

# Effect of Ultrasound Treatment in the Mass Transfer and Physical Properties of Salted Duck Eggs

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## ABSTRACT

The acceleration of the traditional process (TP) of salting duck eggs was studied using an ultrasound technique (60 kHz and 140 W) under three different process conditions—UPC1 (running time of 240 min), UPC2 (running time of 480 min), and UPC3 (running time of 720 min) during 48 hr. The ultrasound processes (UP) were compared with the imitated TP for changes in the water and salt contents, salt diffusion, the hardening ratio of egg yolk (HR) and the color of the egg yolk during pickling. It appeared that the rate of salt content in both the egg white and egg yolk was significantly increased while the rate of water content was significantly decreased when compared to the TP during pickling. The rates of L\*, a\* and b\* color changes under the UP were more extended than those of TP during pickling. The HR was not changed during the first 36 hr for the TP while it was significantly increased for UP. An increased duration of ultrasonication led to an increased effective diffusivity of NaCl through the eggshell during salting, which was much greater than that of the TP. Among the three UP conditions, UPC3 after 48 hr provided an HR approximately equal to the TP after 288 hr and the diffusivity coefficient of NaCl was about 45–46 fold compared to the TP over the same period. In this study, the running time of the UP conditions seemed to be the major factor in accelerating the process of salting duck eggs.

**Keywords:** salted egg, pickling, salt diffusion, water diffusion, ultrasound

## INTRODUCTION

The egg has a long history of being recognized as an important food ingredient and nutrient source for humans, as a large amount of complete, high quality protein (which contains all the essential amino acids required by humans) and a significant amount of several vitamins and minerals can be found in the egg (Watkins, 1995; Gutierrez *et al.*, 1996).

Salted egg—one of the most traditional and popular preserved egg products—generally,

can be made by brining eggs in saturated saline or by coating the egg with a soil paste mixed with salt for about 15–30 d (Chi and Tseng, 1998; Lai *et al.*, 1999). Salted eggs made from duck egg attain more desirable characteristics than do hen eggs (Li and Hsieh, 2004). Furthermore, customers anticipates a greater value in the egg yolk than in the egg white (Kaewmanee *et al.*, 2009a).

Traditionally, the desirable characteristics of salted egg yolk include an orange color, oil exudation and a gritty texture. During pickling, the yolk gradually becomes solidified and hardened.

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The egg white loses its viscosity, becomes watery and changes in proportion to the total volume of the egg (Chi and Tseng, 1998). The egg white proportion is increased whereas the egg yolk proportion is decreased during salting. During salting, the oil exudation from the egg yolk increases (Schultz *et al.*, 1968). Conventionally, egg is coated with a paste-like mixture consisting of red soil, salt and water or immersed into a salt solution for 20–30 d at around 27 °C (Chi and Tseng, 1998).

The hardening ratio of the yolk was defined as the weight percentage of the hard exterior yolk and has been used as an index for the completeness of salting (Wang *et al.*, 2013). During salting, the solidification of the egg yolk is initiated near the vitelline membrane and formation proceeds toward the centre from the exterior. The interior yolk is still in liquid form, but becomes more viscous with the further dehydration of the exterior salted yolk. As the yolk protein becomes more concentrated, interaction between the protein molecules, including lipoproteins, can occur (Chi and Tseng, 1998). Salted egg yolk was reported to be more dehydrated and could form a gritty texture, with grittiness being the major factor affecting consumer acceptance of salted egg product (Chi and Tseng, 1998).

However, a low energy efficiency, a long processing time, quality deterioration and environmental problems are common issues associated with the traditional process (Chi and Tseng, 1998). For these reasons, the food industry is searching for alternative technologies to improve the mass transfer kinetics (Rastogi *et al.*, 2002) such as high intensity ultrasound application (Cárcel *et al.*, 2007). Ultrasound is already an established technique for characterizing the physical properties of many biological and nonbiological materials (McClements, 1995). These effects not only increase the mass transport kinetics but also imply structural changes and consequently changes in the textural properties (Pohlman *et al.*, 1997; Wu *et al.*, 2000; Vercet

*et al.*, 2002; Jayasoorya *et al.*, 2007; Gabaldón-Leyva *et al.*, 2007).

Both high intensity and low intensity ultrasound have been applied in the food industry (McClements, 1995). High intensity ultrasound is used to physically alter the properties of the material through which it propagates. It utilizes relatively high power levels (in excess of 1 W.cm<sup>-2</sup>) and low frequencies (below 0.1 MHz). Ultrasound applications, especially in the dehydration process, could enhance food drying to improve not only mass transfer but also product quality (Bantle and Eikevik, 2011).

In the formation of salted egg during pickling, the pickling method and pickling time are important factors in the composition and characteristics of the egg, especially the egg yolk (Chi and Tseng, 1998). Duck egg has great biochemical and structural complexity. Changes in the NaCl and moisture contents probably modify salted egg characteristics such as color, texture and flavor. The salted egg white was considered appropriate as it contained 4–7% sodium chloride (Kaewmanee *et al.*, 2009a and b). The higher salt level in salted egg might contribute to the thermal aggregation of egg white. Different processes of pickling may affect the removal of water from the egg yolk such as oil exudation, protein denaturation and color, followed by texture or taste.

The immersion method has been found to be fast and convenient for the production of salted egg (Yang and Chen, 2001). An appropriate combination of an ultrasonic technique with an effective pickling rate can increase the effective diffusion during the pickling process compared to the traditional process. In addition, prolonging the duration of ultrasonication may obtain good pressure gradients inside and outside the eggshell, which could provide a high pickling efficiency. The principle aims of this study were to reduce the processing time while at the same time providing a comparable quality of salted duck egg compared with the traditional process. Therefore,

the objectives of this study were to investigate the mass transfer of ultrasound dehydration and the changes in several physical properties of salted duck egg using an ultrasound technique compared with the traditional method.

## MATERIALS AND METHODS

### Raw material and sample preparation

Fresh duck eggs were purchased at the local Amornphan market, Chatuchak, Bangkok, Thailand. Eggs with similar weight (65–75 g) and width (45–55 mm) were selected to minimize differences in the samples. The selected eggs were divided into two portions corresponding with the ultrasound technique and the traditional method. For the ultrasound process, 15 eggs were selected and washed with distilled water and then placed in the brine solution (concentration 25% weight per weight; w/w). Commercial salt (99.9% pure) from Thai Refine Salt Co. Ltd. was used in the study.

### Pickling process in ultrasound machine

The eggs were submerged in the brine solution contained in the ultrasound machine (Ultrasound vegetable and fruit cleaner, UC5105; TISTR; Pathum Thani, Thailand) with a frequency of 60 kHz and power of 140 W. Three sets of experiment were performed involving: (1) ultrasound process conditions 1 = UPC1: run 10 min. $\text{hr}^{-1}$  during a 12 hr day over two consecutive days with a total running time of 240 min; (2) ultrasound process condition 2 = UPC2: run 20 min. $\text{hr}^{-1}$  during a 12 hr day during two consecutive days with a total running time of 480 min; and (3) process condition 3 = UPC3: run 30 min. $\text{hr}^{-1}$  over 12 hr daily for two consecutive days with a total running time of 720 min.

Three eggs were removed for analysis after 12, 24, 36, and 48 hr. Prior to analysis, the eggs were washed with distilled water, dried with tissue paper, placed in the grid container for 1–2 min, and then weighed. The egg white (EW) and egg yolk (EY) were manually separated using

a teaspoon to determine the salt and moisture contents. The salt and moisture contents of each salted egg were measured using two replications and the data were summarized as an average of three salted eggs.

### Traditional method

Thirty eggs were washed with distilled water and submersed in a brine solution in a plastic bag and sealed (concentration of 25%, w/w). The container was placed in a dark place at room temperature for 16 d.

### Determination of salt content in egg white and egg yolk

The salt concentration in the EW and EY of the salted eggs was determined by the Mohr method (Nielsen, 2010). A sample of 2 g of the EW and EY were diluted with 18 g of distilled water. The mixture was put in a can and boiled gently using an automatic, electric rice cooker (Model SR-3NA-S; Panasonic; Bangkok, Thailand) for about 5 min. Then, the mixture was filtered through Whatman No. 4 paper. The clear filtrate was used in the titration process and the salt concentration was determined using Equation 1 (detail of the method was described in Nielsen, 2010):

$$\% \text{ NaCl} = \frac{\text{mL of AgNO}_3}{\text{g (or mL) of sample}} \times \frac{\text{mol AgNO}_3}{\text{L}} \times \frac{58.5}{\text{mol NaCl}} \times \frac{1 \text{ L}}{1000 \text{ mL}} \times 100 \times \text{dilution factor} \quad (1)$$

where mol is the molecular weight.

### Determination of moisture content in egg white and egg yolk

The moisture content of both the EW and EY was determined by the oven method—namely, 5 g of sample was dried at 105 °C for 24 hr in a hot air oven (Association of Official Analytical Chemists, 2000).

### Determination of hardening ratio of egg yolk

The hardening ratio of the salted EY

was defined as the weight percentage of hard exterior yolk according to the method of Chi and Tseng (1998) and Wang *et al.* (2013) with minor modification. The EY was rolled on filter paper to remove the EW and then weighed. After scraping out the soft part of the EY, the weight of the hardened yolk was measured where the EY had been hardened. The interior yolk (soft or liquid) was removed using a teaspoon (only the interior portions that were not hard enough were scraped out) after the EY was cut open with a knife. The hardening ratio corresponding to the pickling time was determined using Equation 2:

Hardening ratio (%) =  $(W_{ex}/W_0) \times 100$  (2)  
where  $W_{ex}$  is the weight of the hardened yolk and  $W_0$  is the weight of the egg yolk, both measured in grams.

#### Determination of color of egg yolk

The EY corresponding to the pickling time was placed into a transparent plastic bag for color determination. The surface color of the EY was measured using a colorimeter (Chroma meter, model CR-300; Konica Minolta; Osaka, Japan). Measurement was based on the CIELAB system with color values of  $L^*$ ,  $a^*$  and  $b^*$  determined. (Wang *et al.*, 2013) The observation angle was perpendicular to the light source in the laboratory. Each treatment was measured in three replications.

#### Determination of effective diffusivity during ultrasonic pickling process

The inner membrane is a very important source of mass transfer resistance to NaCl transport through the eggshell (Chen *et al.*, 1999). However, since it was difficult to peel the shell membrane completely from the eggshell, the diffusion coefficient of NaCl penetrating the shell with the membrane were determined according to the method of Chen *et al.* (1999) and Wang *et al.* (2013). Considering the eggshell with membrane as a thin film during the pickling process is defined as Equation 3:

$$J = \frac{D}{L} A (C_1 - C_2) \quad (3)$$

where  $J$  is the diffusion flux measures the amount of substance that was flow through area during a time interval. In this case  $J$  measures a single component across a thin film with an area  $A$  measured in square meters and a thickness  $L$  measured in meters,  $C_1$  and  $C_2$  are the solute concentrations on either side of the film measured in kilograms per cubic meters and  $C_1 > C_2$  and  $D$  is the effective diffusivity of the solute going through the eggshell with membrane measured in square meters per second.

According to Chen *et al.* (1999), the mass balance for NaCl for the eggshell in each test can be written as Equation 4:

$$V_l \frac{\partial C_{s,i}}{\partial t} \approx -DA_s \left( \frac{C_{s,i} - C_{s,\infty}}{\delta} \right) \quad (4)$$

where  $C_{s,i}$  is the sodium chloride concentration inside the eggshell and  $C_{s,\infty}$  is sodium chloride concentration outside eggshell both measured in kilograms per cubic meter,  $A_s$  is the both measured cross sectional area perpendicular to the pathway of sodium chloride diffusion measured in square meters,  $V$  is the volume of the fluid contained in eggshell measured in cubic meters and  $\delta$  is the thickness of eggshell measured in meters.

If  $C_{s,\infty}$  does not change over time, Equation 4 can be integrated from the start of each experiment to any point of time,  $t$ , according to Chen *et al.* (1999) and followed by Wang *et al.* (2013) as Equation 5.

$$\frac{C_{s,i} - C_{s,\infty}}{C_{s,i,0} - C_{s,\infty}} = \exp \left[ - \left( \frac{DA_s}{\delta V_l} \right) t \right] \quad (5)$$

where  $C_{s,i,0}$  is the initial NaCl concentration inside the eggshell.

$D$  can be determined using Equation 6:

$$D = -t^{-1} \left( \frac{\delta V_l}{A_s} \right) \ln \left( \frac{C_{s,i} - C_{s,\infty}}{C_{s,i,0} - C_{s,\infty}} \right) \quad (6)$$

where  $t$  is the pickling time in seconds;  $\delta$  is the thickness of the eggshell with membrane in meters,

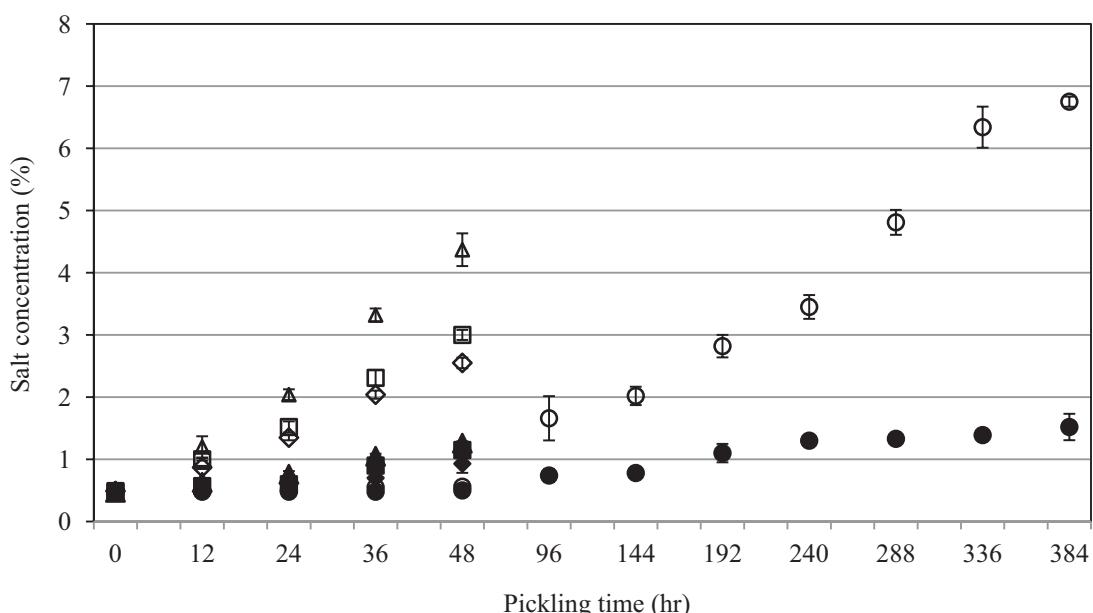
$V_l$  is the volume of the egg in cubic meters,  $A_s$  is the cross section area perpendicular to the pathway of NaCl diffusion in square meters,  $C_{s,i}$  is the NaCl concentration inside the eggshell in kilograms per cubic meter during pickling,  $C_{s,i,o}$  is the initial NaCl concentration inside the eggshell in kilograms per cubic meter and  $C_{s,o}$  is the NaCl concentration outside the eggshell in kilograms per cubic meter.

## RESULTS AND DISCUSSION

### Changes in salt concentration of egg white and egg yolk during pickling

Changes in the salt concentration of duck eggs were obtained during pickling up to 48 hr by ultrasound and up to 384 hr (16 d) by the traditional method (Figure 1). An increase in the salt concentration of both the EW and EY was observed during pickling. The initial salt content was 0.49 and 0.47% in the fresh EW

and EY, respectively. During pickling, there was a large difference in the salt content of the EW and EY corresponding to the different processing conditions. The increase in the salt content of the EW and EY commenced after 12 hr. The salt content of the EW was noticeably different between UPC3 and its counterparts. The salt content of the EW in UPC3 increased rapidly to 1.2% after 12 hr and had increased to 4.37% after 48 hr, which was approximately equal to that at 240–288 hr of pickling using the traditional process. The salt content of the EW from the traditional method increased just a little from 0.49% to 0.56% after 48 hr and then increased slowly to 1.66% after 96 hr and to 6.75% after 384 hr of pickling. The salt content of the EY from the UPC1 and UPC2 methods was not much different while there was a difference between UPC1 and UPC3. The salt content of the EY increased slightly from 0.47 to 0.63% after 12 hr of ultrasound with UPC3, and then increased gradually to 1.26% after 48 hr.



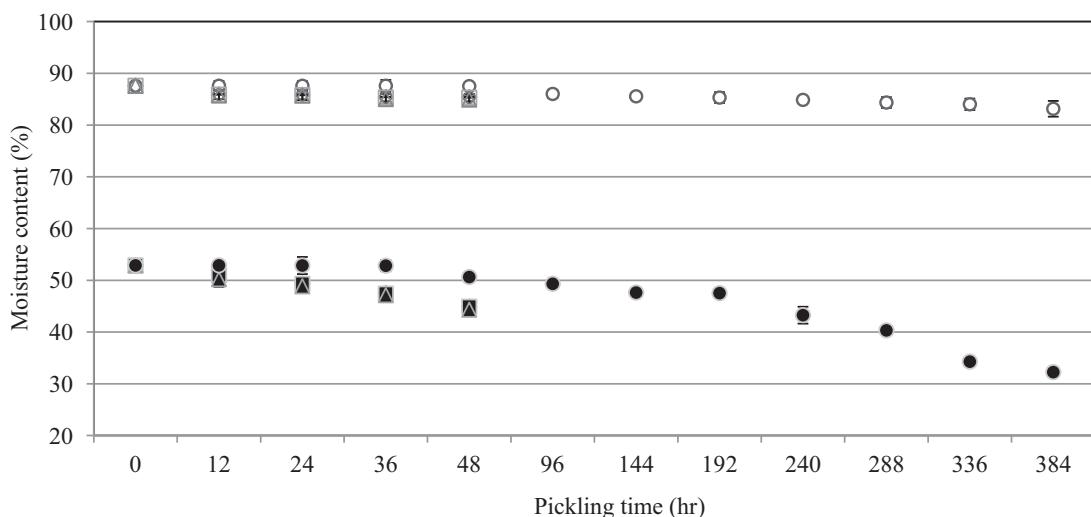
**Figure 1** Changes of salt concentration of egg white (EW) and egg yolk (EY) during pickling ( $\diamond$  = EW under process condition 1;  $\square$  = EW under process condition 2;  $\Delta$  = EW under process condition 3;  $\circ$  = EW under the traditional process;  $\blacklozenge$  = EY under process condition 1;  $\blacksquare$  = EY under process condition 2;  $\blacktriangle$  = EY under process condition 3;  $\bullet$  = EY under traditional process). (Vertical error bars represent  $\pm$  SD.)

Using the traditional method did not change the salt content of the EY much after 12 hr pickling, and it only rose to 0.50% after 48 hr of pickling and then reached 1.52% after pickling for 384 hr. Greater salt diffusion was observed using the ultrasound process compared to the traditional method over the same period. The salt contents of both the EW and EY of UPC3 after 48 hr were nearly equal to those of the traditional method after 288 hr (12 d). The decreased water content of the EW may have been due to the effect of osmosis (explained later) while the increased salt content of both the EW and EY may have been due to the diffusion of salt together with the dehydration of the EY. These results were also confirmed by other researchers (Chi and Tseng, 1998; Wang *et al.*, 2013). Moreover, according to those researchers, there were several reasons influencing the moisture reduction and salt diffusion during pickling such as the difference in the osmotic pressure between the EW and EY, the permeability of the eggshell and the shell membrane to salt, and the different changes in the pore size and structure of the eggshell. The application of ultrasound in this

study could have caused such effects, especially as the longer period under ultrasound was applied.

### Changes in moisture content during pickling

Changes in the moisture content of the EW and EY were observed during pickling up to 48 hr by ultrasound and up to 384 hr by the traditional method (Figure 2). The initial moisture content of the EW and EY of fresh eggs was 87.60 and 52.88%, respectively. There was a decrease in the moisture content in both the EW and EY during pickling. In the EW, the moisture content reduced from 87.60 to 85.72% after 12 hr with UPC3 and then reduced slowly to 84.93% after 48 hr. The moisture content of the EW in the traditional method was not much changed after 12 hr of pickling and then slowly decreased. After 384 hr, the moisture content of the EW was down to 83.15%. The moisture content of the EY reduced rapidly from 52.88 to 50.22% after 12 hr and to 44.32% after 48 hr with UPC3. Similarly, the moisture content in the EY under the traditional method decreased from 52.88 to 50.63% after 48 hr, and rapidly reduced to 32.25% after 384



**Figure 2** Changes in moisture content of egg white (EW) and egg yolk (EY) during pickling (◊ = EW under process condition 1; □ = EW under process condition 2; Δ = EW under process condition 3; ○ = EW under the traditional process; ♦ = EY under process condition 1; ■ = EY under process condition 2 ▲ = EY under process condition 3; ● = EY under traditional process). (Vertical error bars represent  $\pm$  SD.)

hr pickling. The moisture content reductions within 48 hr pickling of the EW and EY under the ultrasound processes were higher than that under the traditional method over the same period, especially for the EY.

In the salting process, water first migrated from the EW through the eggshell and eggshell membrane to the environment. As the pickling time progressed, the water inside the EY continually migrated from the EY to the EW and then to the environment through the eggshell and membrane. The reduction in the moisture content of the EW and EY may have been due to the loss of water from the EW and EY caused by the osmotic process. These results were in agreement with Eshtiaghi *et al.* (1994), Fernandes *et al.* (2009) and Wang *et al.* (2013) regarding osmotic pressure. Furthermore, the physical effect of the sound waves of the ultrasound process together with the different salt concentrations inside and outside the egg may have resulted in different pore sizes and structure of the eggshell and eggshell membrane during the pickling process. Wang *et al.* (2013) found that the different pore sizes and structure of the shell were part of the reason why there was a reduction in the moisture content in the EW. In addition, Fernandes *et al.* (2009) concluded that ultrasonic waves can cause a rapid series of alternative compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly (the sponge effect). Ultrasound produces cavitations, which may be helpful to remove strongly attached moisture while the sponge effect caused by the ultrasound application may be responsible for the creation of microscopic channels (Fernandes *et al.*, 2009). Moreover, there was a higher rate of moisture reduction in the EY than in the EW over the longer pickling time which may have been due to the increased salt content and osmotic dehydration in the EY.

### Hardening ratio of egg yolk

The hardening ratio of the EY was defined as the weight percentage of the hard exterior yolk.

Together with grittiness, the hardening ratio of the EY was the major factor affecting consumer acceptance of salted egg product (Chi and Tseng, 1998) and was used as an index for the completeness of pickling (Wang *et al.*, 2013). The hardening ratio of EY increased rapidly during pickling under ultrasonic conditions whereby the increased running time led to an increased hardening ratio (Figure 3). The hardening ratio increased from 0 to 50.72% after 48 hr with UPC3. However, the hardening ratio changed slowly under the traditional process. There was less change in the hardening ratio under the traditional method during the first 36 hr of pickling. The increase in the hardening ratio started after 48 hr and then increased up to 89.58% after 384 hr. The hardening ratio under UPC3 after 48 hr was higher than for the traditional process after 240 hr.

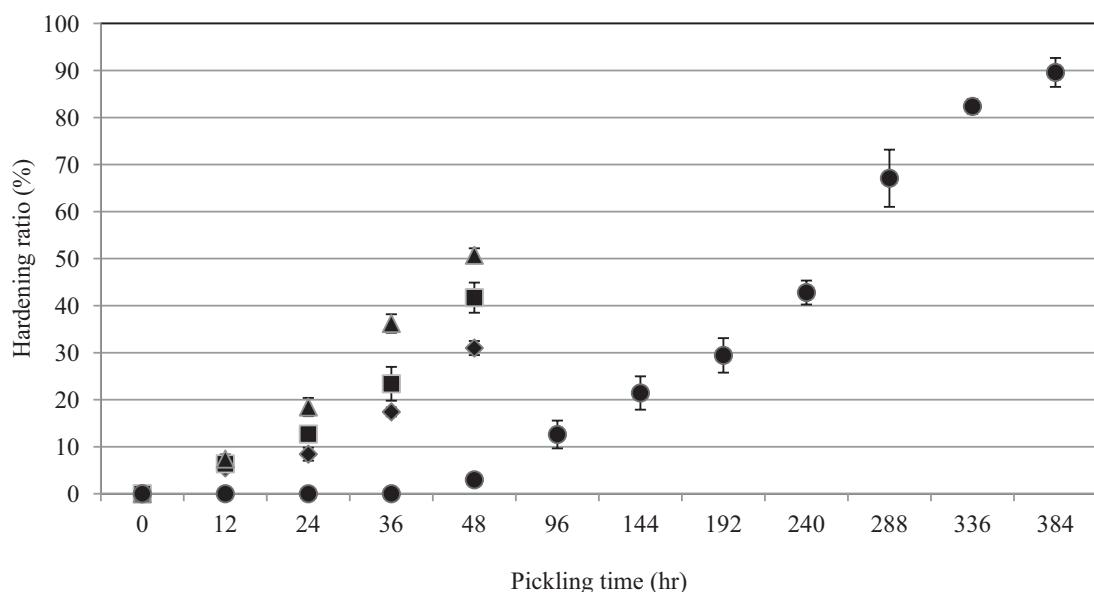
After pickling, there was a much greater salt content in the EW than in the EY, with the salt diffused from the EW to EY occurring without any exchange of air. Owing to the salt permeation to the EW, the hardening ratio of the EY increased. During pickling, the solidification of the EY was initiated near the vitel-line membrane and proceeded toward the center, with formation from the exterior. The gel-network was formed due to protein denaturation (Wang *et al.*, 2013). The hardening ratio increased during the pickling time which was in accord with the increased hardness of the EY. As a greater period of ultrasound was applied, the structure of the salted EY became more solidified corresponding with greater dehydration. Salting induced solidification of the yolk accompanied with oil exudation and the development of a gritty texture (Kiosseoglou, 2003). Under UPC3, the hardening ratio reached 50% after 48 hr. Wang *et al.* (2013) used pulsed pressure for salting egg and then the hardening ratio could reach about 70% after 48 hr. The difference may have been due to the different techniques. Although the hardening ratio in the current study was less than that in the research of Wang *et al.* (2013), the hardening ratio was

much greater than at 240 hr under the traditional method.

### Changes in colour during pickling

Color changes in the EY of the salted eggs were observed (Figure 4) with some fluctuations in the values of  $L^*$ ,  $a^*$  and  $b^*$  during the pickling. Overall, the values of  $L^*$ ,  $a^*$  and  $b^*$  decreased during the pickling process. The color of the EY was influenced by the salting process and the salting time. Different lightness values were observed at different salting times with the lightness under UPC3 being more changed in comparison with its counterparts. The  $a^*$  and  $b^*$  values of the ultrasound processes had decreased after 48 hr especially under UPC3. However, after 48 hr, the  $a^*$  value did not seem to be substantially changed under the traditional process. The  $b^*$  value of the traditional process changed after 24 hr. In general, the color of the EY became darker and more orange during pickling where ultrasound was used. Changes in the color of the EY during salting might have been related to the moisture loss, the increased salt content, the amount of free

lipids, pigments and the denaturation of protein, especially in the outer layer of the EY. The lower moisture content was associated with the higher concentration of the pigments which had migrated during pickling. As a longer period of salting was applied, greater amounts of free lipid may have been localized in the outer layer of the yolk due to the higher oil exudation in the EY. The greater amount of free lipids can solubilize the color pigment (Lai *et al.*, 1999). The pigments in EY are carotenoid and riboflavin (Sugino *et al.*, 1996). Moreover, a little heat was generated as a longer period of ultrasound was applied which accelerated the salt diffusion, enhanced dehydration and caused protein denaturation. The protein denaturation in the presence of solubilized pigments and a lower moisture content may have led to the formation of the pale color at the outer layer of the yolk. This phenomenon may result in a sample with decreased light scattering. Moreover, in the presence of salt, the aggregation might form to a greater extent than under the ultrasound process.

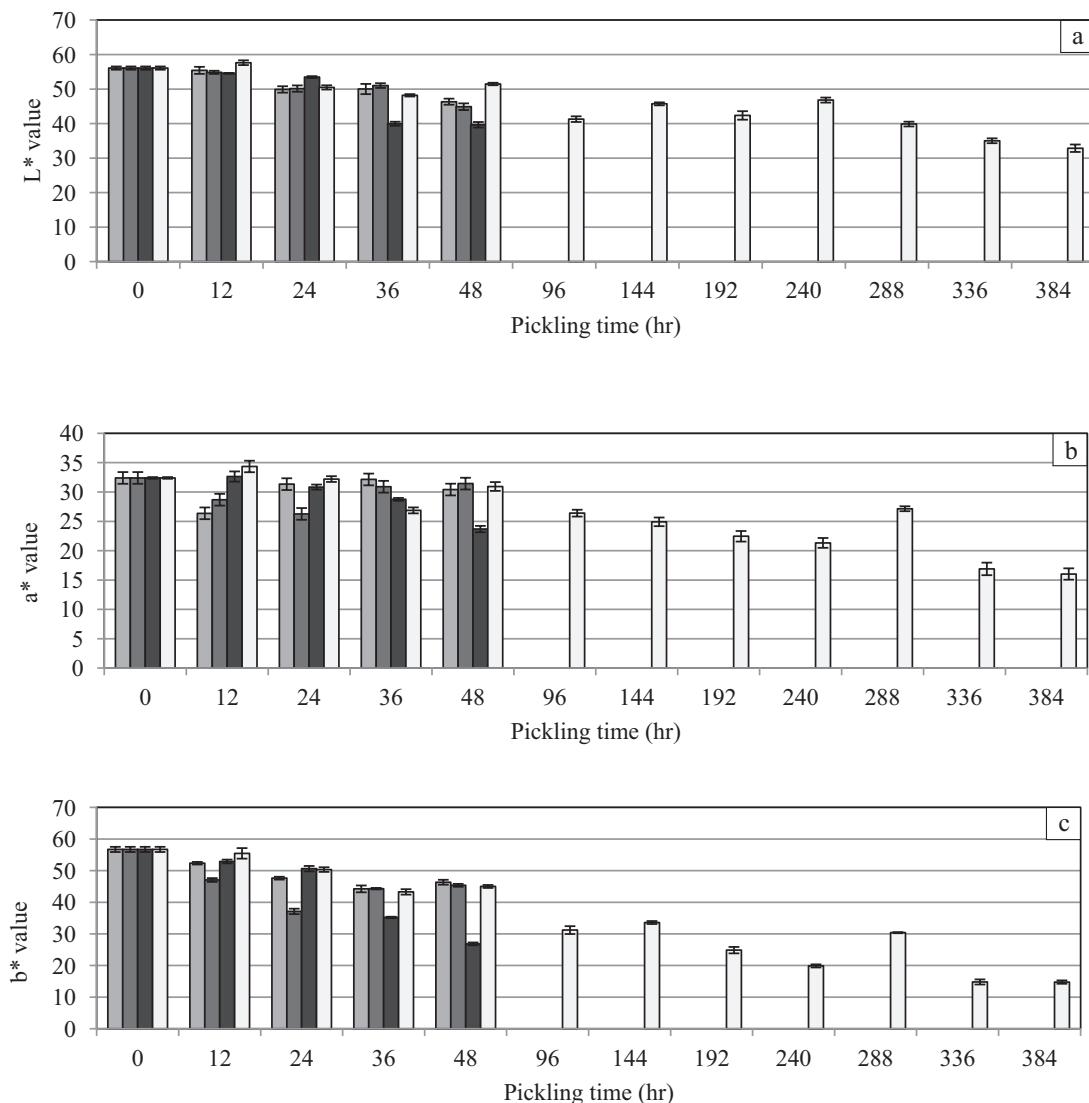


**Figure 3** Changes in hardening ratio of egg yolk (EY) during pickling (◆ = EY under process condition 1; ■ = EY under process condition 2 ▲ = EY under process condition 3; ● = EY under traditional process); (Vertical error bars represent  $\pm$  SD.)

### Effective diffusivity

The diffusion coefficient of NaCl through the eggshell was calculated at different times during the pickling process of salted duck egg. There was a large increase in the effective diffusivity after 12 hr of pickling between the ultrasonic and traditional processes. With UPC3, the effective diffusivity increased rapidly from  $7.03 \times 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$  at 12 hr to  $1.78 \times 10^{-11} \text{ m}^2 \cdot \text{s}^{-1}$  at 36 hr and then increased slightly to  $1.80 \times$

$10^{-11} \text{ m}^2 \cdot \text{s}^{-1}$  at 48 hr (Figure 5). With the traditional process, the effective diffusivity steadily increased from  $1.82 \times 10^{-13}$  to  $3.78 \times 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$  after 384 hr of pickling. The diffusivity increased slowly and only obtained a noticeable value after 96 hr. The diffusivity did not seem to be much changed over the period from 96 to 288 hr; however, it increased again after 288 hr of pickling. The diffusivity coefficient of UPC3 was approximately 46 times greater than for salted eggs under the traditional



**Figure 4** Change in L\* (a), a\* (b) and b\* (c) values of egg yolk (EY) during pickling. (■ = EY under process condition 1; ▒ = EY under process condition 2; ▒ = EY under process condition 3; □ = EY under traditional process). (Vertical error bars represent  $\pm$  SD.)

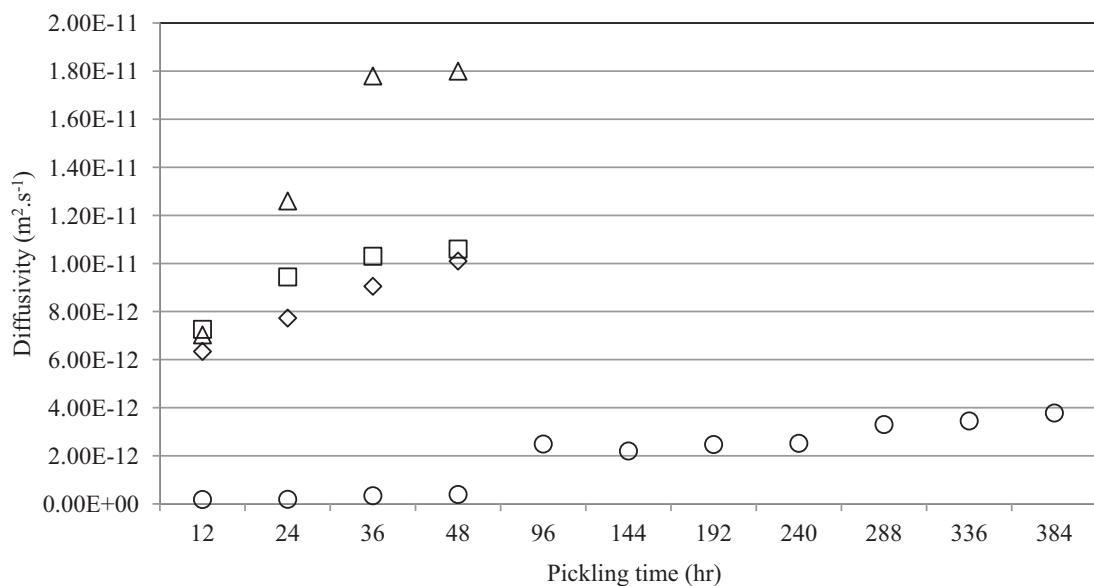
process over the same period after 48 hr. This result showed that the process of mass transfer of salt on the salted egg under ultrasound was more efficient than that under the traditional process.

An increased ultrasound time led to an increase in the effective diffusivity coefficient during pickling. The effective diffusivity values seemed to show the same trend among the different ultrasound processes, with a rapid increase from 12 to 36 hr and a slight increase from 36 to 48 hr. The diffusion under UPC1 and UPC2 did not seem to be substantially enhanced after 36 hr while under UPC3 it was noticeably different. Among the ultrasound conditions, the significant mass transfer of UPC3 was enhanced after 24 hr in comparison with its counterparts. The diffusion of salt into the EW that occurred concurrently during pickling was due to pressure and concentration differences inside and outside the eggshell as mentioned earlier. These differences were greater at the beginning of the salting process due to the lower salt concentration inside the eggshell. However, as the salt concentration increased to a certain level, it led to a reduction in the driving force

inside and outside the eggshell, which explained the later reduced salt diffusion. The different diffusivity coefficients between different process conditions during pickling might have been a result of different increases in the salt content of the EW and solidification of the EY which influenced the driving force of salt diffusion during pickling. Similar explanations were also proposed by Farr (1990), Dorenburg and Knon (1993), Chi and Tseng (1998) and Wang *et al.* (2013).

## CONCLUSION

Ultrasound greatly enhanced the changes in the salt and water contents in salted duck egg during pickling. Among the different ultrasound process conditions tested, increasing the duration of ultrasonication led to a faster increase in the salt content of the EW and the EY. A more rapid increase in the hardening ratio of the EY was also observed during pickling under UPC3 in comparison with its counterparts. However, the ultrasound process conditions caused color fluctuations when compared with the traditional



**Figure 5** Effect of process condition on diffusion in egg white (EW) during pickling ( $\diamond$  = EW under process condition 1;  $\square$  = EW under process condition 2;  $\Delta$  = EW under process condition 3;  $\circ$  = EW under traditional process).

method. UPC3 could increase the diffusivity coefficient of NaCl through the eggshell by about 45–46 fold compared to the traditional process after 48 hr. In general, the EW and the EY under ultrasound were subjected to greater dehydration and higher salt diffusion compared with the traditional process. The longer duration of ultrasonication was the key parameter for salted egg, as this enhanced the mass transfer and accelerated changes in the physical properties of salted duck egg. Based on this study, a longer duration (greater than 720 min) of ultrasonication may shorten the process of producing salted duck eggs and provide promise of comparable quality with the traditional method.

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#### LITERATURE CITED

Association of Official Analytical Chemists AOAC. 2000. **Official Method of Analysis**. 17th ed. Association of Official Analytical Chemists. Arlington, VAirgina, U.S.A.

Bantle, M and T.M. Eikevik. 2011. Parametric study of high-intensity ultrasound in the atmospheric freeze drying of peas. **Drying Technol.** 29(10): 1230–1239.

Cárcel, J.A., J. Benedito, C. Roselló and A. Mulet. 2007. Influence of ultrasound intensity on mass transfer in apple immersed in a sucrose solution. **J. Food Eng.** 78(2): 472–479.

Chen, X.D., Y. Freeman, F. Guo and P. Chen. 1999. Diffusion of sodium chloride through chicken eggshell in relation to an ancient method of egg preservation. **Food Bioproducts Process** 77(C1): 40–46.

Chi, S.P. and K.H. Tseng. 1998. Physicochemical properties of salted pickled yolks from duck and chicken eggs. **J. Food Sci.** 63(1): 27–30.

Dorenburg, H. and D. Knon. 1993. Cellular permeabilisation of cultured plant tissue by high electric field pulse an ultrahigh pressure for recovery of secondary metabolites. **Food Biotech.** 7:35–38.

Eshtiaghi, M.N., R. Stute and D. Knorr. 1994. High pressure and pretreatment effects on drying, rehydration, texture and color of green beans, carrots and potatoes. **J. Food Sci.** 59: 1168–1170.

Farr, D. 1990. High pressure technology in food industry. **Trends in Food Sci. Tech.** 1: 14–16.

Fernandes F.A.N., M.I. Gallão and S. Rodrigues. 2009. Effect of osmosis and ultrasound on pineapple cell tissue structure during dehydration. **J. Food Eng.** 90: 186–190.

Gabaldón-Leyva, C.A., A. Quintero-Ramos, J. Barnard, R.R. Balandrán-Quintana, R.T. Talamás-Abbud and J. Jiménez-Castro. 2007. Effect of ultrasound on the mass transfer and physical changes in brine bell pepper at different temperature. **J Food Eng.** 81(2): 374–379.

Gutierrez, M.A., H. Takahashi and L.R. Juneja. 1996. Nutritive evaluation of hen eggs, pp.25–35. In T. Yamamoto, L.R. Juneja, H. Hatta and M. Kim, (eds.). **Hen Eggs: Their Basic and Applied Science**. CRC Press., Boca Raton, FL, USA.

Jayasooriya, S.D., P.J. Torley, B.R. D'Arcy and B.R. Bhandari. 2007. Effect of high power ultrasound and ageing on the physical properties of bovine Semitendinosus and Longissimus muscles. **Meat Sci.** 75(4): 628–639.

Kaewmanee, T., S. Benjakul and W. Visessanguan. 2009a. Changes in chemical composition, physical properties and microstructure of duck eggs as influenced by salting. **Food Chem.** 112: 560–569.

Kaewmanee, T., S. Benjakul and W. Visessanguan. 2009b. Effect of salting processes on chemical composition, textural properties and microstructure of duck egg. **J. Sci. Food Agric.** 89: 625–633.

Kiosseoglou, V. 2003. Egg yolk protein gels and emulsions. **Current Opinion in Colloid and Interface.** 8: 356–370.

Lai, K.M., S.P. Chi and W.C. Ko. 1999. Changes in yolk states of duck egg during long-term brining. **J. Agric. Food Chem.** 47(2): 733–736.

Li, J. and Y.P. Hsieh. 2004. Traditional Chinese food technology and cuisine. **Asia Pacific J. Clin. Nutr.** 13: 147–155.

McClements, D.J. 1995. Ultrasonic characterization of foods, pp. 93–116. *In* A.G. Gaonkar, (ed.). **Characterization of Food: Emerging Methods.** Elsevier Science B.V. Amsterdam, the Netherlands.

Nielsen, S. 2010. Sodium determination using ion selective electrodes, Mohr titration, and test strips, pp. 75–81. *In* S. Nielsen, (eds.). **Food Analysis Laboratory Manual.** 2nd ed. Springer., New York, NY, USA.

Pohlman, F.W., M.E. Dikeman and D.H. Kropf. 1997. Effects of high intensity ultrasound treatment, storage time and cooking method on shear, sensory, instrumental color and cooking properties of packaged and unpackaged beef pectoralis muscle. **Meat Sci.** 46(1): 89–100.

Rastogi, N.K., K.S.M.S. Raghavarao, K. Niranjan and D. Knorr. 2002. Recent developments in osmotic dehydration: methods to enhance mass transfer. **Trends Food Sci. Technol.** 13(2): 48–59.

Schultz, J.M., H.E. Snyder and R.H. Forsythe. 1968. Co-dried carbohydrates effect on the performance of egg yolk solids. **J. Food Sci.** 33: 507–513.

Sugino, H., T. Nitoda and L.R. Juneja. 1996. General chemical composition of hen eggs, pp. 13–24. *In* T. Yamamoto, L.R. Juneja, H. Hatta and M. Kim, (eds.). **Hen Eggs: Their Basic and Applied science.** CRC Press., Boca Raton, FLorida, USA.

Vercet, A., C. Sánchez, J. Burgos, L. Montañés and P.L. Buesa. 2002. The effects of manothermosonication on tomato pectic enzymes and tomato paste rheological properties. **J. Food Eng.** 53(3): 273–278.

Wang, X., Z. Gao, H. Xiao, Y. Wang and J. Ba. 2013. Enhanced mass transfer of osmotic dehydration and changes in microstructure of pickled salted egg under pulsed pressure. **J. Food Eng.** 117: 141–150.

Watkins, B.A. 1995. The nutrition value of the egg, pp. 177–191. *In* W.J. Stadelman and O.J. Cotterill, (eds.). **Egg Science and Technology.** The Harworth Press. New York, NY, USA.

Yang, S.C. and K.H. Chen. 2001. The oxidation of cholesterol in the yolk of selective traditional Chinese egg products. **Poultry Sci.** 80: 370–375.