim package in R (Ardia and Mullen, 2010).

Relative Weight Loss of Eggs The relative weight loss (**RWL**) was observed to increase linearly with the d of storage from the experimental data, which implies that the kinetics, or the primary model, of weight loss is of the zeroth order, as shown in Eq. (6), which assumes a constant rate of weight loss at a given temperature. A polynomial model, as shown in Eq. (7), is used as the secondary model describing the temperature dependence of the weight loss rate.

$$\frac{dRWL}{dt} = c_{RWL}\ (T) \tag{6}$$

$$c_{RWL}\ (T) = 1.143 \times 10^{-3} T^2 - 1.355 \times 10^{-2} T + 6.050 \times 10^{-2} \tag{7}$$

where t and T are the time and temperature, respectively.

Figure 1(A) compares the sampled average data from the experiments, which are indicated by symbols, and the model fittings, which are indicated by thick lines. The error bars in the graph represent the standard deviations of the measured data. Although the experimental measurements show largely scattered data, the model fittings match the averaged experimental data well. According to Perez-Rodríguez and Valero (2013), the acceptable bias factor value for a predictive model could be 0.75 to 1.25. A_f and B_f for the constant temperature cases were found to be 1.116 and 0.940, respectively. The developed predictive model was found to have good accuracy. Figure 1(B) tests the application of the predictive model for the fluctuating conditions. The predicted weight loss change shows a stepwise increase in time due to the stepwise shifts in temperature, which is in good agreement with the experimental data. Based on the values $A_f = 1.116$ and $B_f = 0.940$ for the fluctuating temperature conditions, the developed predictive model for the relative weight loss could be applied to estimate the change in the fluctuating temperature condition.

Haugh Unit The change rate of the haugh unit (HU) decreases with time, as shown in Figure 2(A). The kinetics of the HU change is different from zeroth order, but the order is not yet known. Figure 5 compares the effect of the model kinetic order on the fitted lines. Although the 3 fitted lines appear to be close to each other, the initial change rate increases, whereas the

Table 2. Comparison of accuracy and bias factors of the predictive models of different order for egg Haugh unit for constant and fluctuating temperature conditions.

Temperature condition (°C)	Model order											
	0		1		2		3		4		5	
	A_f	B_f	A_f	B_f	A_f	B_f	A_f	B_f	A_f	B_f	A_f	B_f
Constant	1.037	0.989	1.028	0.994	1.023	0.997	1.021	0.999	1.023	0.999	1.026	0.999
Fluctuating	1.030	1.018	1.025	1.012	1.026	1.006	1.028	1.001	1.032	0.997	1.036	0.993

A_f = accuracy factor; B_f = bias factor.

Table 3. Comparison of accuracy and bias factors of the predictive models of different order for egg yolk index for constant and fluctuating temperature conditions.

Temperature condition (°C)	Model order											
	5		6		7		8		9		10	
	A_f	B_f	A_f	B_f	A_f	B_f	A_f	B_f	A_f	B_f	A_f	B_f
Constant	1.037	0.996	1.037	0.997	1.036	0.997	1.036	0.998	1.037	0.998	1.038	0.998
Fluctuating	1.043	0.960	1.041	0.962	1.039	0.964	1.038	0.966	1.038	0.967	1.038	0.969

A_f = accuracy factor; B_f = bias factor.

change rate decreases in the later phase with the model order. Table 2 compares the A_f and B_f of the models with different orders. The third order kinetic model was selected over the others, because A_f and B_f are the best for the constant temperature cases in which the model coefficients were determined.

$$\frac{dHU}{dt} = c_{HU}\ (T)HU^3 \tag{8}$$

$$c_{HU}\ (T) = 2.720 \times 10^{-8}T^2 - 3.124 \times 10^{-7}T + 1.370 \times 10^{-6} \tag{9}$$

where t and T are the time and temperature, respectively.

The developed model was applied to predict the HU change in time for the given temperature histories, and the result is shown in Figure 2(B). The model depicts the stepwise change in the HU in time well, and A_f and B_f are 1.028 and 1.001, respectively, for the fluctuating temperature conditions.

Yolk Index The change rate of the yolk index (YI) decreases with time, as shown in Figure 3(A). A polynomial model, as shown in Eq. (11), is used as the secondary model describing the temperature dependence of the change in the yolk index. As shown in Table 3 for the yolk index, both the accuracy factor and the bias factor values from the fifth order to 10th order models are close to one under all temperature conditions. However, when we observe the respective values of the constant temperature conditions, the eighth order model performs better than the rest of the models, with A_f and B_f values of 1.036 and 0.998, which is closest to one, respectively. This indicates that the changes in the yolk index follow eighth order kinetics. The eighth order model is more accurate for predicting the egg freshness in terms of the yolk index and is shown in Eq. (10).

$$\frac{dYI}{dt} = c_{YI}(T)YI^8 \tag{10}$$

$$c_{YI}(T) = 1.249 \times 10^{-2} \times T^2 - 1.542 \times 10^{-1} \times T + 6.756 \times 10^{-1} \tag{11}$$

where t and T are the time and temperature, respectively.

The developed model is applied to predict the yolk index change over time for the given temperature histories, and the result is shown in Figure 3(B). The model depicts the stepwise change in the yolk index over time well, and A_f and B_f are 1.038 and 0.966 for the fluctuating temperature conditions, respectively.

The recommended shelf life for eggs is 35, 21, 14, and 7 d when eggs are stored in the temperature range of 0 to 10 °C, 10 to 20 °C, 20 to 25 °C, and 25 to 30 °C, respectively, in Korea (Korean Ministry for Food, Agriculture, Forestry and Fisheries, 2010). In Japan, it is 50, 23, 13 d when stored below 10, 20, and 25 °C, respectively (Korean Ministry for Food, Agriculture, Forestry and Fisheries, 2010). The shelf life is estimated to be 28 d (3 to 5 wk) when stored refrigerated after packaging, in the United States (United States Department of Agriculture, 2016). Eggs have a shelf life of 28 d from date laid to their "best before" date in the United Kingdom if they were stored below 20 °C (National Health Service, 2015). Although the government of Australia and New Zealand states that there is no need to keep eggs refrigerated in distribution (Food Standards Australia New Zealand, 2011), the consumer group in Australia (Consumer site of Australian Egg Farmers, 2014) recommends keeping fresh eggs refrigerated and the shelf life of refrigerated ones to be 6 weeks. Although the criteria for setting the egg shelf life could vary with region as shown above, it tends to be based on refrigerated distribution for freshness and represents the meaning of "best before" as society develops.

Complying with the guideline in Korea (Korean Ministry for Food, Agriculture, Forestry and Fisheries, 2010), the shelf life is a period when the Haugh unit reaches the value of around 59, which is the average value eggs reach the expiration date at 10, 20, and 30 °C temperature conditions starting at the initial value of 88, according to the definition of the recommended shelf life for eggs in Korea. Figure 2(B) shows the Haugh unit change under the fluctuating temperature conditions with the initial value of around 80, showing that the experimental and model predictions are in good agreement even longer periods than the value of the Haugh unit becomes lower than 56 at which it is believed that the eggs reach the expiration date. Therefore, the period considered in the study reflects the entire distribution process of eggs while the freshness of eggs matters.

Conclusions

In this study, a noteworthy result was the visibility of a rapid decrease in the Haugh unit and a rapid increase in the weight loss rate for short times at high temperatures. The results showed that there was a significant change in the weight loss rate, the yolk index, the albumen index, and the HU under all of the temperature conditions considered during the respective storage times.

The overall purpose of this study was satisfied by developing models that predicted the weight loss rate, the Haugh unit, and the yolk index values as a function of the time the eggs were exposed to the temperatures selected. The data from the constant (at 5, 10, 20, and 30°C) temperature conditions were used to determine the coefficients of the egg quality prediction models, which consisted of the primary model controlling the change rate of the quality indicator at a temperature condition in form of a differential equation, and the secondary model considering the variation of the change rate with temperature in a quadratic polynomial form.

The developed models were applied to data obtained under fluctuating (at 10 to 20 and 10 to 30°C) temperature conditions, and good model performance results, in terms of the accuracy factor and bias factor, were obtained. The model performance evaluation revealed that the zeroth order kinetic model, third order kinetic model, and eighth order kinetic model were more accurate for the weight loss rate, the Haugh unit, and the yolk index, respectively. The models depicted the stepwise change in the weight loss rate, the HU, and the yolk index in time well for the fluctuating temperature conditions, and the A_f and B_f values were 1.116 and 0.940, 1.028 and 1.001, and 1.038 and 0.966, respectively.

The developed models can be used to predict egg freshness changes in terms of the weight loss rate, the Haugh unit, and the yolk index at any temperature condition within the range of 5 to 30°C during storage. The models can simulate the freshness quality of eggs during storage in their supply chain during commercial display.

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