Kinetic modeling impacts of relative humidity, storage temperature, and air flow velocity on various indices of hen egg freshness

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ABSTRACT Storage experiments were conducted to study the impacts of the environmental factors (temperature (T) (°C), relative humidity (RH) (%), and air flow velocity (VEL) (m/s)) on the hen egg quality indices and to develop kinetic model(s) for freshness prediction. VEL had negligible effect on relative weight loss (RWL). All factors had significant effect on Haugh unit (HU) but only T impacted *S*-ovalbumin content (SO). Fitted regression lines for the RWL and the HU had determination coefficient (R^2) of 0.996 and 0.95, respectively. The HU equation reflected impacts of all factors, and the impact of temperature shift-up increases the HU decrease, where the impact decreases with RH and increases with flow velocity. Kinetic model for SO was developed using isothermal (5, 10, 20, 25, and 28.5°C) conditions and validated under dynamic (10 to 20 and 10 to 28.5°C) conditions. The accuracy and bias factor values were 1.091 and 0.917 at 10 to 20°C and 1.206 and 1.204 at 10 to 28.5°C, respectively, which indicates that the SO model performed well. The SO model can be used along with the HU model (as the HU model can reflect the combined effect of temperature, humidity, and air flow velocity) to predict hen egg freshness at 5 to 28.5°C storage condition.

Key words: egg freshness, Haugh unit, air flow velocity, *S*-ovalbumin, kinetic model

INTRODUCTION

Shell eggs deteriorate in internal quality with time and this depends on the shell and internal content of the egg (Adeogun and Amole 2004). Poor storage conditions may cause deterioration of egg quality that can reduce eggs grade within a few days and consequently loss and waste of eggs may result. The principle degrading factors are high storage temperature and dehydration (Tabidi 2011). Research results by Jin et al. (2011) reported that egg weight loss, albumen pH, and Haugh unit (**HU**) are parameters that are greatly influenced by the storage temperature and time. Samli

et al. (2005) has also reported that pH is a useful means for describing changes in albumen quality over time during storage and significant increases in yolk pH were observed with increasing storage time. Ovalbumin, the most abundant protein component in shell eggs, is gradually converted into *S*-ovalbumin during storage, which is an irreversible and extremely heat-stable form compared with ovalbumin, determined by a thermogram of the differential scanning calorimeter (Smith and Back 1965; Huntington et al. 1995). The formation of *S*-ovalbumin is affected by both pH and temperature and increases with time of storage at a rate which increased with pH (Smith and Back 1962). Huang et al. (2012b) also reported that *S*-ovalbumin formation positively correlated with the storage temperature, and high temperature could accelerate this formation. The *S*-ovalbumin content (**SO**) increases from 18% of the egg white to 86% after 6 mo of refrigerated storage (Smith and Nguyen 1984; Alleoni and Antunes 2004). Refrigeration and coating treatments reduce the rate of its formation (Alleoni and Antunes 2004).

An investigation by Whitelock et al. (1994) on peach quality during storage showed that storage conditions such as temperature, relative humidity, and storage air

flow had significant ($P < 0.05$) effect on weight loss rate during storage. Huang et al. (2012a) reported that relative humidity did not affect the SO of eggs during storage. The storage conditions may vary during distribution (transportation and storage) than the specified value. To estimate the influence of these variations on egg quality during distribution, the different egg quality indices should be evaluated under different environmental conditions. Therefore, models predicting egg freshness quality change rate as influenced by environmental factors are helpful for estimating the shelf-life of shell eggs during storage and/or market display.

Studies including the impacts of significant environmental factors in storage on egg quality changes during expected storage life are needed. Several storage trials at different temperature conditions have been conducted during previous times to assess egg quality. There are some models that describe the effect of temperature on egg freshness quality indices. Studies carried out in order to set up techniques for prediction 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 (Dutta et al. 2003; Yongwei et al. 2009; Yimenu et al. 2017b), the use of spectroscopy (Kemps et al. 2007; Giunchi et al. 2008), the assessment of albumen viscosity (Kemps et al. 2010), the use of *S*-ovalbumin as an indicator (Huang et al. 2012a), and prediction at variable temperature conditions (Yimenu et al. 2017a). All these previous studies considered only the effect of temperature to estimate model parameters, which may not consider the significant influences of other environmental factors on the change rate of egg quality indices. Changes in egg freshness quality indices as influenced by other environmental factors such as relative humidity and air flow velocity were not investigated yet. There are no models to relate egg freshness change rates to combined effects of storage temperature, relative humidity, and air flow velocity. Therefore, experiments are needed to be conducted under different conditions by varying environmental factors in hen egg storage units.

The aim of the present study was to determine correlations between the freshness of hen eggs and the surrounding environmental conditions during storage. The specific objectives were (1) to study the impacts of the environmental factors (temperature (°C), relative humidity (%) and air flow velocity (m/s)) on the egg quality indices such as weight loss, Haugh unit, and *S*-ovalbumin content using regression analysis, (2) to develop kinetic model(s) for freshness prediction using constant temperature data and validate it under dynamic temperature conditions.

MATERIAL AND METHODS

Experimental Materials and Storage

Freshly laid special class (first or second grade eggs weighing between 60 and 68 g per egg) unfertilized

Table 1. Experimental conditions.

Condition number	Relative humidity (%)	Temperature (°C)	Flow velocity (m/s)
1	35.5	15	0.05
2	44.7	25	0.05
3	33.2	15	0.55
4	42.4	25	0.55
5	64.5	15	0.05
6	70.1	25	0.05
7	64.3	15	0.55
8	74.1	25	0.55
9	96.3	15	0.05
10	98.9	25	0.05
11	94.3	15	0.55
12	99	25	0.55

and unwashed hen egg samples in their commercial packaging (cartons, each containing 10 egg specimens) were supplied directly from Ireefarm Egg Company, Seoul, and the storage experiments were conducted at Korea Food Research Institute. Storage experiments were performed in 2 parts at different times: part 1 for studying environmental impacts and part 2 for prediction modeling. The storage experiments in the respective parts of the study were conducted at the same time.

In part 1, samples were stored at 6 temperature controlled storage chambers (constant temperature rooms equipped with air blast fans) (REI Technology Co., Seoul, Korea). Three storage units were set at 15°C and the other 3 storages were set at 25°C. The storage conditions were shown in Table 1. The specific temperatures were chosen to include the common temperature during storage and the abusive temperature, which is well within the temperature range during egg distribution. Miniature, programmable, electronic data loggers were used to constantly monitor the temperature with ±0.3°C accuracy (HL-1D/TL-1D, Rotronic Measurement Solutions, Taiwan) and relative humidity with measurement range and accuracy of 0 to 99% RH (−20 to 70°C) and ±2.5% RH, respectively (TR-72*i*, T&D Corporation, Japan), in the storage chambers. Temperature data loggers were placed inside the storage chambers and plastic covers to monitor storage environment. Relative humidity data loggers were also placed in both storage chambers and plastic covers to monitor humidity during storage period. Air velocity inside the chambers and plastic covers was measured at intervals of 30 min for 24 h using a hand-held Testo 400 anemometer (Brandt Instruments, Inc., Prairieville, LA) with Vane and Pitot tube Measuring Range of 0 to 12,000 fpm (0 to 60 m/s) and 0 to 8,000/20,000 fpm (0 to 40/100 m/s), respectively, and the average value was considered.

In part 2, similar storage chambers as in part 1 were used and set at 5, 10, 20, 25, and 28.5°C to create constant temperature conditions. In addition, 2 variable temperature conditions were established and specific time-temperature scenario for each variable profile was applied in temperature programmable storage

chambers. 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 28.5°C (isothermal steps per repeated temperature cycle: 24 h at 10°C, 24 h at 28.5°C). Similar temperature data loggers as the ones used in part 1 were placed inside the storage chambers as well as attached to egg surface and egg core, to monitor storage air, egg surface, and egg core temperature, respectively. The egg core temperature measurements were used during quality prediction model development, as the surrounding air temperature usually deviate from the egg core temperature.

Experimental Set-up

Part 1: 2 storage set-point temperatures (**T**) in °C (T: 15 and T: 25), 3 relative humidities (**RH**) in % (RH: low, RH: medium, and RH: high), and 2 storage air flow velocities (**VEL**) in m/s (VEL: high and VEL: low) were designed in the 6 temperature controlled storage chambers described in the above section. Egg samples were divided into 12 groups and moved to their corresponding treatments in 6 storages as shown in Table 1. Some egg cartons were stored on a shelf under a plastic cover having perforations (LDPE plastic) to allow gas exchange and positioning it in the chamber away from direct airflow so that negligible air velocity is attained; other egg cartons were stored on a separate shelf in the same chamber without covering and positioned to provide maximum airflow across the cartons to allow high air velocity. The high air flow velocities were attained by circulation using similar electric fans and the low air velocities were attained by free convection under plastic covers. The maximum and medium humidities were attained by using ultrasonic humidifier (DLE-US-06, 3Htech Co., Daejeon, Korea). The low humidity was attained under normal conditions without humidification.

The experiments were carried out for a total period of 29 and 10 d at 15 and 25°C, to observe the variation trends of weight loss rate, Haugh unit, yolk index, albumin index, yolk pH, albumin pH, and *S*-ovalbumin formation. Egg quality indices were measured per 3-d interval at 15°C and 2-d interval at 25°C.

Part 2: 7 storage experiments (5 at constant and 2 at variable temperatures) were designed as described in the previous section. Experiments were carried out for a total period of 10 d at 28.5°C, 10 d at 25°C, 21 d at 20°C, 26 d at 10 to 20°C, 13 d at 10 to 28.5°C, and 98 d at 5°C as well as 10°C storage temperatures. The egg quality indices were measured every 1, 2, 3, 2, 1, and 7 d for the 28.5, 25°C, 20, 10 to 20, 10 to 28.5, and 5°C as well as 10°C storage samples, respectively. The same egg quality indices were measured as in part 1. Data from fluctuating temperature conditions were used to validate the quality prediction models developed using data collected under isothermal conditions.

Egg sampling

Egg sampling was performed in a similar way during both part 1 and part 2 of the study. During each sampling time, 2 egg cartons (each containing 10 eggs) were randomly selected from each treatment group. One carton was used for albumen index, yolk index, and Haugh unit; another carton was used for pH (albumen, yolk) and *S*-ovalbumin content. For weight loss rate, on the initial day of the storage experiment, 3 packs (each containing 10 eggs) were randomly selected and individual eggs were labeled from 1 to 20. The eggs were identified and labeled by pasting a masking tape with appropriate identification tag around the sharp end of the egg.

Egg Quality Evaluation

Weight Loss Weight (in grams) was established by individual weighting of each labeled egg, using an analytical balance (Carter 1975) during each experiment day. Egg weight was measured using a 200 g × 0.1 g capacity digital scale (Model CSG 201F, OHAUS Corporation). This is done by placing the egg on plastic holder on the flat surface of the scale ensuring that the scale is set to 0.0 g before measurement. Egg weight loss was determined as the difference between successive weights of eggs at different weighing days. Weight loss percentage was calculated in relation to day 0 egg weight (g). The difference between the day 0 egg weight and the weight after each time point was expressed as a percentage of the day 0 egg weight.

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

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

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

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

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

Haugh unit was determined from egg weight and albumen height of a broken egg spread on a horizontal plate using the expression below (Haugh 1937):

$$HU = 100 \log \left(H + 7.51 - 1.7\,W^{0.37} \right) \qquad (3)$$

where H = Albumen height (mm), W = the weight of egg when tested (g)

pH Measurement After separating yolk and albumen, putting each into a beaker and homogenizing, pH values of the albumen and yolk were measured using a pH meter (TA-70, DKK-TOA Corporation, Japan). The pH meter was calibrated using buffer solutions at pH 4 and 7 before measurements. Measurements were performed on 3 replicates and average values were reported.

S-ovalbumin Content The SO of the egg white was measured using the method described by the literature (Huang et al. 2012a).

Phosphate buffer: 13.7 g $NaH_2PO_4\cdot2H2O$ and 43.1 g Na_2HPO_4 was dissolved in 1 L of deionized water, 20-fold diluted, adjusted to pH 7.5.

Precipitant: 0.5 mol/L NaCl plus 0.1 mol/L CH_3COONa, Values CH_3COOH pH adjusted to 4.7.

Biuret solution: 1.8 g $CuSO_4\cdot5H_2O$ and 7.2 g $C_4O_6H_2KNa\cdot4H_2O$ was dissolved in 500 mL of deionized water, 36 g NaOH was dissolved in 360 mL deionized water, mixed 1 spare.

Five grams of egg whites was placed in a 100-mL beaker, and 25 mL of 0.5 mol/L phosphate buffer (pH 7.5) was added; the mixture was agitated for 5 min with a magnetic stirrer. Afterward, 5 mL of the suspension was placed into 2 test tubes; one of the tubes was heated at 75°C for 30 min. Upon cooling, 5 mL of the precipitating solution was added in each test tube, and the solution was transferred to centrifuge tubes with the addition of another 5 mL of precipitating solution. After resting for 10 min, the tubes were centrifuged at 10,733 × g for 5 min at 4°C and the supernatant was obtained and filtered. Two milliliters of the filtered supernatant was placed in a test tube with 4 mL of Biuret solution added. This supernatant aliquot was left to rest for 30 min, and the absorbance was determined at 540 nm using a Beckman DU-70 spectrophotometer (Fullerton, CA). The results were expressed as a percentage of *S*-ovalbumin in the total amount of ovalbumin.

Statistical Analysis

The obtained data were subjected to ANOVA analysis using the statistical analysis system (SAS 2008) whereby comparison of mean values were conducted with LSD test at $P < 0.05$ significance level. The R program for Windows was used for regression analysis of environmental factors and to fit the experimental data to model equations to obtain the coefficients of the equations (R Development Core Team 2011).

The comparison between the observed and predicted values of SO 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 1 is an effective and practical measure of predictive model validity. To evaluate the prediction error of each model, these statistical characteristic indices (bias factor (B_f) and accuracy factor (A_f)) were employed:

$$B_f = 10^{\frac{\sum \log\left(c_{\text{predicted}} / c_{\text{observed}} \right)}{n}} \qquad (4)$$

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

where c_{observed} is the value of each data experimentally observed, $c_{\text{predicted}}$ is the value predicted at the same time as the data were observed, and n is the number of observations.

RESULTS AND DISCUSSION

Egg Quality Changes During Storage

Table 1 shows the experimental condition considered in this study to investigate the impact of different environmental factors on the change of egg freshness indices. Storage time and temperature significantly affected almost all parameters of egg quality investigated in the present study. An analysis of variance showed that temperature and storage time had significant ($P < 0.05$) effect for all egg quality indices, although RH and airflow were not significant for SO content (Figure 3). Egg weight, Haugh unit, yolk index, and albumen index significantly ($P < 0.001$) decreased with increased storage time and temperature. Initially, albumen and yolk pH were shown to have an increasing trend and then shown a non-uniform trend by increased storage time and temperature, attaining higher values at the end of the experiments. S-ovalbumin content significantly ($P < 0.001$) increased by increased storage time and temperature.

Increase in storage temperature accelerated egg weight loss and as the storage duration increased, egg weight loss was increased at considered temperatures (15 and 25° C). 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), Lee and Chung (2014), and Yimenu et al. (2017a). Normally eggs stored for longer periods of time loss from their initial weight, due to the evaporation of the water from their content and, to a much lesser extent, loss of CO_2, ammonia, nitrogen, and hydrogen sulfide gas from the albumen (Haugh 1937; Obanu and Mpieri 1984; Scott and Silversides 2000).

Figure 1 shows the HUs change over time under different environmental conditions. The different colors
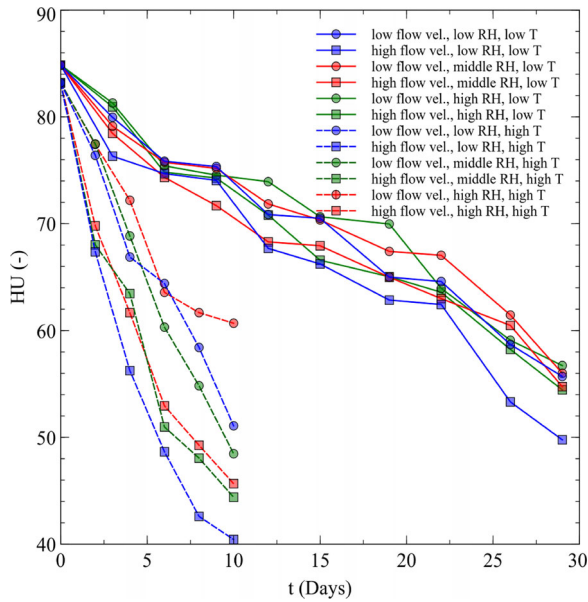
Figure 1. Haugh unit changes in time observed in the experiments.

Figure 2. Relative impacts of environmental factors on Haugh unit change.

compare the impact of RH. Blue, green, and red stand for low, middle, and high RH conditions. Circles are for low flow velocity conditions, whereas squares represent high flow velocity ones. Data with solid lines are taken from the temperature condition of 15°C, and those with dashed ones are for the condition of 25°C.

Haugh unit values decreased with an increase in storage time at both storage temperatures (15 and 25°C), and a greater decrease in HU values were found at higher temperature (25°C) than at lower temperatures (15°C) (Figure 1). Haugh unit reduction happens due to the decrease in thick albumen height, because during egg storage albumen becomes thinner and loses CO_2, allowing rupture of the electrostatic complex between lysozyme and ovomucin (Scott and Silversides 2000). These results are in agreement with those of Samli et al. (2005), Akyurek and Okur (2009), Jin et al. (2011), Tayeb (2012), Tebesi et al. (2012), Akter et al. (2014), Lee and Chung (2014), and Yimenu et al. (2017a), who reported a significant ($P \leq 0.05$) decrease in HU due to storage time and temperature.

There was a confirmed rapid increase in SO after storage at 15 and 25°C, and the formation velocity at 25°C was significantly ($P \leq 0.05$) higher than that at 15°C. The result indicated that high temperature could accelerate the S-ovalbumin formation, which supports the former reports (Alleoni and Antunes 2004; Huang et al. 2012a).

Modeling Environmental Impacts on Hen Egg Quality Indices

Changes in values of the relative weight loss, the Haugh units, and the S-ovalbumin content were analyzed statistically using regression analysis. The relative impact of each environmental factor (temperature, relative humidity, and air flow velocity) on the varia-
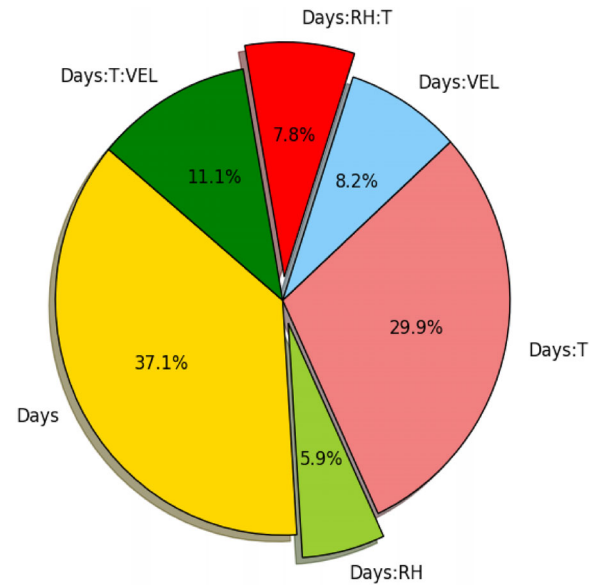
tion of egg quality indices analyzed by the open-source statistics program, R (R Development Core Team 2011) for windows.

Weight Loss It was observed that the rate of weight change in time depends on RH (%) and temperature. The weight loss rate increases with temperature and decreases with RH as expected. Weight change was greatly affected by RH and the rate increased with lower RH. With decreasing RH, weight change increased for high and low airflow velocity. Although RH has the major influence on egg weight loss, air velocity is still a factor. The effects of the RH× airflow interaction were apparent because the weight change was higher for high airflow than low airflow.

The flow velocity was found not to affect the weight loss for the given range of change. The determination coefficient (R^2) was estimated to be 0.996. The regression equation was

$$\text{RWL} = 1.0 + \left(2.077 \times 10^{-3} + 3.350 \times 10^{-6} \ RH \right. $$
$$\left. \times \ (T - 6.651) - 3.440 \times 10^{-4} T \right) \times \text{Days}$$

(6)

where RH and T are the relative humidity and temperature, respectively.

The summation of the numbers in parenthesis in Eq. (6) was always negative for the conditions considered in this study. The magnitude of weight loss rate was the number in the parenthesis in Eq. (6), and found to increase with temperature and decrease with relative humidity. The interaction between RH and temperature in Eq. (6) indicated that the impact of RH increases with temperature, which implies RH becomes more impactive with the increase of storage temperature.

Figure 2 represents the relative impact of each environmental factor on the variation of the relative weight

loss analyzed by the open-source statistics program, R. Time, relative humidity, and temperature were the significant factors, whereas that of flow velocity was negligible.

Haugh Units Figure 1 shows the HU changes over time under different environmental conditions. The different colors compared the impact of RH. Blue, green, and red stand for low, middle, and high RH conditions. Circles were for low flow velocity conditions, whereas squares represented high flow velocity ones. Data with solid lines were taken from the temperature condition of 15°C, and those with dashed ones were from the condition of 25°C.

Both RH and air velocity had significant ($P \leq 0.05$) effect on HU values (Figure 2). The difference between high airflow and negligible airflow treatment was significantly greater at low RHs and high temperature (Figure 1).

The variation of HU over time was analyzed using the regression analysis. The determination coefficient (R^2) was estimated to be 0.95. The equation was shown below

$$\text{HU} = 81.86 + 3.263 \cdot Days \times \left(1 - 4.601 \times 10^{-3}RH\right.$$
$$- 8.529 \times 10^{-2}T + 1.130VEL + 3.386$$
$$\left. \times 10^{-4}T \cdot RH - 8.066 \times 10^{-2}T \cdot VEL\right) \quad (7)$$

where RH, T, and VEL are the relative humidity, temperature, and air flow velocity, respectively.

The decrease of HU under the combined effect of the environmental factors during storage time can be determined using Eq. (7). The impact of each environmental factor on the change of HU with time could be evaluated by taking the partial derivative of Eq. (7) with respect to each factor of interest.

$$\frac{dHU}{dT} = 3.263 \cdot \text{Days} \times \left(-8.529 \times 10^{-2} + 3.386\right.$$
$$\left. \times 10^{-4}RH - 8.066 \times 10^{-2}\text{VEL}\right) \quad (8)$$

$$\frac{dHU}{dRH} = 3.263 \cdot \text{Days} \times \left(-4.601 \times 10^{-3}\right.$$
$$\left. + 3.386 \times 10^{-4}T\right) \quad (9)$$

$$\frac{dHU}{dVEL} = 3.263 \cdot \text{Days} \times \left(1.130 - 8.066 \times 10^{-2}T\right) \quad (10)$$

The impact of temperature shift-up increased the negative slope in Eq. (8) to speed up the HU decrease, where the impact decreased with RH increased with flow velocity. Plugging in the temperature range considered, 15 to 25°C in Eq. (9), the value in the parenthesis turned to be positive indicating the high RH alleviating the decreasing rate of HU with time, and the impact was more effective under higher temperature. The flow
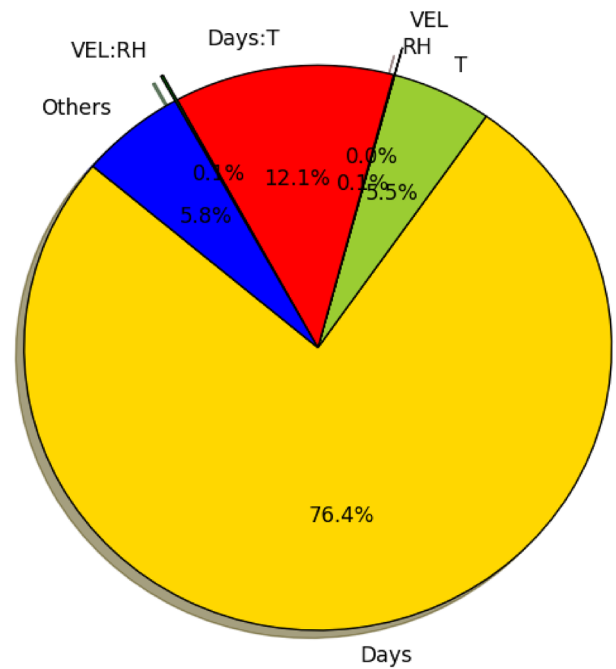

Figure 3. Relative impacts of environmental factors on *S*-ovalbumin change.

velocity accelerated the decrease of HU, and the impact became more significant with temperature as shown in Eq. (10).

Ignoring the influence of RH and VEL,

$$HU = 81.86 + 3.263 \cdot \text{Days} \cdot (0.038737 - 0.003397T) \quad (11)$$

S-ovalbumin Contents It was statistically analyzed that *S*-ovalbumin change was independent of RH condition. Figure 3 clearly shows that the RH did not affect the change. The change was a strong function of time and temperature condition only. The difference between RH treatments as well as high airflow and low airflow treatments were not significant ($P > 0.05$) both at low temperature and high temperature conditions. The RH × airflow interaction was also not significant for SO change (Figure 3). Consequently, the change in SO during storage was expressed only as a function of time and temperature using a kinetic model described in the following section.

Kinetic Model Development For S-ovalbumin Variation

The optimum set of model parameters 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). That was done by the process of minimizing the error between the experimental observations and the solutions of Eqs. (12) and (13) by assuming values of model parameters.
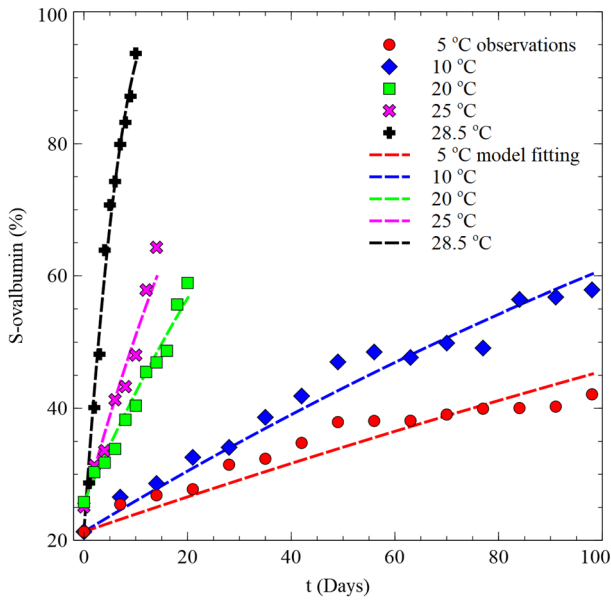
Figure 4. Comparison between observed *S*-ovalbumin histories with the model fitting data under constant temperature conditions.

Figure 5. Comparison between observed *S*-ovalbumin histories with the model predictions under fluctuating temperature conditions.

Table 2. The accuracy and bias factors of the model fitting the *S*-ovalbumin histories under constant temperature conditions.

Temperature condition (°C)	A_f (–)	B_f (–)
5	1.059	0.972
10	1.040	0.982
20	1.033	1.013
25	1.043	1.009
28.5	1.039	1.015

A_f = accuracy factor; B_f = bias factor.

The time histories of SO showed convex upward shape. Equations (12) and (13) were used to mimic the behavior.

$$\frac{dSO}{dt} = \mu(T)\left(1 - \frac{SO(t)}{100}\right)^d \qquad (12)$$

$$\mu(T) = \begin{cases} a_0 + a_1 \cdot T + a_2 \cdot T^2 & 5 \leq T \leq 25\,°C \\ a_0 + a_1 \cdot T + a_2 \cdot T^2 + a_3 \cdot \frac{(T-25)}{(28.5-25)} & T > 25\,°C \end{cases}$$

$$(13)$$

where a_0, a_1, a_2, a_3, and d are model parameters, which are determined to be 4.347×10^{-1}, 6.156×10^{-2}, 7.264×10^{-3}, and 7.640, respectively. t and T are the time and temperature, respectively.

Figure 4 shows the comparison of the observed *S*-ovalbumin histories with the model fitted ones under constant temperature conditions. They showed very good agreement with the accuracy and bias factor very close to 1 as listed in Table 2.
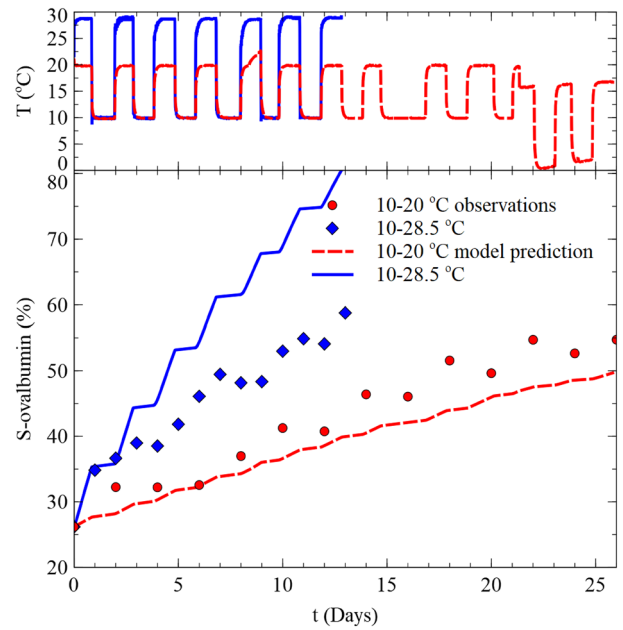
Figure 5 compares the experimental observations with the model predictions under 2 fluctuating temperature conditions. The *S*-ovalbumin change in time was calculated by integrating Eqs. (12) and (13) with the measured temperature histories shown in Figure 5. The prediction underestimated the *S*-ovalbumin increase under 10 to 20°C condition, where it overestimated under 10 to 28.5°C. The accuracy and bias factors were 1.091 and 0.917 at 10 to 20°C and 1.206 and 1.204 at 10 to 28.5°C, respectively. According to Perez-Rodrıguez and Valero (2013), the acceptable bias factor value for a predictive model could be 0.75 to 1.25, and the developed model was acceptable. However, the prediction performance was found to be inferior to the cases using other quality indices such as relative weight loss, Haugh unit, and yolk index, which had the A_f and B_f values of 1.116 and 0.940, 1.028 and 1.001, and 1.038 and 0.966, respectively, at 10 to 30°C (see Yimenu et al. 2017a).

CONCLUSIONS

The environmental impact analysis result in the current study showed that all storage factors had significant effect on the HU, whereas only temperature had significant effect on the (SO. This indicates that the HU regression model can be considered as the better model for prediction of egg freshness, as it reflect the combined effect of temperature, humidity, and air flow velocity. Therefore, it can be concluded that the SO kinetic model can be used to predict egg freshness along with the HU model at 5 to 28.5°C storage condition during hen egg distribution.

ACKNOWLEDGMENTS

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