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Influence of water activity and dry-heating time on egg white powders quality

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ABSTRACT

Egg white powders typically undergo thermal treatment at 60 °C for 10–14 days to control *Salmonella*. Increasing water activity (a_w) of egg white powders and treatment temperature can sharply reduce processing time, but its effect on product quality is unclear. This study aims to determine the impacts of a_w and dry-heating time on egg white powders' color and bulk properties. Egg white powders were conditioned to three different a_w (0.30, 0.45, 0.60) in equilibration chambers at 23 °C. The samples were then treated at 80 °C for up to 24 h. These treatments were selected based on an earlier study to achieve more than 6-log reduction of *Salmonella* in egg white powders. After treated, the egg white powders samples with higher a_w and longer dry heating time were significantly brighter ($L^* = 91.7 \pm 0.01$) and showed a soft yellow coloration ($H^* = 95.58 \pm 0.05$, $C^* = 18.02 \pm 0.05$). The loose, tap and particle bulk densities of the treated samples decreased with higher a_w, but increased with longer dry-heating time. The Hausner ratio for treated samples was ≈1.5, indicating that samples are difficult to fluidize.

1. Introduction

Egg white powders are a popular food ingredient because of their natural emulsification and foamability properties. They are preferable to liquid egg white in large scale food production because of less stringent requirements for storage and transportation (Katekhong & Charoenrein, 2018). Egg white powders are mainly used as an ingredient for ready-to-eat foods, such as salad dressings, pastries, and ice cream (Thammasena, Fu, Liu, & Liu, 2020). Egg white powders are a high bioactive peptide source. The consumption of these egg white peptides has numerous health benefits, such as better blood pressure regulation, antioxidant effects, neuroprotective and anti-diabetic properties, anti-inflammatory effects, anti-angiotensin, and bone growth promotion activity (Grootaert et al., 2019; Quan & Benjakul, 2019).

In industrial production, liquid egg white undergoes numerous transformations to become a powder. Processing begins with egg white desugarization, then pH adjustment, followed by concentration, and finally, the liquid egg white is spray-dried (Lechevalier, Nau, & Jeantet, 2013; Sharma, Singh, Sarkar, Singh, & Premi, 2012). The resulting egg white powders are then packaged and heated at 58 °C–60 °C for 10–14 days as the pasteurization step (dry-heating) (Boreddy, Birla, Froning, Thippareddi, & Subbiah, 2014). Research data have shown that different processing conditions have different impacts on egg white's bioactive peptides. For example, peptides from fried egg whites have increased anti-hypertensive effects compared to boiled egg whites (Grootaert et al., 2019). Therefore, it can be inferred that dry-heating should impact the egg white powders' peptides, which may be reflected in the final color or density of the finished product.

Egg white powders are a low-moisture food; i.e., the water activity (a_w) is lower than 0.6 (Santillana Farakos, Frank, & Schaffner, 2013). Water activity is defined as the ratio of water vapor pressure in a food system to the satutated water vapor pressure at the same temperature (Liu, Tang, Tadapaneni, Yang, & Zhu, 2018). This property indicates the availability of free water within a product that can participate in different chemical, physical and biological processes and affect the quality of a given product (Cauvain & Young, 2008; Tadapaneni, Syamaladevi, Villa-Rojas, & Tang, 2017). Typically, there is no growth of bacterial pathogen at a_w below 0.6; foods at such low a_w are generally considered microbially safe (Enache, Podolak, Kataoka, & Harris, 2017). However there have been multiple outbreaks caused by pathogens, in particular *Salmonella*. This microorganism can survive for long periods of time in low-moisture foods (Syamaladevi, Tadapaneni, et al., 2016).

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Table 1
Proximate composition of egg white powders samples.

	Egg White Powders
Moisture (% w/w)	6.9 ± 0.3
Ash (%w/w)	5.3 ± 0.1
Fat (%w/w)	0.6 ± 0.0
Protein (% w/w)	84.3 ± 0.7
Carbohydrate (by difference - %w/w)	2.9 ± 0.8

Mean ± SD, n = 3.

Salmonella outbreaks have been associated with numerous low-moisture foods, such as raw almonds, German chocolate, peanut butter, infant foods, spices, wheat flour, and bakery products (CDC, 2004; Keller, VanDoren, Grasso, & Halik, 2013; Nummer, Shrestha, & Smith, 2012; Podolak, Enache, Stone, Black, & Elliott, 2010; Rushdy et al., 1998; J. P.; Smith, Daifas, El-Khoury, Koukoutsis, & El-Khoury, 2004; Werber et al., 2005; Zweifel & Stephan, 2012).

Thermal treatments at around 70 °C are generally used to inactivate *Salmonella* in intermediate and high moisture foods. These treatments achieve high inactivation rates in short times (0.06–0.2 min) (Syamaladevi et al., 2016; Villa-Rojas et al., 2017). However, in low-moisture foods, much higher temperatures are needed due to the enhanced thermal resistance of *Salmonella* in dry environments. Notably, the thermal treatment time required to inactivate *Salmonella* increases exponentially with decreasing a_w (Liu et al., 2018; Xu et al., 2019). These studies suggest that an alternative to reducing thermal treatment times is to increase the a_w of low-moisture food (Xu et al., 2019).

Heat treatments may change protein structures of egg powders and can potentially inactivate protease inhibitors, denature proteins and also coagulate proteins. Changes in protein structures may also alter the appearance and functional properties of egg powders (Quan & Benjakul, 2019). *Salmonella* Enteritidis is the most common transovarian infection in eggs; the egg white powders must receive appropriate thermal treatments to minimize damage while rendering safe products. Since conventional dry-heating for egg white powders requires a prolonged thermal treatment, increasing a_w of egg white powders and increasing treatment temperature would reduce operation time, costs, and achieve higher inactivation rates of *Salmonella* (Whiley & Ross, 2015; Xu et al., 2019). Our previous studies have shown that a 3 h thermal treatment at 80 °C is sufficient to achieving at least 6-log reductions of *S.* Enteritidis PT30 in egg white powders at an a_w range between 0.3 and 0.6, measured at room temperature (Pérez-Reyes, Jie, Zhu, Tang, & Barbosa-Cánovas, 2020). However, there are no studies assessing how the a_w and dry-heating time (where no water is added nor removed) at 80 °C affects quality factors of egg white powders, particularly color and bulk properties.

Color is an important indicator of food quality since it is normally the first attribute perceived by the consumer that could lead to acceptance or rejection (Petsong, Benjakul, & Vongkamjan, 2019). Color can change with temperature and moisture content because of chemical or biological reactions during dry-heating. Therefore, it is essential to minimize these changes in order to reduce the chance for rejection (M. Koç, Koç, Güngör, & Ertekin, 2012). Furthermore, researching food powders' bulk properties is very important since the data collected allows for proper design of dry-heating operations. Additionally, informed decisions could be made concerning packaging and storage conditions of the products (Shirkole & Sutar, 2018). The objective of this study was to determine the impacts of a_w, temperature and dry-heating time on the color and bulk properties of egg white powders.

2. Materials and methods

2.1. Egg white powders

Spray-dried egg white powders from Hoosier Hill Farm LLC, US was selected for this study. The industrial processing of this product includes a desugarization and pH adjustment step (Lechevalier et al., 2013). The egg white powders proximal composition was determined by Siliker Inc., Northern California Laboratory (Salida, CA) utilizing standard analytical methods (Table 1) (AOAC, 2012).

100 g batches of egg white powders were conditioned to three different values of a_w (0.30 ± 0.02, 0.45 ± 0.02, 0.60 ± 0.02) at about 23 °C for 5–7 days in equilibration chambers (EW-34788-00, Cole Parmer, IL, USA) designed at Michigan State University (Smith & Marks, 2015). The a_w values of these samples were confirmed using a water activity meter (Aqualab 3 TE series, Decagon Devices, Pullman, WA) at room temperature. Afterward, the conditioned egg powder samples were packed and sealed in aluminum foil bags (9 cm high, 13 cm length, 0.11 thickness) from Paire State Group, US. These airtight aluminum foil bags are FDA compliant and considered high barrier packages (Dudbridge, 2016).

For the thermal treatments (dry-heating), the packaged egg white

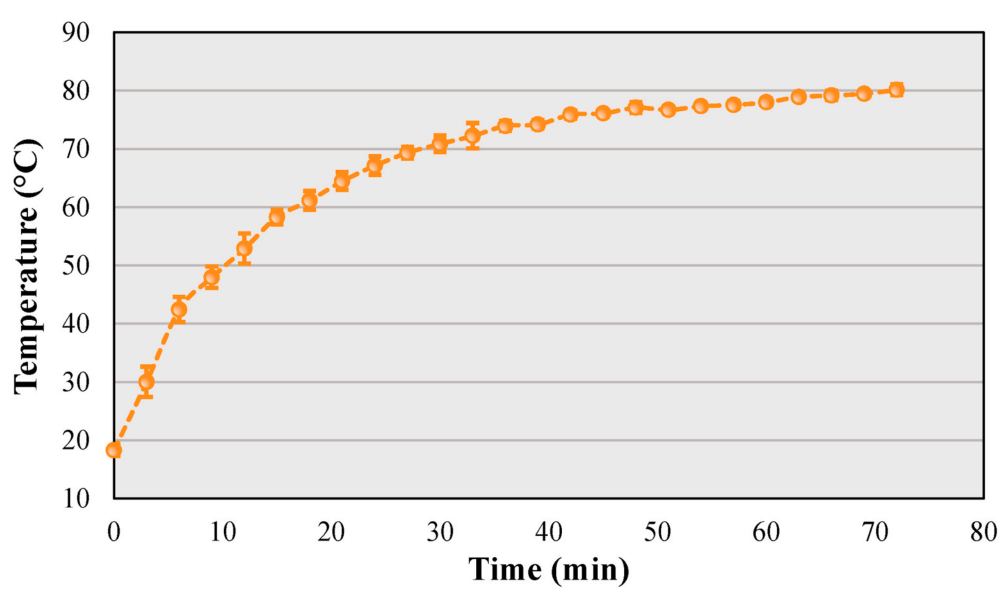

Fig. 1. Temperature at the center of packaged egg white powders when heated to 80 °C. Data points are the average of at least two independent samples (n = 2), mean ± standard deviation (SD).

Table 2
Thermal inactivation of *Salmonella* Enteritidis PT30 in egg white powders at different a_w.

$a_{w20^{\circ}C}$	$a_{w80^{\circ}C}$	$D_{80^{\circ}C}$-value (min)	Time for 6-log reduction (min)
0.30 ± 0.02	0.48	25.8 ± 0.3	156
0.45 ± 0.02	0.56	13.3 ± 0.3	78
0.60 ± 0.02	0.66	6.1 ± 0.1	36.4

These data were reported in Pérez-Reyes et al., 2020, mean ± standard deviation (SD).

powders were placed in a hot-air oven (Fisher Scientific., Isotemp 650G, USA) at 80 °C and held for 2, 4, 8, 12, and 24 h.

These times covered the required treatment to achieve more than 6 log reduction of *Salmonella* in egg white powders, including the come-up time for the egg white powders to reach 80 °C (Fig. 1). Our previous research showed that the $D_{80^{\circ}C}$-value (the time required to achieve a log reduction at 80 °C) of *S.* Enteritidis PT30 in egg white powders preconditioned to an initial a_w of 0.30 ± 0.02 are 25.8 ± 0.3 min (Pérez-Reyes et al., 2020). Therefore, the time necessary to get a 6-log reduction of *S.* Enteritidis PT30 would be 2.6 h (Table 2). Estimated treatment times at 80 °C to achieve a 6-log reduction of *S.* Enteritidis PT30 samples that were preconditioned to 0.45 and 0.6 at room temperature are also included in Table 2. Previous research determined that a_w of egg white powders increases from 0.30 ± 0.02, 0.45 ± 0.02, 0.60 ± 0.02 to 0.48, 0.56, and 0.66, respectively, when heated from room temperature to 80 °C (Table 2) (Pérez-Reyes et al., 2020).

The above treatments were conducted in triplicate. The quality of the treated samples was evaluated after each treatment.

2.2. Color measurement and analysis

For color measurement, the treated egg powders were poured into Petri Dishes to form a layer of ≈12 mm thickness (Caparino et al., 2012). The CIELab color space was selected as the scale to evaluate the color of the samples. CIElab is an international standard accepted by the Commission Internationale d'Eclairage (CIE), and it is the most commonly used in the food industry (de Oliveira, Leme, Barbosa, Rodarte, & Pereira, 2016). This color scale consists of 3 main parameters, L*, which measures the lightness of an object in a range of 0–100; a* is a chromatic component ranging between −120 and + 120, indicating a coloration where the extremes are green and red; and b*, also a chromatic component with a range between −120 and + 120, where the extremes are blue and yellow (Muhammad Zahir, Yahaya, & Omar, 2020). The L*, a*, and b* values were determined using a Minolta Spectrophotometer CM-5 (Minolta Co., Osaka, Japan), previously calibrated, from five readings.

After obtaining the L*, a*, b* values, the Hue angle (H*) was calculated. The Hue angle is an analytical tool that describes the color and in terms of red, yellow, green, and blue values and it is calculated as follows (Dag, Kilercioglu, & Oztop, 2017):

$$H^* = 180 + atan\left(\frac{b^*}{a^*}\right) \quad (1)$$

Chroma or relative saturation, which is a factor that distinguishes between vivid and dull colors, was also calculated as follows (Muhammad Zahir et al., 2020):

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (2)$$

The total color changes (ΔE) between samples heat-treated at different a_w levels and the untreated sample were calculated from:

$$\Delta E = \sqrt{\left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]} \quad (3)$$

$$\Delta L^* = L^* - L_0^* \quad (4)$$

$$\Delta a^* = a^* - a_0^* \quad (5)$$

$$\Delta b^* = b^* - b_0^* \quad (6)$$

where L_0*, a_0*, and b_0* indicate color parameters of the egg white powders sample without a thermal-treatment or a_w modified. A high ΔE represents a significant color change in comparison to the reference material (Koç et al., 2012).

2.3. Bulk density

The bulk density of a food powder is an essential quality factor since it provides information for storage, processing, and packaging of a powder product (Juliano & Barbosa-Cánovas, 2010). Bulk density is subdivided into two main categories: loose and tap bulk density, both were calculated for the egg white powders samples (Ding et al., 2020).

Approximately 9 g of each sample was freely poured into a 25 ml glass graduated cylinder (readable at 1 ml). Loose bulk density [ρ_0 (kg/m^3)] is defined as the mass of particles [m (kg)] that occupies a unit volume [V (m^3)] of a bed, it was calculated as follows (Nguyen, Nguyen, Mounir, & Allaf, 2018):

$$\rho_0 = m/V \quad (7)$$

To obtain the bulk tap density [ρ_t (kg/m^3)], each sample was repeatedly tapped by lifting and dropping the cylinder under its weight at a vertical distance of 14 ± 2 mm high until there was no observed difference in volume between subsequent measurements. The following equation was used to calculate bulk tap density:

$$\rho_t = m/V' \quad (8)$$

where V′ is the volume that remains constant after the sample was tapped several times (Caparino et al., 2012).

For the purpose of assessing the egg white powders flowability, the Hausner ratio (H_R) was evaluated as follows:

$$H_R = \rho_t/\rho_0 \quad (9)$$

where ρ_0 is the loose bulk density, and ρ_t is the tapped bulk density. This ratio measures the grade of fluidization of a powder (Saker, Cares-Pacheco, Marchal, & Falk, 2019). Powders with a Hausner ratio smaller than 1.25 can easily flow, while powders with a Hausner ratio higher than 1.4 have limited flowability (Barbosa-Cánovas, 2005). Measurements were carried out at room temperature in four replicates for all the treated samples.

2.4. Porosity

A powder sample has an initial volume in a container. But after tapping the container, the volume of the powder changes; this movement indicates that particles were rearranged by vibration, filling the voids in bulk (Barbosa-Cánovas, 2005). This phenomenon is caused by bulk voidage or porosity (ε), which is related to tap bulk density as follows:

$$\rho_t = \rho_s(1-\varepsilon) + \rho_a\varepsilon \quad (10)$$

where ρ_s is the particle density, and ρ_a is the air density. Since the density of air is too small compared to that of the egg powder, it can be neglected, and therefore the porosity of a powder sample may be expressed as (Nguyen et al., 2018):

$$\rho_t = \rho_s(1-\varepsilon) \quad (11)$$

or

$$\varepsilon = 1 - \frac{\rho_t}{\rho_s} \quad (12)$$

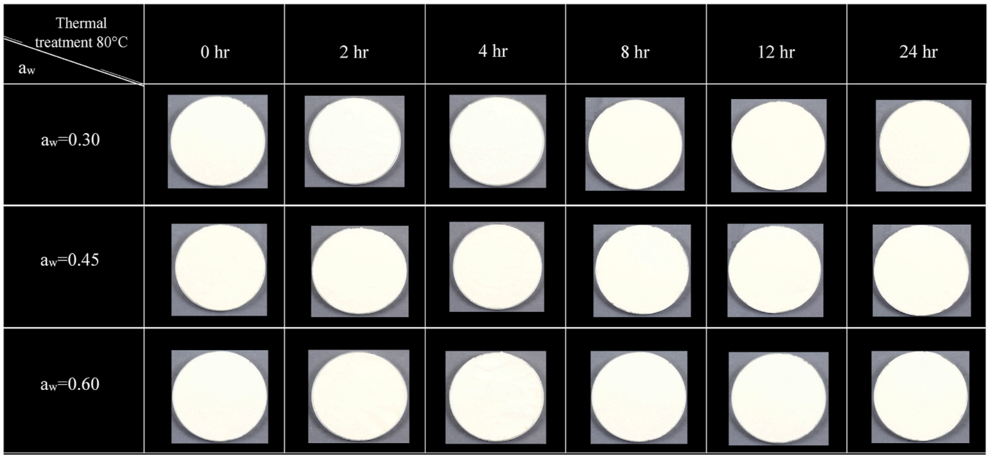

Fig. 2. Representative photographs of egg white powders with different a_w submitted to dry-heating at 80 °C at different times.

To determine the value of the egg powder samples' porosity, the ρ_s of each sample had to be calculated. The pycnometer method was used in this study in which 2.5 ± 0.04 g of each sample was placed in an empty pycnometer (25 ml) and filled with toluene. Toluene was selected because of its ability to penetrate the external pores without dissolving the material (Caparino et al., 2012). The ρ_s (kg/m^3) is determined from the net weight of dry powder divided by the net volume of the powder, calculated from the volume of the pycnometer, subtracting the volume of the added liquid:

$$\rho_s = \frac{(m_s - m_0)\rho_l}{(m_1 - m_0) - (m_{s1} - m_s)} \quad (13)$$

where m_s is the weight of the bottle filled with the powder sample, m_0 is the weight of the empty bottle, ρ_l is the density of the toluene (kg/m^3), m_l is the weight of the bottle filled with the liquid, and m_{s1} is the weight of the bottle filled with both the solid and the liquid (Barbosa-Cánovas, 2005).

2.5. Statistical analysis

The impacts of a_w and thermal treatment (dry-heating) time on color, bulk density and porosity of the egg white powders samples were analyzed for statistical significance ($p < 0.05$) using ANOVA in Minitab 17 (Minitab Inc, State College, PA).

3. Results and discussion

3.1. Color analysis

The color of egg white powders samples preconditioned at different a_w was affected by the different thermal treatments (dry-heating). But color changes were not easily detected by visual examination (Fig. 2). However, when analyzed using the colorimeter, clear trends in the changes ($p < 0.05$) of the L*, a*, and b* values were observed (Fig. 3). Overall, the L* values of the samples at a_w of 0.30 were lower (darker) than that of the samples at a_w of 0.45 and 0.60. There was no significant difference in the L* values (Fig. 3a) between the samples that had a_w values of 0.45 and 0.60 at each heating time. The L* value of the egg white powders samples in general increased (becoming lighter) with increasing dry-heating time. The maximum increase in L* value (~0.8) was observed after the 24 h treatment in the samples at $a_{w80°C}$ of 0.30. But their L* values were still much lower than the L* values of the egg white powders samples at the two higher levels of water activity, even before the heat treatments.

The higher water content of the samples at the two high a_w values may explain the higher L*. A high-water content may cause an increase of the reflected light (Ciurzyńska, Lenart, & Gręda, 2014; Clydesdale, 1991; Romano, Argyropoulos, Nagle, Khan, & Müller, 2012). Similar behavior occurs when dry products are rehydrated. Also, the denaturation rate of proteins and enzyme inhibitors in egg white powders increases with time, generating chemical changes reflected in the L* values (Ays, Kirca, & Cemeroglu, 2003; Quan & Benjakul, 2019).

A significant difference ($p < 0.05$) was also observed in the a* values of the samples (Fig. 3b). When a_w was increased, the a* value also increased at any given heating time. The a* value for all the three samples decreased with treatment time. As an example, the a* values of egg white powders at $a_w = 0.45$ decreased from −1.7 to −1.8. In general, there was a ~0.1 reduction of a* values over the dry-heating time at each a_w value.

The b* values ranged from 17.2 to 18.5 (Fig. 3c). There was a significant increase in the b* value when the a_w of samples decreased from a_w value of 0.60 to 0.30. Lower water content diminishes the lightness, increasing the samples' yellowness, which explains the trend in b* values. Also, b* values were affected by dry heating time. It was observed that longer dry heating time generated yellower samples which corresponding to larger b*. Changes in protein structures favored for temperature and greater exposure time may explain these color changes (Clydesdale, 1991; Katekhong & Charoenrein, 2018).

The egg powder samples had Hue angles values between 95.4 and 96.0 (Fig. 4a). The Hue angle values of the samples at a_w of 0.30 were higher than that of the samples at a_w of 0.45 and 0.60. It was observed that the Hue angle increased with increasing dry heating time. The maximum increase in the Hue angle (~0.2) was observed after the 24 h treatment time in the samples at a_w of 0.45. Hue angle values range from 0 (red) to 90 (yellow) and 180 (green) to 270 (blue). Egg white powders samples had Hue angle values close to 90, indicating that the samples were mainly in the yellow spectrum (Renard et al., 2011). The chroma value indicates the saturation level of color; the egg white powders samples had a low saturation level between 17.3 to 17.8 (Fig. 4b) and reached the highest levels when the a_w value was 0.30. It is important to mention that the saturation level of the colors of the egg white powders samples increased linearly with dry heating time. However, these values indicate that the yellow coloration in egg powders was soft (Clydesdale, 1991).

The ΔE values of the thermal treated egg white powders samples and control are shown in Table 3. The color measures obtained for the sample without any treatment were L* = 90.15, a* = −1.78, and b* = 17.70 with a_w of 0.32 ± 0.02 at room temperature. The samples corresponding to the lower ΔE values had lower values of a_w and experienced the shortest thermal treatment time. The samples with an a_w of 0.60 and thermal treatment of 24 h significantly deviated from the original color. However, there was no significant difference ($p > 0.05$) in ΔE when the

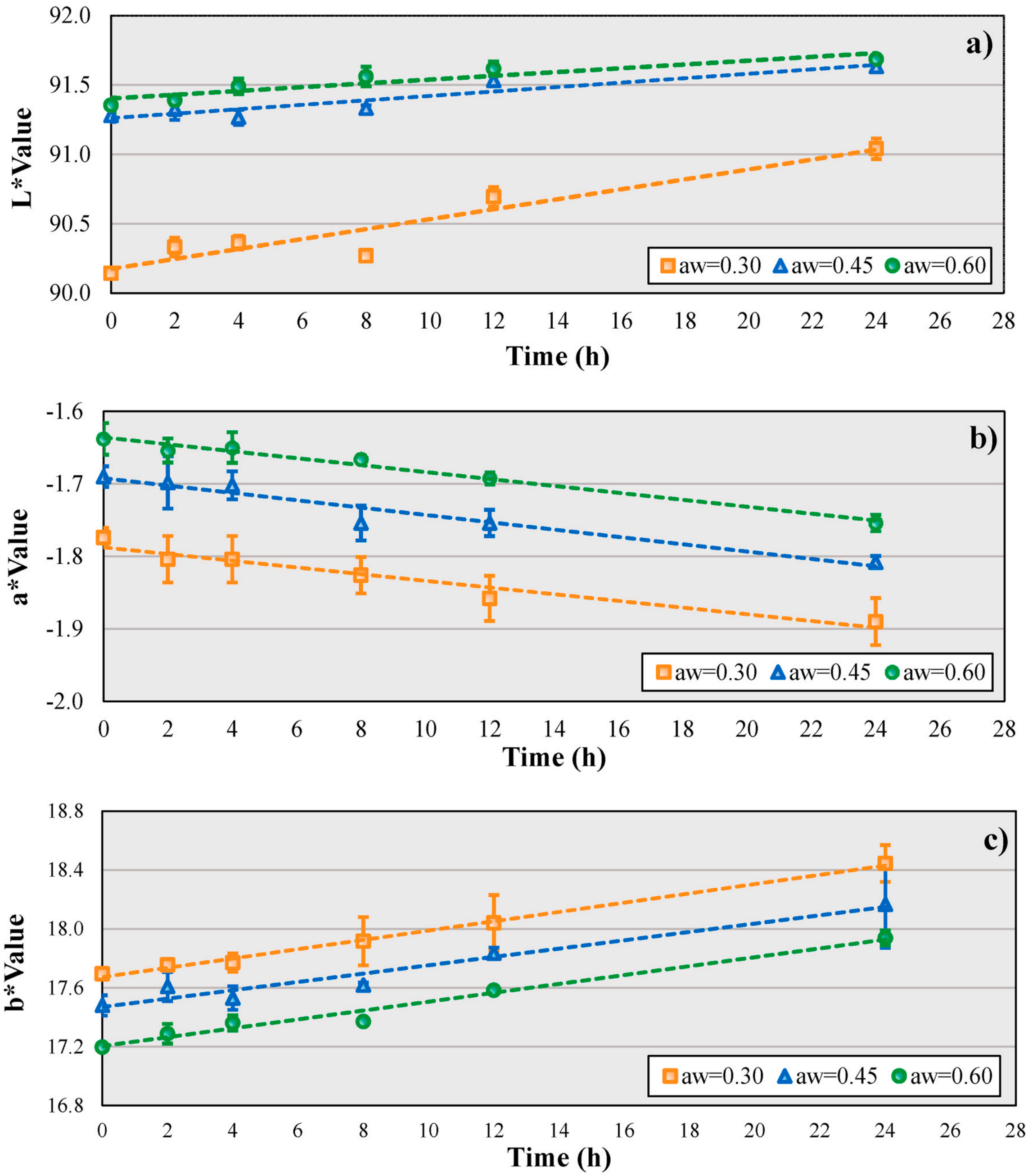

Fig. 3. Lightness (a), a* (b), and b* (c) values of egg white powders at different a_w treated with dry-heating at 80 °C for different times. Data are represented as mean ± standard deviations (SD), n = 3.

samples had an a_w value of 0.30 or 0.45 after 24 and 8 h of thermal treatment, respectively. As mentioned before, recent studies correlated higher a_w with a higher thermal inactivation of pathogens in low moisture food (Xu et al., 2019). Therefore, using this information, it is possible to select an a_w value where color changes will be minimized while also producing a safer product.

3.2. Loose and tap bulk density

The values of loose and tap bulk densities decreased significantly ($p < 0.05$) with increasing the a_w of the powders (Fig. 5). When a_w was increased from 0.30 to 0.60 at 80 °C, the loose bulk density of the egg white powders samples experienced a 16% reduction, from 395.8 to 333.2 kg/m^3 (Fig. 5a), while the tap bulk density of the same samples was reduced by about 14%, from 595.3 to 505.8 kg/m^3 (Fig. 5b). These density reductions with the increased a_w at a given temperature may have resulted from the fact that higher a_w corresponds to a high moisture content of a sample. As a_w increases, solid particles absorb more water, forming liquid bridges. The increased interparticle forces between open shaped molecule structures expanded the volume of the egg white powders (Chang, Kim, Kim, & Jung, 1998; B. Koç, Eren, & Kaymak Ertekin, 2008). In addition, water molecules replace other molecules from the egg white powders, and because the density of the water (1000 kg/m3) is lower than the density of the solid particles of the powder, the sample density decreases (Tabatabaeefar, 2003). Other studies indicate that increased water content could lead to protein oxidation in this powder. The oxidation causes changes in the protein noncovalent bonds that generate aggregates, resulting in larger particle sizes (Wang, Zhao, Niu, Wang, & Chen, 2018). In general, increasing moisture content increased the volume of the egg white powders. This was also reported

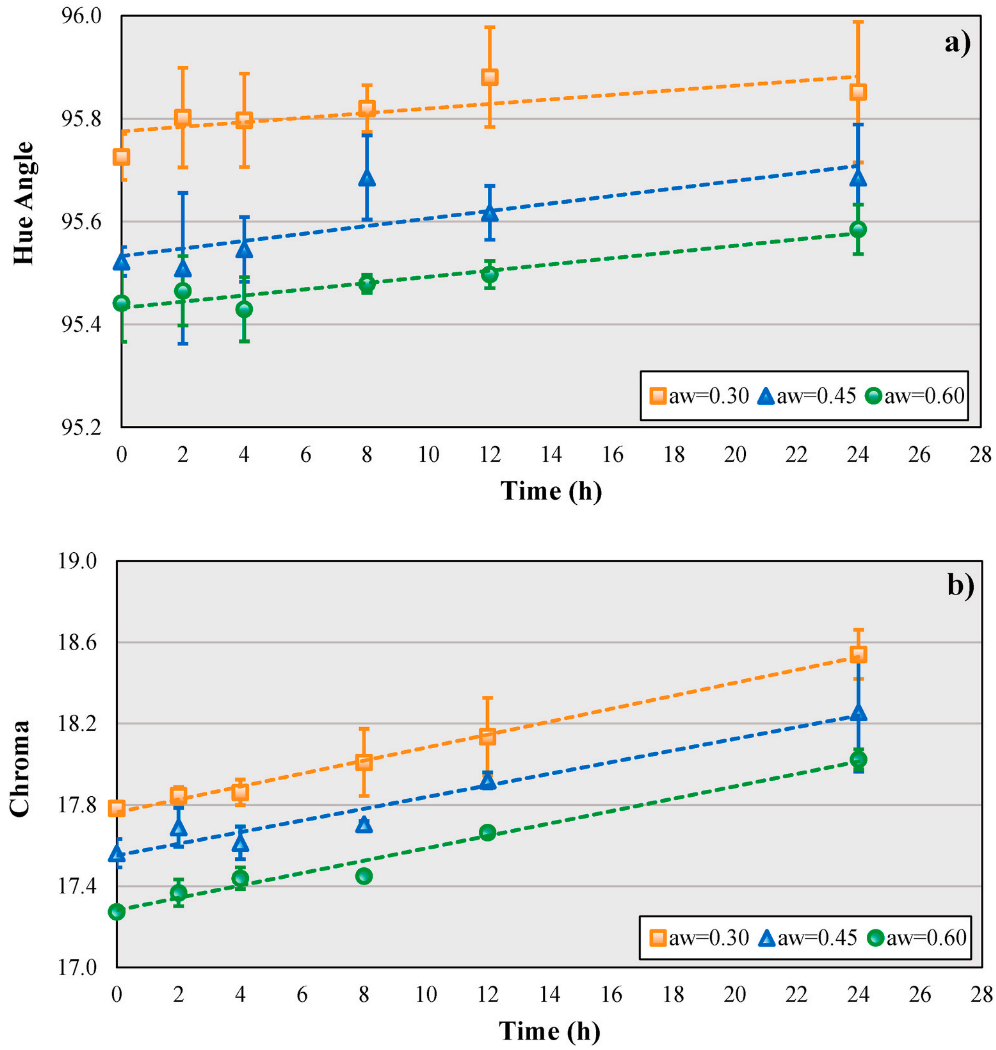

Fig. 4. Hue angle (a) and Chroma (b) values of egg white powders at different a_w treated with dry-heating at 80 °C at different times. Data is represented as mean ± standard deviations (SD), n = 3.

Table 3
Total color change (ΔE) of egg white powders at different a_w after thermal treatments at 80 °C.

$a_{w20°C}$	Thermal treatment at 80 °C					
	0 h	2 h	4 h	8 h	12 h	24 h
0.30 ± 0.02	0.03 ± 0.01^{h}	0.19 ± 0.02^{g}	0.24 ± 0.01^{g}	0.27 ± 0.04^{g}	0.66 ± 0.02^{f}	1.24 ± 0.09^{de}
0.45 ± 0.02	1.15 ± 0.04^{de}	1.18 ± 0.07^{de}	1.13 ± 0.04^{e}	1.19 ± 0.02^{de}	1.39 ± 0.03^{bc}	1.53 ± 0.06^{ab}
0.60 ± 0.02	1.31 ± 0.05^{cd}	1.31 ± 0.03^{cd}	1.38 ± 0.05^{abc}	1.45 ± 0.07^{abc}	1.47 ± 0.05^{abc}	1.55 ± 0.01^{a}

ΔE is calculated using the original egg white powders as a reference. Mean ± standard deviations (SD), n = 3. $^{a–h}$ Means with the different superscript letters within the table indicate significant differences ($p < 0.05$).

in Nishad, Selvan, Mir, and Bosco (2017).

Loose and tap bulk densities of egg white powders samples increased with increasing dry-heating time. The loose bulk density of a_w 0.45 egg powder samples increased from 356.4 to 374.4 kg/m^3 (Fig. 5a), while the tap bulk density increased from 543.2 to 568.1 kg/m^3 (Fig. 5b). These density increases might have been caused by increasing denaturation of egg white proteins while increasing thermal treatment time (Nishad et al., 2017; Pérez-Gago & Krochta, 2001). An increased denaturation rate provides other benefits such as the destruction of protease inhibitors. Therefore, a longer thermal treatment time will improve egg white powders proteins digestion and assimilation (Quan & Benjakul, 2019). The loose and tap bulk density values obtained for egg white powders were similar to other high protein products like milk and yogurt powders (Barbosa-Cánovas, 2005; Koç, Sakin-Yılmazer, Kaymak-Ertekin, & Balkır, 2014).

As expected, the tap bulk density values were higher than the loose bulk density, mainly because loose bulk density depends on the density of powder particles and the spatial arrangement of particles in the powder bed. When the egg white powders were tapped, particles were rearranged because of the vibration, filling the voids in bulk, therefore increasing the density (Juliano & Barbosa-Cánovas, 2010).

The results for the Hausner ratio are shown in Table 4 and its values were ≈1.5, indicating that egg white powders samples do not flow easily (Nishad et al., 2017). The Hausner ratio significantly increased ($p < 0.05$) for all the samples with increasing a_w, indicating that the cohesiveness of powder increases with moisture content and that egg white powders are hygroscopic (Juarez-Enriquez et al., 2017; Saker et al., 2019).

3.3. Particle density and porosity

The particle density (ρ_s) of the treated samples ranged from 1140.7 to 1492.8 kg/m^3 (Fig. 5c). These ρ_s values were similar to the values

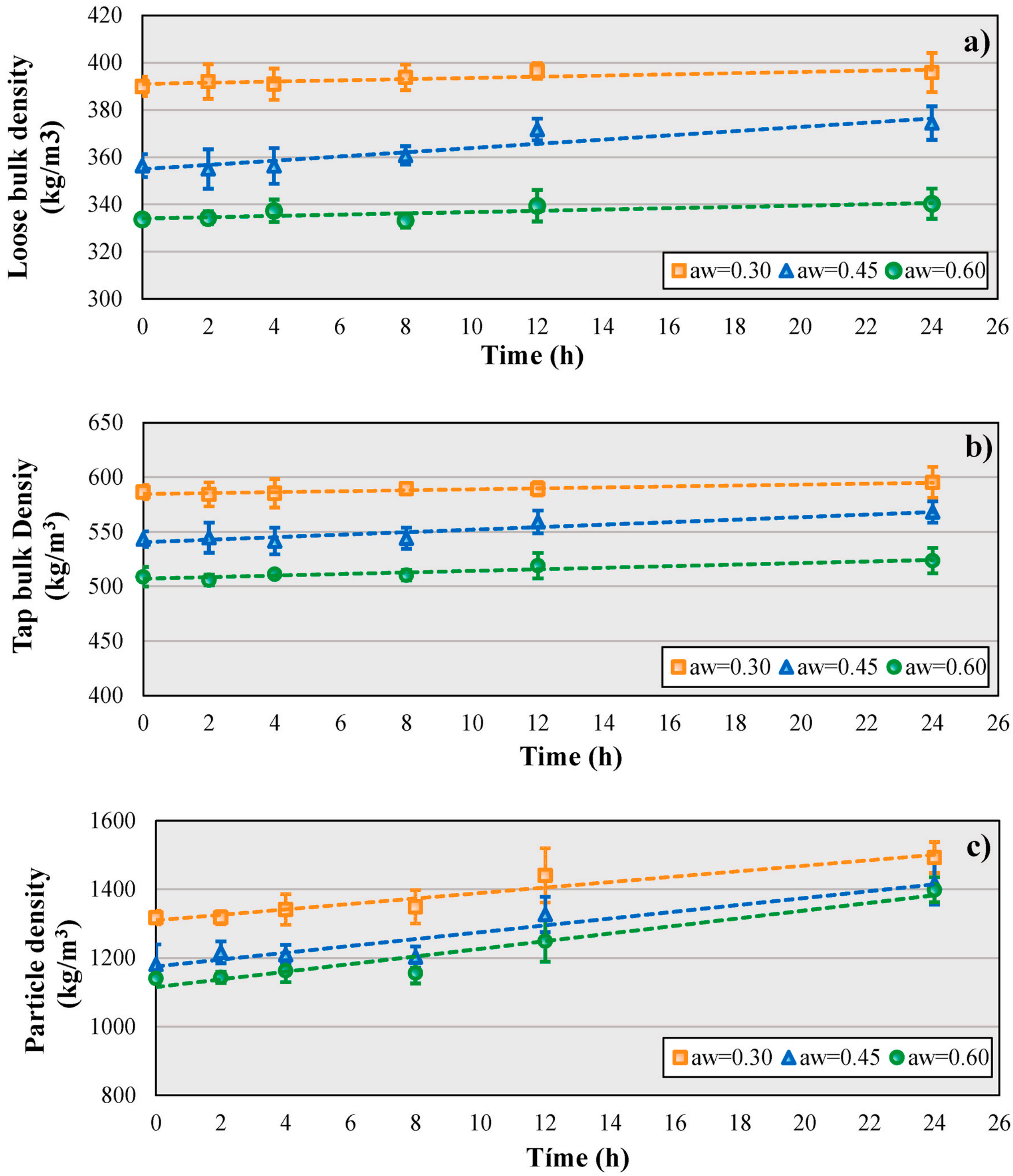

Fig. 5. Loose bulk density (a), tap bulk density (b) and particle density (c) values of egg white powders treated with dry-heating at 80 °C at different times. Data are represented as mean ± standard deviations (SD), n = 3.

Table 4
Hausner ratio of egg white powders at different a_w treated at 80 °C for different times.

$a_{w20°C}$	Thermal treatment at 80 °C					
	0 h	2 h	4 h	8 h	12 h	24 h
0.30 ± 0.02	1.50 ± 0.01^{abc}	1.49 ± 0.02^{bc}	1.49 ± 0.02^{abc}	1.49 ± 0.02^{abc}	1.48 ± 0.02^{c}	1.50 ± 0.01^{abc}
0.45 ± 0.02	1.51 ± 0.01^{abc}	1.52 ± 0.02^{abc}	1.52 ± 0.02^{abc}	1.51 ± 0.02^{abc}	1.50 ± 0.01^{abc}	1.52 ± 0.01^{abc}
0.60 ± 0.02	1.52 ± 0.02^{abc}	1.51 ± 0.02^{abc}	1.52 ± 0.02^{abc}	1.53 ± 0.01^{ab}	1.53 ± 0.01^{ab}	1.54 ± 0.01^{a}

Mean ± standard deviation (SD), n = 3. $^{a–c}$ Means with the different superscript letters within the table indicate significant differences ($p < 0.05$).

obtained for high protein content foods, i.e., yogurt powders (B. Koç et al., 2014). Our results indicate that particle density decreases with increasing a_w. As mentioned earlier, this trend is correlated with high moisture content. The water molecules have a high affinity with the egg white powders molecules, generating a significant volume increase. However, since the density of water is lower compared to the density of solid particles, the increase in mass is smaller (Nishad et al., 2017). Results also show a trend where with longer thermal treatment time at 80 °C, the particle density increases at each a_w. These increases in the particle density are correlated with the denaturation rate of egg white powders protein. Denaturation causes the peptide chains to go through stretching and uncoiling, consequently resulting in denser egg white powders particles (Quan & Benjakul, 2019). The maximum density of dry protein solids is around 1500 kg/m3; our observations indicate that

Table 5
Porosity of egg white powders at different a_w treated at 80 °C for different times.

$a_{w20°C}$	Thermal treatment at 80 °C					
	0 h	2 h	4 h	8 h	12 h	24 h
0.30 ± 0.02	0.55 ± 0.00^{def}	0.56 ± 0.01^{cdef}	0.56 ± 0.01^{bcdef}	0.56 ± 0.02^{bcdef}	0.59 ± 0.02^{abcd}	0.60 ± 0.00^{ab}
0.45 ± 0.02	0.54 ± 0.02^{f}	0.54 ± 0.02^{def}	0.55 ± 0.02^{def}	0.55 ± 0.02^{ef}	0.58 ± 0.02^{bcdef}	0.60 ± 0.02^{abc}
0.60 ± 0.02	0.55 ± 0.01^{def}	0.55 ± 0.01^{cdef}	0.56 ± 0.02^{bcdef}	0.56 ± 0.01^{cd}	0.58 ± 0.02^{abcde}	0.63 ± 0.01^{a}

Mean ± standard deviation (SD), n = 3. $^{a–f}$ Means with the different superscript letters within the table indicate significant differences ($p < 0.05$).

as thermal treatment time increases, egg white powders density approached a maximum of 1500 kg/m^3. Based on these findings, it can be concluded that as the treatment time increases beyond 24 h, particle density value would eventually reach a constant (Fischer, Polikarpov, & Craievich, 2004).

The porosity values of the egg powder samples are presented in Table 5. There was a significant increase ($p < 0.05$) in porosity when the a_w was 0.60, and the dry heating time was increased to 24 h. A similar trend was found in black pepper and paprika powders (Meghwal & Goswami, 2015; Shirkole & Sutar, 2018). A powder with a low tap bulk density has more intergranular porosity, and the increase in moisture content makes the powder more cohesive, and thus prevent the collapse of the structure of the powder (Nishad et al., 2017; Shirkole & Sutar, 2018). This research data will enable a better selection of a higher a_w value and thermal treatment time to obtain an egg white powders with desirable flowability and porosity.

4. Conclusions

The color and the bulk properties of egg white powders were significantly affected by a_w and thermal treatment (dry-heating) time. Increasing a_w and dry heating time resulted in lighter egg white powders samples, with a soft yellow coloration. Both the loose and tap bulk densities of egg white powders decreased when a_w was increased from 0.30 to 0.60. Porosity was the highest when a_w was increased to 0.60, and the thermal treatment was for 24 h. These results could be used to better identify a_w values and dry heating times for pathogen control with minimal color change and adequate egg white powders bulk properties. However, it is desirable to conduct a systematic pilot-scale testing to validate our findings for industrial implementation.

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Conflict of interest and authorship conformation form

Please check the following as appropriate:

- All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.
- This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
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CRediT authorship contribution statement

Marco E. Pérez-Reyes: Writing - original draft, collected test data, designed the study, interpreted the results. **Juming Tang:** Writing - review & editing, designed the study. **Gustavo V. Barbosa-Cánovas:** interpreted the results, discussed, and corrected the manuscript. **Mei-Jun Zhu:** designed the study, Writing - review & editing.

Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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