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Influence of packaging methods on the dry heat inactivation of *Salmonella* Typhimurium, *Salmonella* Senftenberg, and *Salmonella* Enteritidis PT 30 on almonds

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ABSTRACT

In this study, we evaluated the efficacy of dry heat treatment on 3 types of packaging to inactivate *Salmonella* on almonds. Almonds inoculated with *Salmonella* Typhimurium, *Salmonella* Senftenberg or *Salmonella* Enteritidis PT 30 were treated with dry heat under three types of packaging (open, ambient-sealed or vacuum-sealed), and their color changes were evaluated after the dry heating. The *Salmonella* populations were reduced according to this sequence: open < ambient-sealed < vacuum-sealed heating. Heat treatment of vacuum-sealed almonds for 1 h reduced these three pathogens by 4.59–5.84 log CFU/g and below the detection limit (1.0 log CFU/g) at 90 and 95 °C, respectively. The thermal processing of sealed and open-packaged almonds at 90 °C for 1 h reduced these *Salmonella* serovars by 2.96–3.94 and 0.86 to 2.49 log CFU/g, respectively. Subjecting the three types of packaged almonds to dry heat did not affect the almond color values. The water contents of ambient and open-sealed heat treated samples were reduced significantly ($P < 0.05$). In conclusion, the combination treatment of dry heat and vacuum packaging was significantly effective at inactivating of *Salmonella* on almonds without producing color changes.

1. Introduction

People have enjoyed consuming nuts since prehistoric times (Song, Kim, & Kang, 2019). In recent years, nuts have attracted attention because consumers are increasingly concerned about the health and nutrition values of food (Hong, Yao, Xie, & Li, 2020). Nuts contain phytochemicals including polyphenolic compounds, phytosterols, phenolic acid and carotenoids (Bolling, Chen, McKay, & Blumberg, 2011). In addition, nut consumption reduces cardiovascular disease, type 2 diabetes and numerous other causes of mortality (Luo et al., 2014). Almonds are one of the most recognizable nuts in the world, accounting for 28% of the nut market in 2011 (Jeong, Baik, & Kang, 2017). Unfortunately, there have been several outbreaks due to *Salmonella* contaminated almonds. From 2000 to 2001 in Canada and the United States, there was a large outbreak of salmonellosis due to the consumption of *Salmonella* Enteritidis PT 30-contaminated almonds. As a result of this outbreak, 168 people became infected with *S.* Enteritidis PT 30 (Isaacs et al., 2005). From 2003 to 2004, 29 cases of *S.* Enteritidis PT 30 infections linked to almond consumption were reported (CDC, 2004). There was also an outbreak of *S.* Enteritidis PT 30 infections in Sweden from 2005 to 2006 linked to almonds (Müller et al., 2007). In every instance, *S.* Enteritidis PT 30 was implicated. However, in 2009, there was an outbreak of *Salmonella* (including Montevideo, Newport and Senftenberg)-contaminated pistachios (CDC, 2009). *Salmonella* Typhimurium was also detected in almonds (Danyluk et al., 2007).

In 2007, the USDA mandated that almonds be pasteurized to reduce *Salmonella* by a minimum of a 4-log range (ABC, 2007a). The USFDA approved several processes, including steam processing, blanching, oil roasting, dry roasting and propylene oxide (PPO) fumigation to reduce the microbial contamination levels in almonds (USDA, 2007). Dry roasting almonds is the most popular almond processing method. However, to inactivate *S.* Enteritidis PT 30 by > 4 log, roasting almonds

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for 100 min at 121.1 °C is required according to recommendations from the Almond Board of California (ABC, 2007b). Although this step will satisfy the USDA mandate, conventional heating, such as dry roasting, is an energy and time-intensive intervention (Song & Kang, 2016). PPO fumigation is the only non-thermal treatment among USFDA-approved pasteurization methods for almonds, but PPO is banned in Europe and many other countries because of its possibility of leaving harmful residues in food (Li, Kou, Cheng, Zheng, & Wang, 2017; Sánchez-Maldonado, Lee, & Farber, 2018). Blanching uses hot water for a short time but requires an additional drying step. Because of these disadvantages of the FDA-approved methods, researchers are focusing on non-thermal pasteurization interventions. Hertwig et al. (2017) used cold plasma to reduce the pathogens on almonds. Fifteen min of cold plasma treatment reduced *S.* Enteritidis PT 30 by more than 5 log CFU/g; however, color changes were observed. Goodridge, Willford, and Kalchayaband (2006) reported that treating with a high hydrostatic pressure of 60,000 psi and a temperature of 50 °C for 5 min reduced *S.* Enteritidis PT 30 by less than one log CFU/g.

Dry heat is a type of conventional heating for processing foods in a hot air oven, and it is usually used to sterilize medical equipment (Veerabadran & Parkinson, 2010). In the food science field, dry heat is usually used to inactivate foodborne pathogens in low-water activity food such as nuts and seeds (Bari et al., 2009; Feng, Churey, & Worobo, 2007; Hu, Churey, & Worobo, 2004). However, the primary disadvantage of applying dry heat to foods is its longer treatment time. Bari et al. (2009) used 55 and 60 °C for 4 days, Hu et al. (2004) used 55 °C for 7 days and Feng et al. (2007) used 55 °C for 8 days. To reduce the treatment time, dry heat is usually combined with other control interventions. Hong and Kang (2016) used the combination of dry heat and hydrogen peroxide to reduce foodborne pathogens on alfalfa seeds. Neetoo and Chen (2011) used high hydrostatic pressure and dry heat to inactivate *E. coli* and *Salmonella* on alfalfa seeds. Similarly, the combination treatment of chlorine dioxide and dry heat (Bang et al., 2011) was tested to control pathogens on radish seeds. However, these combination treatments are time intensive intervention which take over 12 h. An improved method to increase the effect of dry heat and reduce the treatment time is needed.

Pasteurization treatment can have detrimental effect on the quality of on almonds. Ban et al. (2018) reported that superheated steam (140 °C for 40 s) decreased the L^* value of almonds. And Li, Kou, Hou, Ling, and Wang (2018) reported that during radio frequency heating water loss of almonds occurred. Additionally, Shirani, Shahidi, and Mortazavi (2020) reported that argon cold plasma treatment increased hardness of almond slices. The control intervention which do not affect the quality of almond is needed.

Therefore, the objectives of this study were to evaluate the influence of the packaging methods on the dry heat inactivation of foodborne pathogens on almonds and to document the quality changes based on the color value and the moisture content following dry heat treatment.

2. Materials and methods

2.1. Bacterial strains and cell suspension

S. Typhimurium DT 104 and *S.* Enteritidis PT 30 were obtained from the bacterial culture collection of Seoul National University (Seoul, Republic of Korea), and *S.* Senftenberg KVCC 0590 was obtained from the Korea Veterinary Culture Collection (KVCC; Anyang, Republic of Korea) for this study. Stock cultures were prepared by mixing 0.7 ml of tryptic soy broth (TSB; Difco, BD, Sparks, MD) at 37 °C for a 24 h culture with 0.3 ml of sterile 50% (v/v) glycerol and storing them at −80 °C. Working cultures were streaked onto tryptic soy agar (TSA; Difco, BD), incubated at 37 °C for 24 h and stored at 4 °C.

2.2. Preparation of inoculum

For each experiment, an inoculum was prepared individually for each strain using the method described by Danyluk, Uesugi, and Harris (2005). Each strain of *S.* Typhimurium, *S.* Senftenberg and *S.* Enteritidis PT 30 was incubated in 30 ml of TSB at 37 °C for 24 h, 100 μl was dispensed into 30 ml of TSB, and the medium was cultured at 37 °C for 18 h. One ml of the overnight culture was spread onto each of 5 TSA plates followed by incubation at 37 °C for 24 h to create a bacterial lawn. The bacterial lawn was harvested by adding 4.5 ml of 0.2% peptone water (PW; Difco) to each plate and rubbing the surface with a sterile cotton swab. For each *Salmonella* serovar, cell suspensions corresponding to approximately 10^9 CFU/ml were collected from the five plates and pooled. These final suspensions of the three *Salmonella* strains were used separately in this study.

2.3. Sample preparation and inoculation

Raw shelled almonds were purchased from a local grocery store (Seoul, Republic of Korea). For the inoculation, 15 ml of prepared inoculum (*S.* Typhimurium, *S.* Senftenberg or *S.* Enteritidis PT 30) was added to 500 g samples inside sterile plastic bags and then mixed by inverting the plastic bag repeatedly by hand for 1 min. The inoculated samples were dried for 24 h inside a biosafety hood (25 °C) until the moisture contents of the samples were equal to those of the non-inoculated samples (ca. 4.27%, dry basis). The final cell concentration was 6–7 log CFU/g.

2.4. Open, ambient-sealed and vacuum-sealed heat treatment

In this study, we used 3 different packaging methods. First, open heating, or the conventional dry heat treatment, was used. For the open heat treatment, 10 g of *Salmonella*-inoculated almonds were placed in a 90 mm Petri dish and the cover was removed during the heat treatment. The second treatment involved heating the almonds that were sealed under ambient atmospheric (non-vacuum) pressure (ambient-sealing heat treatment). Ten g of inoculated almonds was placed in aseptic nylon-polyethylene bags (100 × 100 mm) with a 0.06 mm film thickness (YH Korea, Seoul, Republic of Korea) and sealed under atmospheric pressure using a sealing machine. Lastly, the heating of the vacuum-sealed almonds was performed. Ten g of inoculated almonds was similarly placed in aseptic nylon-polyethylene bags and vacuum-packaged with a sealing machine (Airzero, Ansan, Republic of Korea). The three types of packaged samples were moved to an oven (Thermostable™ ON-32, Wisd laboratory instruments) with a temperature of 90 or 95 °C and treated for up to an hour in 15 min increments.

2.5. Bacterial enumeration

To enumerate the pathogens, each treated sample was immediately transferred to a sterile stomacher bag (Labplas Inc., Sainte-Julie, Quebec, Canada) containing 90 ml of sterile 0.2% PW and homogenized for 2 min in a stomacher (EASY MIX, AES Chemunex, Rennes, France). After homogenization, 1 ml aliquots of homogenized samples were tenfold serially diluted in 9 ml of sterile 0.2% PW, and 0.1 ml of sample or diluent was spread-plated onto Xylose Lysine Desoxycholate agar (XLD; Difco), a selective medium for the enumeration of generic *Salmonella,* including *S.* Typhimurium, *S.* Senftenberg and *S.* Enteritidis PT 30. When low populations of surviving cells were anticipated, 1 ml aliquots of the original homogenate were equally distributed between four plates and spread-plated.

2.6. Color and moisture content measurement

After the treatment, the Hunter's color values (*L*, *a* and *b*) were measured using a Minolta colorimeter (model CR300, Minolta Co., Osaka, Japan). The moisture content of the almonds was measured with a Mettler-Toledo HB43–S moisture analyzer (Mettler-Toledo, Columbus, OH) to confirm the evaporation of the water.

2.7. Statistical analysis

All the data were analyzed by one-way ANOVA using the Statistical Analysis System (SAS Institute, Cary, NC, USA) and Duncan's multiple range test to determine if there were significant differences ($P < 0.05$) in the mean values of the microorganism populations. The microbial counts were transformed to log values prior to the analysis. One log was used for calculations for cases in which the populations were reduced below the detection limit (1.0 log CFU/g).

3. Results

The initial populations of *S.* Typhimurium, *S.* Senftenberg and *S.* Enteritidis PT 30 on the inoculated almonds were 7.04, 6.20 and 7.54 log CFU/g, respectively. Vacuum heat effectively reduced the levels of the three *Salmonella* serovars on almonds.

The *Salmonella* reductions on the almonds are shown in Figs. 1–6. Fig. 1 shows the inactivation effect of 90 °C dry heat on *S.* Typhimurium in 3 types of packaged almonds. Open heat treatment reduced this pathogen by 0.17 (15 min), 0.74 (30 min), 0.95 (45 min) and 1.11 (60 min) log CFU/g, respectively. Ambient sealing heat treatment inactivated this pathogen by 0.67 (15 min) to 3.94 (60 min) log CFU/g. In heat-treated vacuum-sealed almonds, *S.* Typhimurium was reduced by 0.73 (15 min) to 5.84 (60 min) log CFU/g.

Fig. 2 shows the inactivation of *S.* Senftenberg by 90 °C heating of three different types of packaged almonds. The reduction trend for this pathogen was similar to that of *S.* Typhimurium. Open heat treatment reduced *S.* Senftenberg by 1.33–2.49 log CFU/g. Ambient sealing heat treatment for 15, 30, 45 and 60 min inactivated this pathogen by 1.22, 2.55, 3.47 and 3.71 log CFU/g, respectively. In heat-treated vacuum-sealed almonds, this pathogen was reduced by 1.71 (15 min) to > 5.20 (60 min) log CFU/g.

Fig. 3 shows the effect of 3 types of 90 °C dry heating on the inactivation of *S.* Enteritidis PT 30 on almonds. The reduction trend for *S.* Enteritidis PT 30 in peanut butter under dry heat was similar to the trend for *S.* Typhimurium and *S.* Senfternberg. Open heat treatment inactivated this pathogen by 0.40 (15 min) to 0.86 (60 min) log CFU/g. Ambient sealing heat treatment inactivates this pathogen by 0.58 (15 min) to 2.96 (60 min) log CFU/g. In vacuum-sealed almonds that were heat-treated for 15, 30, 45 and 60 min, *S.* Enteritidis PT 30 was reduced by 0.67, 3.13, 3.79 and 4.59 log CFU/g, respectively.

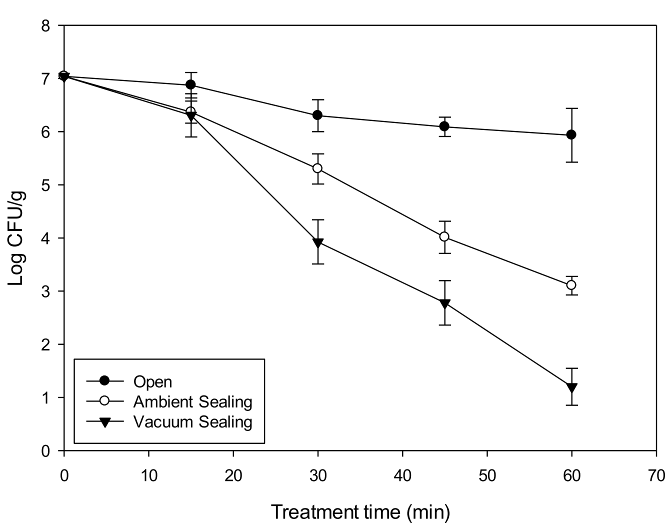

Fig. 1. Survival curves for *Salmonella* Typhimurium on almonds treated with dry heat at 90 °C and packaged with open (●), ambient sealing (○) and vacuum sealing (▾).

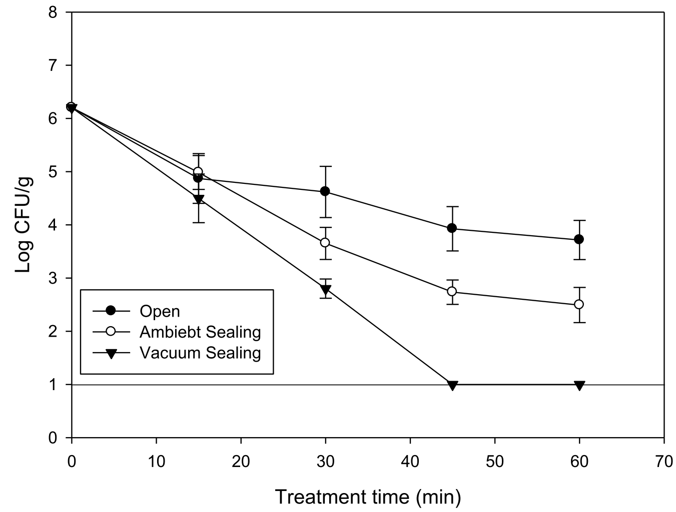

Fig. 2. Survival curves for *Salmonella* Senftenberg on almonds treated with dry heat at 90 °C and packaged with open (●), ambient sealing (○) and vacuum sealing (▾).

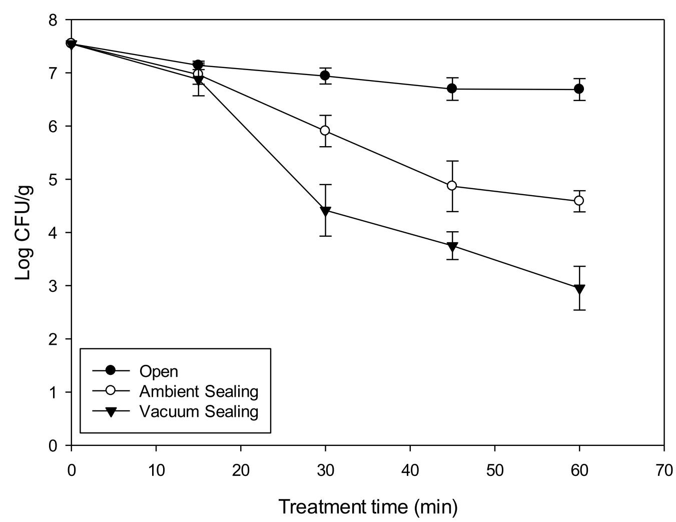

Fig. 3. Survival curves for *Salmonella* Enteritidis PT 30 on almonds treated with dry heat at 90 °C and packaged with open (●), ambient sealing (○) and vacuum sealing (▾).

Fig. 4 shows the inactivation effect of 95 °C dry heat and the 3 types of packaging on the *S.* Typhimurium levels on almonds. Open heat treatment reduced this pathogen by 0.38 (15 min), 0.91 (30 min), 1.05 (45 min) and 1.25 (60 min) log CFU/g, respectively. Ambient sealing heat treatment inactivated the pathogen by 1.15 (15 min) to 4.55 (60 min) log CFU/g. In the vacuum-sealed heat-treated almonds, *S.* Typhimurium was reduced by 1.34 to >6.04 log CFU/g.

Fig. 5 shows the 95 °C dry heat inactivation of *S.* Senftenberg in three types of packaged almonds. The reduction trend for this pathogen was similar to that of *S.* Typhimurium. Open heat treatment reduced *S.* Senftenberg by 1.24 (15 min) to 2.20 (60 min) log CFU/g. Ambient sealing heat treatment for 15, 30, 45 and 60 min inactivated this pathogen by 1.84, 3.10, 4.20 and 4.87 log CFU/g, respectively. In vacuum-sealed heat-treated almonds, this pathogen was reduced by 2.03 to >5.20 log CFU/g.

Fig. 6 shows the effect of 95 °C dry heating and the three packaging types on the inactivation of *S.* Enteritidis PT 30 on almonds. The

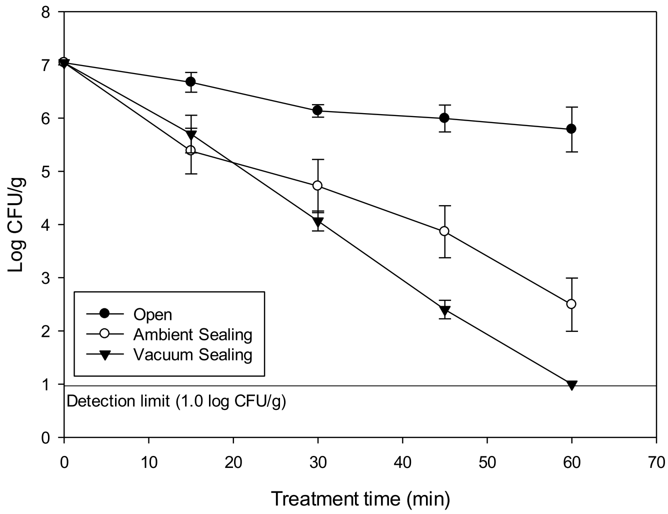

Fig. 4. Survival curves for *Salmonella* Typhimurium on almonds treated with dry heat at 95 °C and packaged with open (●), ambient sealing (○) and vacuum sealing (▼).

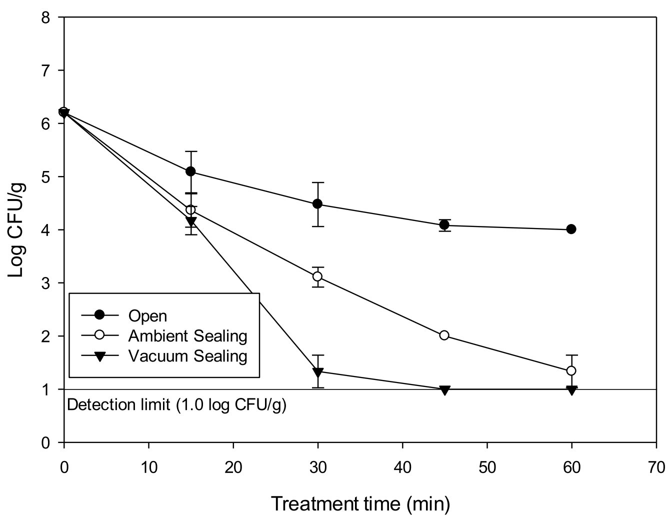

Fig. 5. Survival curves for *Salmonella* Senftenberg on almonds treated with dry heat at 95 °C and packaged with open (●), ambient sealing (○) and vacuum sealing (▼).

reduction trend in *S.* Enteritidis PT 30 on almonds under dry heat was similar to the trend in *S.* Senftenberg and *S.* Typhimurium. Open heat treatment reduced this pathogen by 0.56 (15 min) to 1.34 (60 min) log CFU/g. Sealing heat treatment inactivated this pathogen by 1.31 (15 min) to 4.68 (60 min) log CFU/g. In the vacuum-sealed heat-treated almonds that were treated for 15, 30, 45 and 60 min, *S.* Enteritidis PT 30 was reduced by 1.12, 2.96, 4.65 and > 6.54 log CFU/g, respectively.

Table 1 shows the Hunter's color values and moisture contents of non-treated and dry-heated almonds. The *L, a,* and *b* values of dry heat-treated samples were not significantly different from those of non-treated samples. The moisture content decreased after open and sealed heat treatment but did not significantly change after the vacuum heat treatment.

4. Discussion

A number of studies have addressed the inactivation of foodborne pathogens on nuts by dry heat (Bari et al., 2009; Beuchat & Mann, 2011). However, Bari et al. (2009) used dry heat (60 °C) for several days,

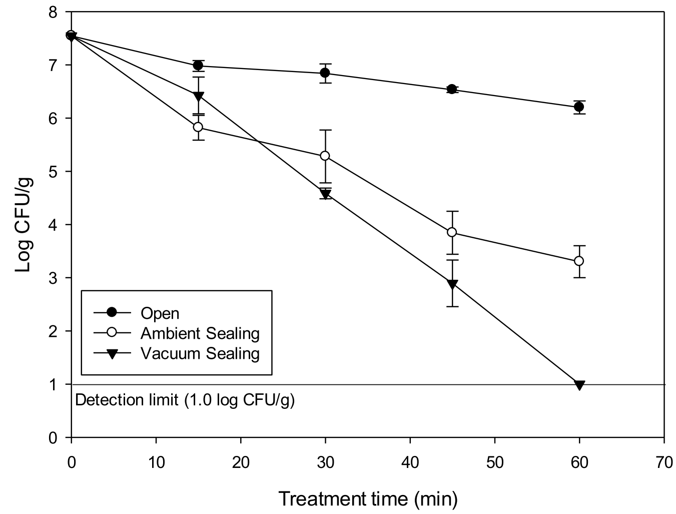

Fig. 6. Survival curves for *Salmonella* Enteritidis PT 30 on almonds treated with dry heat at 95 °C and packaged with open (●), ambient sealing (○) and vacuum sealing (▼).

and at less than 110 °C for 20 min, they were not able to reduce the *Salmonella* in walnuts (Beuchat & Mann, 2011). Conventional heating is the simplest pasteurization method, but it can-not effectively reduce the microorganisms in low-water activity foods. For this reason, many researchers are focusing on other thermal technologies besides dry heat to reduce the pathogens in almonds. Ha and Kang (2015) used near-infrared (NIR) radiant heating to reduce *S.* Enteritidis PT 30 on almonds. Treating with NIR for 5 min reduced this pathogen by approximately 1.0 log CFU/g. Chang, Han, Reyes-De-Corcuera, Powers, and Kang (2010) reported that saturated steam treatment effectively reduced *S.* Enteritidis PT 30, but the treated almonds suffered skin bleaching and detachment. Harris, Uesugi, Abd, and McCarthy (2012) reported that a hot water treatment at 70 °C for 4 min reduced *S.* Enteritidis PT 30 by 3.9 log CFU/g. The sample size was 50 g, and BSA (bismuth sulfite agar) was used as a selective medium for enumerating the *S.* Enteritidis PT 30. Yang et al. (2010) used hot air heating to reduce the presence of *Enterococcus faecium* strain NRRL B-2354 as a surrogate for *S.* Enteritidis PT 30. Hot air heating at 130 °C effectively reduced this microorganism by 7.87 log, but in the process, almonds were roasted to a dark color.

Pathogen resistance to heat is affected by the water contents of foods. Several studies have confirmed that the heat resistance of *Salmonella* is inversely proportional to the water activity. Goepfert, Iskander, and Amundson (1970) reported that the D-values of *Salmonella* Montevideo and *Salmonella* Tennessee in a_w 0.99 sucrose solutions at 57.2 °C were 1.1 and 0.8 min but they increased to 75 and 35.9 min, respectively, when these pathogens were heated to 57.2 °C in a_w 0.87 sucrose solution. This enhanced heat resistance is the primary challenge of low-water activity food pasteurization. Moreover, the moisture content of food usually decreases during dry heating. Limcharoenchat, Marks, and Jeong (2014) reported that during drying heating of almonds at 149 °C for 15 min, the a_w was reduced from 0.54 to 0.22. Dry heating without decreased moisture enhances the inactivation of foodborne pathogens. Jeong, Marks, and Orta-Ramirez (2009) used moist heat to reduce the *Salmonella* Enteritidis PT30 on almonds. Applying 5% moist heat for 3 min reduced this pathogen by 0.61 log, but applying 70% moist heat for 80 s reduced the *S.* Enteritidis PT30 by 2.50 log CFU/g at 121 °C. In this study, we also documented reduced moisture contents following dry heating (from 4.27 to 3.13 at 90 °C and 3.10 at 95 °C). A method to retain the water content of foods during dry heating is needed.

Modified atmosphere packaging (MAP) involves modified internal gas composition. MAP is usually used in meat processing or quality

Table 1
Hunter's color values and moisture content of almonds subjected to three types of packaging plus dry heat for 1 h.

Parameter	Treatment						
	Control	90 °C	90 °C	90 °C	95 °C	95 °C	95 °C
		Open Sealing	Ambient Sealing	Vacuum Sealing	Open Sealing	Ambient Sealing	Vacuum Sealing
L	48.03 ± 2.70	47.60 ± 2.73	48.75 ± 3.43	48.98 ± 3.47	48.38 ± 2.95	47.98 ± 1.45	48.43 ± 3.94
A	16.53 ± 0.87	16.55 ± 0.83	16.80 ± 1.10	17.11 ± 0.31	16.80 ± 0.49	17.59 ± 0.61	17.34 ± 1.08
B	32.17 ± 3.27	29.86 ± 2.95	32.30 ± 1.64	32.27 ± 3.19	32.77 ± 1.99	31.83 ± 1.34	31.08 ± 2.29
Moisture content (%)	4.27 ± 0.04 A	3.13 ± 0.11 C	3.77 ± 0.09 B	4.11 ± 0.08 A	3.10 ± 0.14 C	3.71 ± 0.23 B	4.17 ± 0.01 A

Mean of three replications standard deviation. The *L, a* and *b* values were not significantly different and the moisture contents followed by the same letters within the row are not significantly different ($P > 0.05$).

evaluation studies. Mexis, Badeka, and Kontominas (2009) used MAP for quality evaluation of raw ground almonds; they found that the quality factors of ground almonds were found to be affected by the atmosphere. Vacuum packaging is one of the MAP methods that removes air from the package prior to sealing. Vacuum packaging has the advantage of reducing lipid oxidation by removing oxygen. In this study, the *Salmonella* on the vacuumed-sealed almonds treated with dry heat was reduced more effectively than on almonds that were subjected to open or ambient-sealed heating. This is because vacuum packaging helps to preserve the almond moisture content. The moisture content of almonds treated with vacuum-sealing and dry heat was not significantly different ($P > 0.05$) from that of the control, but those treated with open or ambient-sealing heat were reduced significantly ($P < 0.05$). This evaporation of water affected the heat transfer rate of this food. The thermal conductivity of water (0.58 W/m/°C) is much higher than that of air (0.024 W/m/°C), which leads to faster heat transfer in water (Hong, Park, & Kang, 2019). Based on the results of this study, the moisture content of almonds was maintained with vacuum packaging, which resulted in a continuous rate of heat transfer to the pathogens.

The thermal resistance of pathogens depends on their strain. In this study, *S.* Enteritidis PT 30 showed the greatest resistance to thermal treatment, whereas *S.* Senftenberg showed the least resistance. These results correlate with those of some other studies. Jeong et al. (2017) used radio frequencies to reduce *Salmonella* on almonds. The *S.* Typhimurium and *S.* Senftenberg on almond surfaces were reduced to under the detection limit at 40 s, but *S.* Enteritidis PT 30 was only reduced by 3.7 log CFU/g at 40 s. In addition, the amount of *S.* Senftenberg internalized in almonds was reduced to under the detection limit at 20 s, but *S.* Typhimurium and *S.* Enteritidis PT 30 were only reduced by 2.9 and 2.4 log CFU/g, respectively, at 20 s. Additionally, Harris et al. (2012) reported the D-value of *S.* Enteritidis PT 30 on almonds as 0.39 whereas that of *S.* Senftenberg 775W on almonds was 0.37 following a 88 °C hot water treatment. *S.* Senftenberg 775W is one of the most heat-resistant *Salmonella* isolates (Goepfert et al., 1970).

Conventional heating usually affects the food quality because most foods are heat-sensitive. In this study, we confirmed that dry heating (combined with open-, ambient- or vacuum-sealing) for 1 h did not affect the almond color values. Quality changes in nuts during thermal treatment have been reported several times. Gao, Tang, Billa-Rojas, Wang, and Wang (2011) and Wang, Monzon, Johnson, Mitcham, and Tang (2007) used radio frequency (RF) heating in the development of pasteurization process for controlling Salmonella in almonds and for controlling insects in walnuts. However, the radio frequency treatment increased the peroxide value of the almonds and walnuts. As we noted previously, vacuum packaging has the advantage of preventing lipid oxidation. We did not confirm lipid oxidation during open-, ambient- and vacuum-sealing heat treatments, but several studies have confirmed that vacuum packaging prevents lipid oxidation. Nam and Ahn (2003) reported that the TBARS values of vacuum-packaged raw turkey breast did not change over 10 days of storage at refrigerator temperature. Ahn, Nam, Du, and Jo (2001) reported that the TBARS value of vacuum-packaged cooked beef was not changed during storage, whereas that of aerobic-packaged samples increased significantly ($P < 0.05$).

One of the most important quality factors of almonds is texture. Especially, among many texture values, hardness and crunchiness are the most principal sensory attribute (Civille, Lapsley, Huang, Yada, & Seltsam, 2010). Hardness and crunchiness of almonds are affected by the moisture contents. High moisture contents of almonds resulted in decrease of hardness, crispness and crunchiness (Vicker, Peck, Labuza, & Huang, 2014). Almond Board of California (ABC) announced that 3–6% moisture content of almonds is a common industry standard for raw almonds because it is the optimum conditions for minimizing chemical reactions (ABC, 2014). The result of this study shows that, after dry heat treatment, moisture contents of dry heat-treated almonds are from 3.10 to 4.17% which are suitable for ABC's recommendation. Also, Vicker et al. (2014) reported that there was no significant difference of hardness, crispness and crunchiness of almonds between natural whole low moisture almonds (moisture content: 4.5%) and dry roasted natural whole low moisture almonds (moisture content: 2.3%). Based on this, we can assume that the vacuum heat treatment did not affect the almond texture.

In conclusion, this study evaluated vacuum heat as a novel pasteurization technology for almonds. Vacuum heat treatment effectively reduced *Salmonella* on almonds and did not affect the almond color. The pasteurization effect follows this sequence: open < ambient-sealed < vacuum-sealed heating. Vacuum-sealed heating could be used as an additional control intervention after packaging by the almond industry. However, further investigations must be performed to confirm the effect of different packaging methods combined with dry heat on the physico-chemical quality of almonds.

CRediT authorship contribution statement

Won-Jae Song: Conceptualization, Data curation, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Dong-Hyun Kang:** Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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