Food Control 162 (2024) 110428

Contents lists available at ScienceDirect

Food Control

journal homepage: www.elsevier.com/locate/foodcont

Salmonella control for dried apple cubes

Shuang Zhang [a], Ren Yang [a,b], Xu Zhou [a], Yaohua Feng [c], Juming Tang [a,*]

[a] Department of Biological Systems Engineering, Washington State University, Pullman, WA, 99164, USA
[b] Department of Agricultural and Biosystems Engineering, South Dakota State University, Brookings, SD, 57007, USA
[c] Department of Food Science, Purdue University, West Lafayette, IN, 47907, USA

ARTICLE INFO

Keywords:
Apple
Drying
High humidity air heating
Ascorbic acid
Salmonella

ABSTRACT

Pathogen contamination in low-moisture foods prepared by drying is a food safety concern. Two thermal treatments were explored in this research as pathogen control measures for apple drying operations: high humidity air heating (HHAH) and ascorbic acid (AA) treatments. Their effectivenesses on *Salmonella* inactivation were assessed. Apple cubes (6.4 mm) inoculated with a three-strain *Salmonella* cocktail (*S*. Enteritidis PT 30, *S*. Montevideo, and *S*. Agona 447967) were subjected to HHAH and AA treatments, and then enumerated for the survival of *Salmonella*. In parallel, uninoculated apple cubes treated with HHAH or AA were dried by hot air at 90 °C for 70 min. The moisture content and color values of the dried apple cubes were measured. The results revealed that HHAH treatment at 70 °C for 16 min, at 90 °C for 9 min, and AA treatment using 3.4% ascorbic solutions at 65 °C for 90 s achieved 6.9 ± 0.4, 6.2 ± 0.2, and 7.9 ± 0.6 log CFU/g reduction, respectively. The moisture content of dried apple cubes was not significantly different, highlighting the potential of these methods for enhancing microbial safety of dried apples. The HHAH treatment resulted in an increased browning effect on dried apple cubes, while the AA treatment reduced the browning of dried apple cubes. This study offers valuable insight into preventive controls for pathogen management in food drying operations.

1. Introduction

Salmonella contamination in low-moisture foods (with water activity below 0.6) is a persistent concern in the food processing industry due to enhanced thermal resistance of *Salmonella* in dry environments (Podolak & Black, 2017; Syamaladevi, Tang, Villa-Rojas, et al., 2016). Although low-moisture foods do not support the growth of *Salmonella*, the pathogen can survive in these products for prolonged periods (Finn et al., 2013; Sun et al., 2023; Xie et al., 2022). Recent *Salmonella* implicated recalls and outbreaks have heightened the risks associated with this pathogen in low-moisture foods.

Drying is a common food preservation method that reduces product moisture content to inhibit bacterial growth and provides specific desired food quality attributes (Mujumdar, 2006). Nonetheless, drying is a dynamic process characterized by changing product temperature and moisture content (water activity), which complicates the validation of *Salmonella* inactivation during drying. The rate of drying for a specific product is affected by several variables, including drying temperature and relative humidity, product size and geometry, initial moisture content, product layout in the drying facility, and airflow rate (Li et al., 2021; Mujumdar, 2006; Velić et al., 2004). Any alterations in these factors will result in changes in drying rates. Both commercial drying operations and drying in Home kitchens generally consist of multiple stages, each characterized by unique conditions (Low & Feng, 2024; Mujumdar, 2006). This complexity makes it challenging to accurately replicate drying operations in different food plants or drying environments. Consequently, it is desirable to develop additional preventive measures for the drying industry in order to align with Food Safety Modernization Act (FSMA) regulations. Therefore, two thermal treatment options prior to a drying operation were proposed in this study: (1) high humidity air heating (HHAH), and (2) ascorbic acid (AA) treatments at 65 °C.

Relative humidity (RH) of drying air and water activity (a_w) of food play central roles in the development and validation of thermal processing for pathogen control in low-moisture foods (Casulli et al., 2018; Jin et al., 2020; Xu et al., 2019). Notably, Yang et al. (2022) investigated the impact of controlled RH at 80 °C on the inactivation of *Salmonella* Enteritidis PT 30 in black peppercorns and observed a significant decrease in the *D*-value (time required to achieve 1-log CFU/g reduction) as RH increased from 60% to 80%. Their findings underscore the

* Corresponding author.
E-mail address: jtang@wsu.edu (J. Tang).

https://doi.org/10.1016/j.foodcont.2024.110428
Received 19 December 2023; Received in revised form 26 February 2024; Accepted 4 March 2024
Available online 8 March 2024

potential of high RH thermal processing to effectively achieve a 5-log CFU/g reduction of *Salmonella* in low-moisture foods. In the studies of Yang et al. (2022), the high relative humidities at 80 °C were generated and maintained by an external high-temperature humidity chamber. In this current study, a new approach was used by placing fresh fruit in a closed system with elevated temperature. During heating, the moisture evaporated from the fruits should create a high-humidity environment which would sharply reduce the heat tolerance of *Salmonella* as compared to dry air (Liu et al., 2018). However, there is a need to confirm the effectiveness of such an approach for pathogen control and evaluate the influence on the quality of the dried products.

Ascorbic acid dipping or hot water blanching are commonly used to reduce enzymic browning in industrial drying of fruit and vegetables (El-Shimi, 1993; Krokida et al., 2000). Researchers have also explored their effectiveness on *Salmonella* control as a pre-drying treatment. Dipersio et al. (2003) and Gurtler et al. (2020) reported an additional 2.4-log CFU/g reduction in *Salmonella* when employing ascorbic acid before drying, regardless of the concentration of ascorbic acid solution. DiPersio et al. (2006) also observed an extra 2-log CFU/g reduction with hot water blanching before drying. Dipersio et al. (2007) investigated the potential of blanching in 0.21% citric acid solution (88 °C, 4 min) in inactivating *Salmonella* on carrot slices. Their finding indicated that blanching in citric acid as an integral part of food drying operations could indeed enhance the inactivation of *Salmonella*. However, a notable research gap exists concerning the relationship between temperature and the thermal death time (TDT) of *Salmonella* when subjected to AA treatment. There is a lack of a systematic evaluation of the efficacy of AA treatment on *Salmonella* inactivation and its impact on the quality of the dried products.

Acid dipping and blanching are also frequently used as a pretreatment for home dehydration (Burnham et al., 2001; Low et al., 2022). Of the 979 U.S. home apple dryers suveyed by Low et, al.(2022), about 21% of home apple drying handlers used acidic solutions, and 12% used hot water or syrup to pretreat their apples. The study of Low et al. (2022) also found that most home apple dryers did not use safe food practices; the average number of safe practices was well below the mastery level. Nearly half (47%) of participants who pretreated with acidic solutions did not know the concentration of their solutions. Furthermore, previous studies have indicated that home drying at 60 °C for 6 h may not achieve sufficient bacterial population reduction (Dipersio et al., 2003; Gurtler et al., 2020). Hence, it is imperative to assess the effectiveness of AA treatment on inactivating *Salmonella*, not only as a potential process control measure for food drying manufacturers but also to develop guidelines for home drying practices.

The objectives of this study were to: 1) determine *Salmonella* inactivation of the two different thermal treatments (HHAH and AA treatments), and 2) assess the quality change of the dried apple cubes subjected to the two different thermal treatments. This study utilized Gala apple cubes as the drying material due to their widespread use and previous research indicating that *Salmonella* survival on Gala apples after drying tends to be higher compared to other apple varieties (Gurtler et al., 2020).

2. Materials and methods

2.1. Preparation of apple cubes

Fresh Gala apples were purchased from a local grocery store in Pullman, WA, USA, and stored at 4 °C until use. Before each test, the apples were taken out of the refrigerator. Only undamaged apples were selected, peeled, and cored. To replicate an industry product, the apples were then diced into 6.4 mm cubes using a Dynacube Manual Tabletop Cuber (Dynamic CL003, Dynamic International Ltd., Canada).

2.2. Microbial inactivation tests

2.2.1. Preparation of inoculum and inoculation of apple cubes

A cocktail of three *salmonella* serovars was used for the inoculation of apple cubes in this study. The serovars included *S*. Enteritidis PT 30 (ATCC BAA-1045) (isolated from raw almond; obtained from the University of California, Davis), *S.* Montevideo (488275) (isolated from black and red pepper), and *S.* Agona (447967) (isolated from toasted oats cereal). These bacterial strains were preserved as frozen stock at −80 °C in tryptic soy broth (TSB, Bacto™, Sparks, MD, USA) supplemented with 0.6% (w/v) yeast extract (TSBYE) and 20% (v/v) glycerol.

For each serovar, a loop of frozen culture was twice activated in 9 mL of TSBYE and incubated at 37 °C for 24 h. Subsequently, 1 mL of activated culture was transferred to a 150 mm × 15 mm tryptic soy agar (TSA, Difco™, Sparks, MD, USA) plate supplemented with 0.6% (w/v) yeast extract (TSAYE) and incubated at 37 °C for 24 h. The cells from the agar plates were harvested with 18 mL sterile buffered peptone water (BPW, Difco™, Sparks, MD, USA) and centrifuged at 3000×*g* for 15 min to form a pellet. The pellet was then suspended in 1 mL BPW. To create the three-strain cocktail, equal volumes of *Salmonella* serovars were combined. A total of 3 mL of the combined inoculum was pipetted onto 150 g sample, and the mixture was homogenized by shaking in a sterilized glass jar for 5 min.

The experiment in this study consisted of two main components: 1) assessing *Salmonella* population reduction in HHAH and AA treatments, and 2) evaluating the quality changes of dried apple cubes that have been subjected to the above thermal treatments. The experimental procedures are presented in Fig. 1.

2.2.2. Inactivation treatments

2.2.2.1. High-humidity air heating (HHAH) treatments. The equipment used for the HHAH treatment, as shown in Fig. 2, included a humidity chamber (HCP, Memmert, Schwabach, Germany) and a treatment box that was designed and manufactured by the Engineering Shop of the Washington State University (Pullman, WA). A detailed description of the treatment box can be found in Yang et al. (2022). This equipment was originally developed to investigate the impact of controlled RH on the thermal resistance of *Salmonella* in low-moisture foods (Yang et al., 2022). The treatment box was equipped with two sample holders, each with an internal volume of 25 mL, and four fans (12 V, 0.16 A) to enhance air circulation within the treatment box. Four temperature and RH sensors were placed at the inlet and outlet of the two sample holders to measure the temperature and RH of the incoming and outgoing air. Additionally, a thermocouple was positioned in the middle of each of the two sample holders to monitor the temperature of the apple cubes. Before conducting the experiments, all sensors were calibrated. In this study, the humidity chamber was used only to heat apple cubes, the relative humidity control function of the chamber was turned off. The high-humidity environment surrounding the apple cubes was elevated through moisture evaporation from the heated apple cubes.

Based on preliminary testing, the chamber hot air temperatures for the HHAH treatments of the inoculated apple cubes were determined to be 70 °C and 90 °C. The treatment procedure involved heating the treatment box to a desired temperature, placing two sample holders (each containing 10 g of apple cubes) into the treatment box, and sealing the box immediately. During the HHAH treatment, moisture evaporated from the apple samples. Fans facilitated air circulation and rapidly increased the RH within the treatment box, creating a high-humidity environment. In the treatment development study, *Salmonella* populations on the inoculated samples were counted at various time intervals, namely, 4, 8, 12 and 16 min for the 70 °C treatment, and 2, 4, 6, 8 and 9 min for the 90 °C treatment. Preliminary results indicated that the longest treatment times stated above at each temperature can achieve more than 5-log CFU/g reduction in the *Salmonella* population.

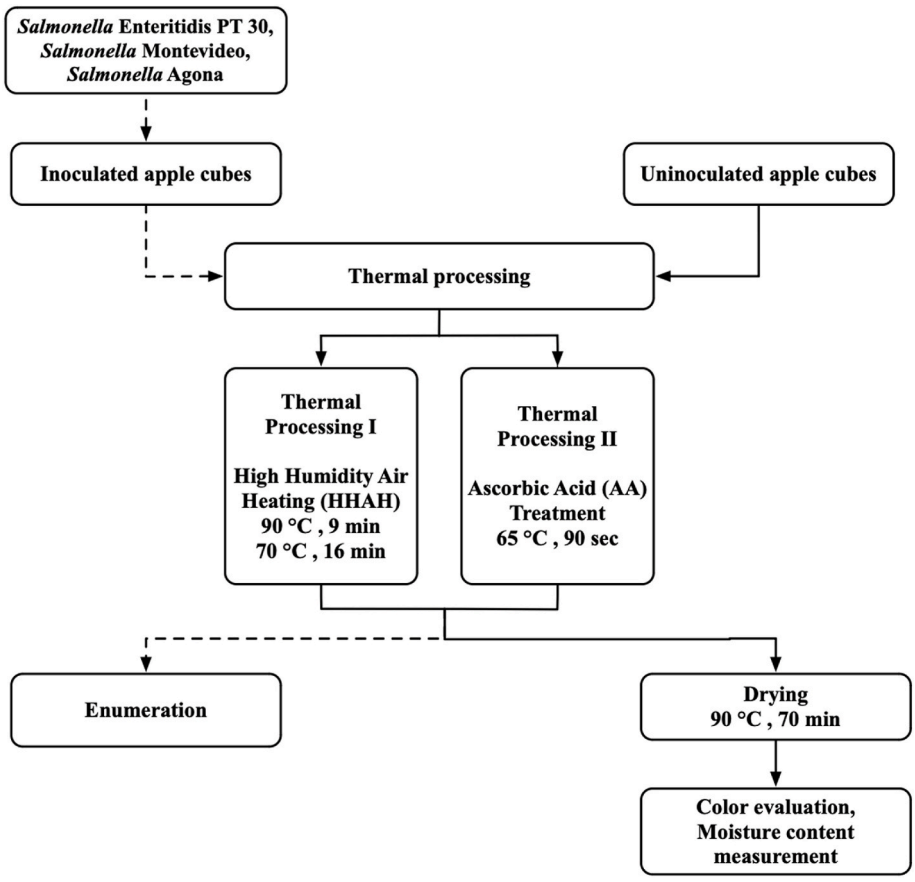

Fig. 1. Procedures and steps of *Salmonella* inactivation validation experiment and apple quality evaluation experiment in this study.

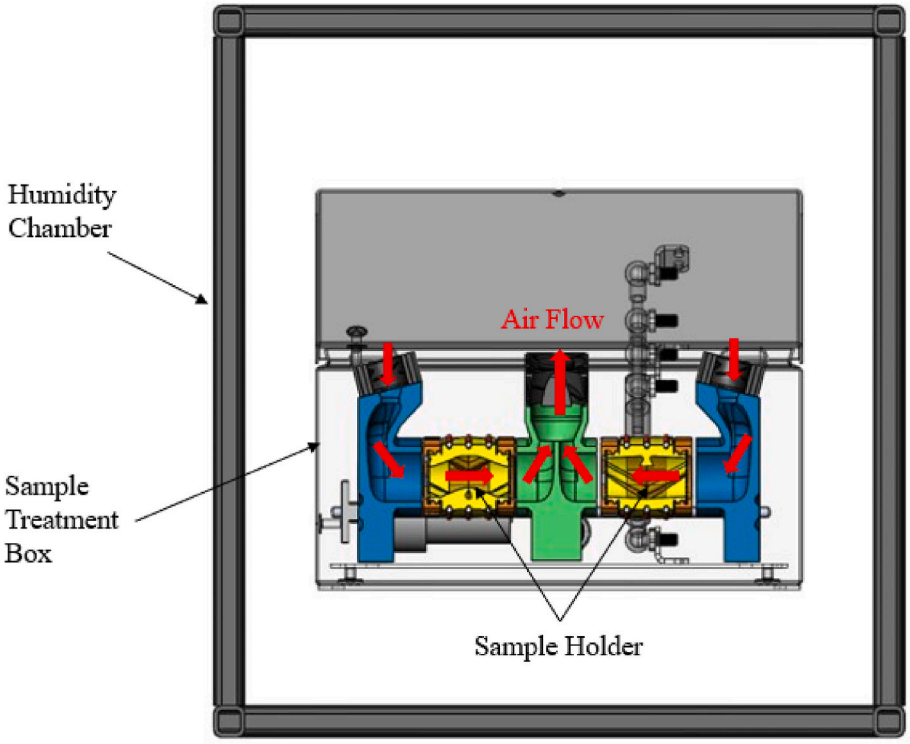

Fig. 2. Schematic diagram of the equipment for high humidity air heating (HHAH) treatment (adapted from Yang et al., 2022).

The above HHAH treatments intensified apple browning, prompting the introduction of pretreatment to mitigate this effect in the quality evaluation study. In a preliminary study, the effect of dipping in different concentrations of ascorbic acid solutions was evaluated, including 0.5%, 2.0% and 3.4%, which are documented in the existing literature (Dipersio et al., 2003; Gurtler et al., 2020). To select the most suitable concentration for AA dipping, the color of the dried apples that had been soaked in various AA solution concentrations (0.5%, 2.0%, 3.4%) at room temperature were compared. The 3.4% AA solution was found to be most effective in minimizing the browning of dried apple cubes. Consequently, the apple cubes were soaked in a 3.4% AA solution for 10 min at room temperature before HHAH treatment.

2.2.2.2. Ascorbic acid (AA) treatments (65 °C). To achieve desired population reduction in *Salmonella* without compromising the quality of apples, the target temperature for the AA treatment was set at 65 °C, which is the equilibrium temperature achieved after immersing apple samples in the solution. Specifically, a cylindrical stainless-steel mesh basket containing 40 g of inoculated apple cubes was submerged into a 1000 mL AA solution preheated to 67 °C in a water bath. The mesh basket provided sufficient space for the apple samples to be uniformly exposed to the AA solution, ensuring uniform sample surface temperature. In preliminary tests, the temperatures of apple cubes and ascorbic acid solution were monitored using fiber optic sensors. Within approximately 30 s, both the temperature of the apple cubes and the ascorbic acid solution reached an equilibrate temperature of 65 °C.

For the treatment development study, the *Salmonella* population reduction was counted at treatment times of 30, 60, and 90 s. Additionally, the pH value and soluble solids content (Brix) of the apple were measured before and after the AA treatment. The pH value was measured using a pH meter, while the soluble solids content was measured using a handheld refractometer (Atago, Bellevue, WA, USA).

Following the inactivation treatments, the apple samples were transferred into BPW for serial dilution. Appropriate dilutions were spread onto TSAYE^{+} plates (TSAYE supplemented with 0.05% (w/v) ferric ammonium citrate (Sigma-Aldrich, St. Louis, MO, USA), and 0.03% (w/v) sodium thiosulfate 5-Hydrate (Mallinckrodt Baker, Phillipsburg, NJ, USA) and inoculated at 37 °C for 24 h to enumerate bacterial counts.

2.3. Food quality evaluation after drying

The microbial inactivation tests showed that 16 min at 70 °C and 9 min at 90 °C as the HHAH treatments, and 90 s at 65 °C as the AA treatments resulted in more than 5-log CFU/g reduction of *Salmonella* in the inoculated apple cubes. For quality evaluation, different batches of apple cubes (without bacterial inoculates) that had undergone the above treatments were subsequently dried using a domestic hot air oven (Nuwave, Vernon Hills, IL). The apple cubes were evenly distributed on a metal rack and positioned in the center of the oven. While industrial drying processes typically involve multiple stages with varying temperatures and durations, this study used a constant drying temperature of 90 °C. The drying time was set to 70 min to achieve the desired moisture content in the dried products, targeting a range between 2% and 5% on a wet basis (w.b.).

After the above drying, the color and moisture content of the apple cubes were assessed. The moisture content of the apple samples was determined using the vacuum oven method (hot air temperature of 70 ± 1 °C for 24 h, AOAC, 1996). The initial moisture content of fresh apples was 86.5% (w.b.). To analyze the color of the fried apples, a computer vision system was employed. This system consisted of a Canon EOS D60 digital camera, a lighting system equipped with two D65 lamps, and a computer equipped with image analysis software. A detailed description of this computer vision system can be found in Zhang et al. (2014). The CIE $L^*a^*b^*$ color parameters, where L^* represents lightness, a^* represents redness, b^* represents yellowness, were utilized to evaluate the impact of the additional thermal treatments on the color of dried apples. To ensure accurate color measurement, the system was initially calibrated with a color reference card (QPcard 203, QPcard AB, Helsingborg, Sweden) using Adobe Photoshop software (Adobe Inc., San Jose, CA) (Zhou et al., 2022). Subsequently, the average L, a, and b values of the apple areas were obtained from the histogram window in Photoshop. The color values obtained from Photoshop were then converted into CIE standard L^*, a^*, and b^* values using the equations in Yam and Papadakis (2004). The total color difference (ΔE) was calculated by the following equation:

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \quad (1)$$

In the above equation, L_0^*, a_0^*, and b_0^* represent the color values of the control group, and L^*, a^*, and b^* represent the color values obtained from the various treatments.

2.4. Statistical analysis

Three replicated tests were carried out for both the microbial validation experiments and quality evaluation tests. Data from these measurements are presented as means with corresponding standard deviations (means ± standard deviations). Statistical analysis was conducted using RStudio (Boston, MA) to perform ANOVA tests for moisture content and color values. The significance level was set at $P = 0.05$.

3. Results and discussion

3.1. HHAH treatment

3.1.1. Temperature and humidity profiles

The temperature and RH profiles at both the inlet and outlet of the sample holder for the treatments conducted at 70 °C and 90 °C are presented in Fig. 3. For the treatment at 70 °C as shown in Fig. 3 (a), the hot air entering the treatment box was initially preheated to 70 °C by the humidity chamber. The air temperature dropped to 63 °C when opening the door and mounting the sample holder into the treatment box. During the initial heating phase, the temperature of the apple sample increased rapidly, and the temperature difference between the inlet and outlet was around 4 °C. By the end of the treatment, the temperature of air at inlet and outlet of sample holder had gradually risen to 69.7 °C. Throughout the 16 min HHAH treatment, the temperature of apple sample gradually increased from 16.9 °C to 62.2 °C. The RH of the treatment air at the outlet of the sample holder rose from 6.5% to 74.0% at the end of the treatment. Over the 9 min treatment at 90 °C as shown in Fig. 3 (b), the temperature of the sample gradually rose from 18.8 to 74.5 °C, and the RH of the treatment air at the outlet of the sample holder from 4.4% to 62.0%.

3.1.2. Microbial reduction during HHAH treatment

Table 1 presents the average *Salmonella* population survival in apple cubes at various time intervals during HHAH treatment at both 70 °C and 90 °C. The initial population of *Salmonella* in apple cubes was 9.5 ± 0.1 log CFU/g. At 70 °C, a 1.0-log CFU/g reduction of *Salmonella* occurred during the first 8 min of the treatment. From time 0–8 min, the RH at the inlet of sample holder increased from 6.5% to 62.7%. Simultaneously, the temperature of apple samples rose from 16.9 to 59.1 °C. During this period, the low RH and temperature led to the small initial *Salmonella* population reduction. Subsequently, as treatment continued, the RH and temperature of the surrounding air increased significantly, resulting in a sharp reduction in *Salmonella* population. The total reduction in *Salmonella* population from 8 to 16 min amounted to a 5.9-log CFU/g. A similar trend also was observed at 90 °C, with only a 0.9-log CFU/g reduction in *Salmonella* during the first 4 min. However, the total population reduction increased to 6.2-log CFU/g at the end of the

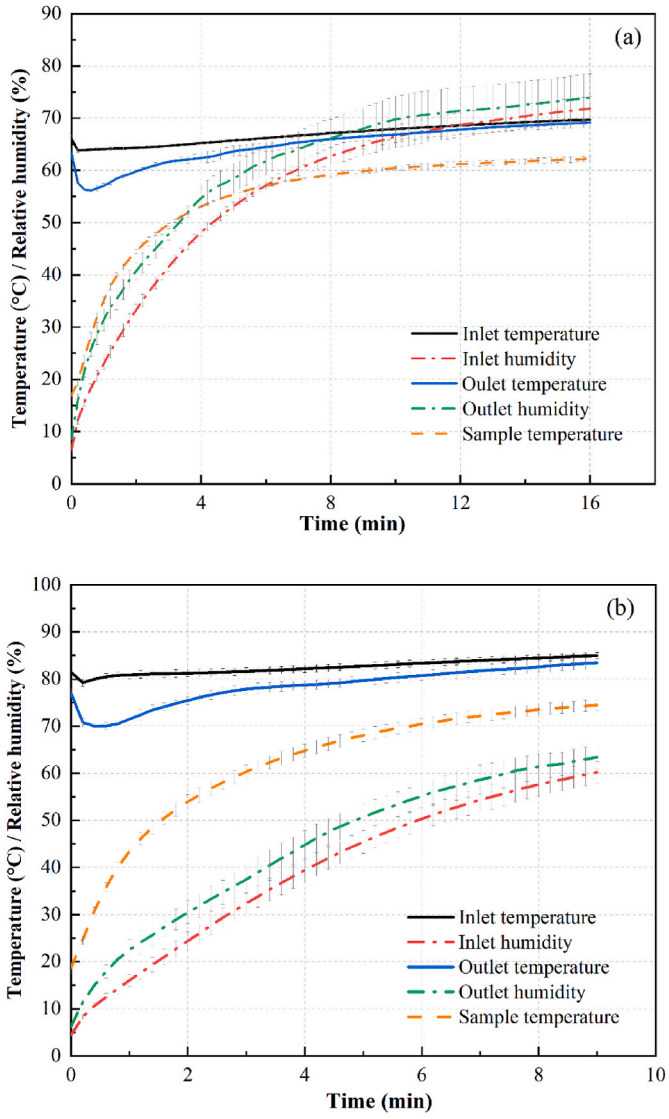

Fig. 3. Temperature and relative humidity of hot air at the inlet and outlet of sample holder in the treatment box at 70 °C (a) and 90 °C (b) (n = 3).

Table 1
Average *Salmonella* population survival on Gala apple cubes during high humidity air heating (HHAH) treatment at 70 °C and 90 °C (n = 3).

Temperature (°C)	Treatment time (min)	*Salmonella* population (log CFU/g)
70	0	9.5 ± 0.1 a[#]
	4	9.2 ± 0.1 ab
	8	8.5 ± 0.1 b
	12	5.9 ± 0.8 c
	16	2.6 ± 0.4 d
90	0	9.5 ± 0.1 A
	2	9.3 ± 0.1 A
	4	8.6 ± 0.1 A
	8	4.4 ± 0.7 B
	9	3.3 ± 0.3 B

[#] Means with different lowercase letters at treatment temperature of 70 °C in the same column are significantly different ($P < 0.05$). Means with different uppercase letters at treatment temperature of 90 °C in the same column are significantly different ($P < 0.05$).

treatment.

In conventional hot air drying, the initial heating stage is characterized by high product water activity but relatively low temperature (below the wet bulb temperature of the drying air) caused by moisture evaporation. As the sample temperature rises above the wet bulb temperature, the product surface water activity decreases. The rapidly reduced product surface moisture content hinders *Salmonella* inactivation (Xie et al., 2021). That is, the enhanced thermal resistance of *Salmonella* in conventional drying operations can be attributed to dry air, as the bacterial cells can rapidly reach thermodynamic equilibrium with their surrounding environment (Liu et al., 2018; Olaimat et al., 2020; Syamaladevi, Tang, & Zhong, 2016). In dry environments, *Salmonella*'s internal water vapor pressure equilibrates with that of the surrounding environment, resulting in prolonged thermal death time (Xie et al., 2021). Grasso-Kelley et al. (2021) found that 120 min and 75 min were required to achieve >6.5-log CFU/g reduction of *Salmonella* during apple drying at 104 °C and 135 °C, respectively. Conversely, bacterial cells are more susceptible to destruction when exposed to high-humidity environments (Yang et al., 2022). The shorter treatment time and lower treatment temperatures employed in this study underscore the greater effectiveness of thermal treatments with HHAH in *Salmonella* inactivation on apple cubes.

3.1.3. Potential application of the HHAH treatment

In this study, the HHAH treatment is introduced as a preventive control measure prior to drying. This treatment capitalizes on the rapid evaporation of moisture from fresh fruit, creating a high-humidity environment within a closed system. Notably, the HHAH treatment offers several advantages over other wet heating methods, such as steam processing. First, it requires no costly equipment, making it a viable economical option. Second, the treatment temperature remains low, helps to preserve the overall quality of the product. Third, the HHAH treatment can be combined with other innovative thermal processing technologies, such as microwave heating and radio frequency heating. These technologies hold the potential to enhance drying efficiency when used as preheating treatments before conventional drying processes (Mujumdar, 2006; Zhou et al., 2019; Zhou & Wang, 2019). The application of microwave or radio frequency heating within the HHAH treatments can rapidly elevate sample temperature while effectively eliminating bacteria within a short time frame. Given the critical role of RH in this thermal treatment, the inclusion of reliable RH sensors is of paramount importance. The sensors should enable real-time monitoring of RH levels throughout the processing, ensuring consistent and effective treatment.

3.2. AA treatment (65 °C)

Table 2 shows the pH and Brix values of apples before and after AA treatment. The pH of the 3.4% AA solution was 2.47, similar to the finding of pH 2.36 by Dipersio et al. (2003). Before AA treatment, the apple's pH was 3.76, which was reduced to 3.36 after treatment. The Brix value of apple declined from 13.8 to 11.4 after AA treatment. The reduction in Brix value following AA treatment can be attributed to the diffusion of fructose, sucrose, and glucose from apple cubes to the solution (Saldivar et al., 2010).

The *Salmonella* inactivation curve during AA treatment is presented in Fig. 4. The *Salmonella* population on apples decreased from 9.9 ± 0.2

Table 2
Measurements of pH and Brix of Gala apple before and after ascorbic acid (AA) treatment (65 °C) (n = 3).

Sample	pH	Brix
Fresh apple (before AA treatment[a])	3.76 ± 0.03 a[#]	13.8 ± 0.0 a
Apple after AA treatment	3.36 ± 0.02 b	11.4 ± 0.2 b

[#] Means with different lowercase letters in the same column indicate significant differences ($P < 0.05$).

[a] AA treatment: apple cubes were immersed in 65 °C ascorbic acid solution for 90 s.

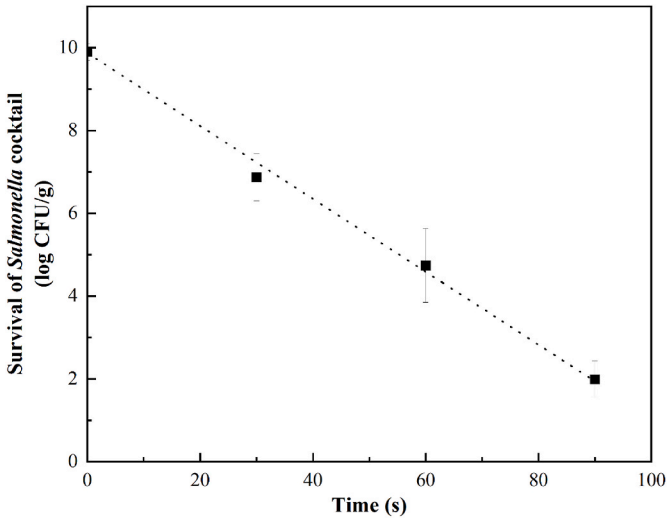

Fig. 4. Survival of *Salmonella* populations on Gala apple cubes treated with ascorbic acid (AA) treatment (3.4 % ascorbic solution at 65 °C) (n = 3).

to 2.0 ± 0.5 log CFU/g, resulting in a reduction of 7.9-log CFU/g after a 90 s treatment. The thermal decimal time (*D*-value) at 65 °C was calculated to be 12.3 ± 0.3 s using a linear regression model. In a study by Juneja et al. (2001), the heat resistance of eight *Salmonella* cocktails in various poultry products was examined using a water bath. The *D*-values for *Salmonella* in beef, pork, turkey, and chicken at 65 °C were found to be 40.2, 52.2, 48, and 35.4 s, respectively. Notably, the lower *D*-value observed in apple cubes after AA treatment in this study may be attributed to the low pH of the AA solution, as *Salmonella* generally exhibits decreased thermal resistance in both low- and high-pH environments (Blackburn et al., 1997).

It is important to note that this study specifically investigated the thermal resistance of *Salmonella* in a 3.4% AA solution. However, based on findings from a survey by Low et al. (2022), only 14 out of 192 participants used AA as a pretreatment, while 119 participants preferred lemon juice (which is rich in citric acid). The *D*-value of *S*. Enteritids in 2.0% (w/w) citric acid (pH 4.8) was reported to be 39.4 s at 62.5 °C (Blackburn et al., 1997). Additional research on the lethality of *Salmonella* when treated with lemon juice is essential, because different acidic solutions can have varying effects on *Salmonella* inactivation (DiPersio et al., 2007), and this information can provide important guidance to individuals.

When implementing the AA treatment as a preventive control in the drying industry, it's crucial to monitor the temperature of the solution. Following the *Guidelines for Validation of Blanching Processes*, published by Almond Board (Almond Board of California, 2007), ensuring the accuracy and calibration of the thermocouple or temperature sensor is of great importance during this process. Furthermore, it is advisable to conduct more thermal inactivation experiments at various temperatures to gather TDT data.

3.3. Color and moisture content of dried apple cubes

Table 3 presents the moisture content data for dried apple cubes subjected to different thermal treatments and drying, which ranges from 2.8% to 3.5% (w.b.). Statistical analysis (ANOVA) revealed no significant differences in moisture content among the different thermal treatment methods.

Color plays a critical role in determining product quality and consumer preferences. Images of dried apple cubes subjected to various thermal treatments are presented in Fig. 5. The HHAH treatment led to increased browning of apples, while AA pretreatment effectively reduced browning due to ascorbic acid's antioxidative properties,

Table 3
Moisture contents of dried apple cubes subjected to different treatments (n = 3).

Treatments	Moisture content (% w.b.)
Control[a]	2.8 ± 0.3 A*
AA (65 °C)[b] + Drying	3.0 ± 0.3 A
AA (25 °C)[c] + HHAH (90 °C)[d] + Drying	3.5 ± 0.4 A
AA (25 °C) + HHAH (70 °C)[e] + Drying	3.1 ± 0.2 A
HHAH (90 °C) + Drying	3.4 ± 0.4 A
HHAH (70 °C) + Drying	2.8 ± 0.3 A

* Means with same letters in the column indicate no significant differences at $P > 0.05$ between groups.
[a] Control: Apple cubes without any pre-treatments were dried in hot air at 90 °C for 70 min.
[b] AA (65 °C): Apple cubes were immersed in a 3.4% ascorbic acid solution (pH 2.47) at 65 °C for 90 s.
[c] AA (25 °C): Apple cubes were immersed in a 3.4% ascorbic acid solution (pH 2.47) at 25 °C for 10 min.
[d] HHAH (90 °C): Apple cubes were treated in the humidity chamber at 90 °C for 9 min.
[e] HHAH (70 °C): Apple cubes were treated in the humidity chamber at 70 °C for 16 min.

inhibiting enzymatic browning. As observed in the images, apples treated with AA (65 °C AA treatment, AA + HHAH) displayed a lighter color compared to those without AA treatment.

To quantify the impact of thermal treatment on apple color, L^*, a^*, and b^* values were analyzed (Table 4). The HHAH treatment at both 70 °C and 90 °C (HHAH + drying) resulted in lower L^* values and higher a^* and b^* values compared to the control group (drying). Conversely, the AA pretreatment groups (AA or 65 °C AA treatment) exhibited higher L^* value and lower a^* and b^* values than the control group. Statistical analysis showed no significant differences in color between HHAH treatment at 70 °C for 16 min and 90 °C for 9 min. Significant differences were, however, observed in product color between the AA treatment and AA + 90 °C HHAH treatment. In comparison to the control group, all treatment groups showed significant differences in color, except for the AA + 70 °C HHAH treatment. Apple cubes treated with AA + 70 °C HHAH displayed color most similar to the control ($\Delta E = 2.72$), which was achieved without any additives of preservatives. Certain consumers are in favor of natural brown colored dried apples that had not been treated with any chemical additives. Thus, a drying process can be tailored to meet specific consumer preferences.

4. Conclusion

This study introduced two thermal treatments — HHAH and AA treatments — with the aim of eliminating *Salmonella* before drying of apple cubes. HHAH treatment at 70 °C for 16 min, at 90 °C for 9 min, and AA treatment using 3.4% ascorbic solution at 65 °C for 90 s achieved 6.9 ± 0.4, 6.2 ± 0.2, and 7.9 ± 0.6 log CFU/g reduction, respectively. But HHAH treatment led to increased browning of dried apple cubes. However, the browning effect was mitigated through AA (25 °C) pretreatment. The AA treatment was able to retain desirable color of the dried apple cubes. The moisture content of the dried apple cubes was not significantly different after applying these thermal treatments, indicating their potential to enhance food safety of drying without compromising product quality. This study suggests that HHAH and AA treatments can be used as highly effective preventive measures against *Salmonella* contamination, both in industrial food processing and home drying applications. Notably, the accurate management of RH is essential when implementing HHAH treatment, emphasizing the need for reliable RH sensors for precise monitoring. Further research into various acidic solutions, such as lemon juice, is needed to provide comprehensive recommendations for home drying practices.

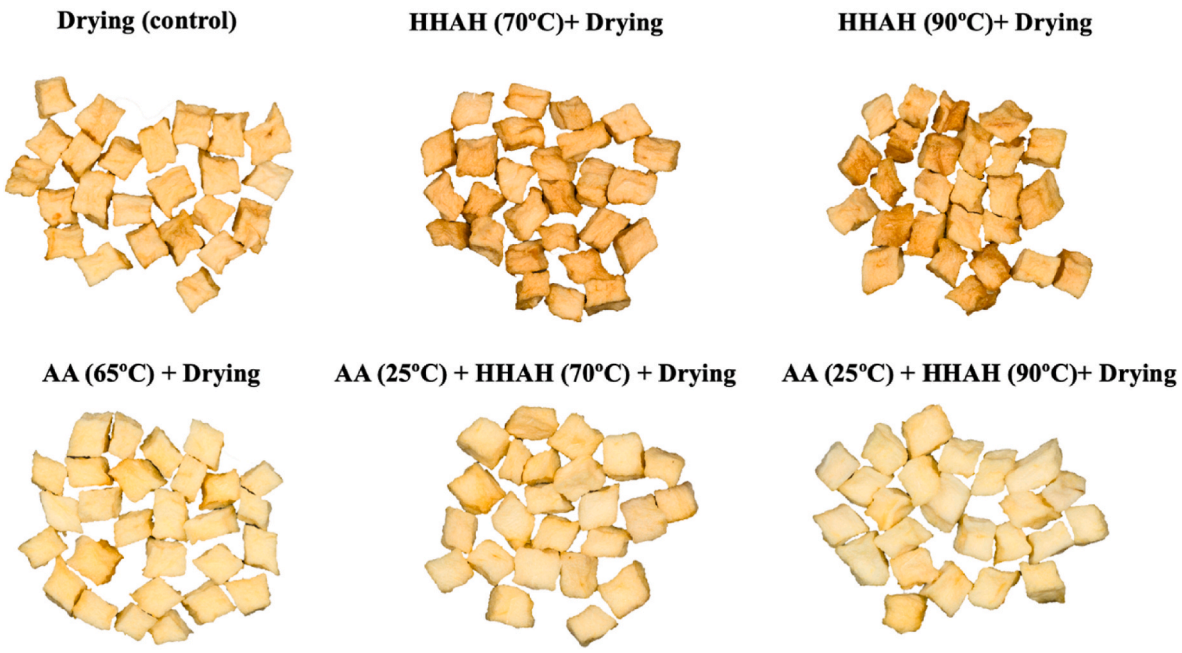

Fig. 5. Effect of different thermal treatments on color of dried apple cubes.

Table 4
Means and standard deviations of color values of dried apple cubes subjected to different treatments (n = 3).

Treatment	L^*	a^*	b^*	ΔE
Control[a]	79.8 ± 1.3 c[#]	9.6 ± 1.3 b	40.5 ± 2.8 bcd	–
AA (65 °C)[b] + Drying	83.0 ± 0.7 a	4.3 ± 0.7 e	37.5 ± 2.5 e	6.9
AA (25 °C)[c] + HHAH (90 °C)[d] + Drying	82.1 ± 1.0 ab	4.8 ± 1.1 de	37.8 ± 2.3 de	6.0
AA (25 °C) + HHAH (70 °C)[e] + Drying	80.9 ± 0.7 bc	7.2 ± 0.8 c	40.1 ± 1.4 cde	2.7
HHAH (90 °C) + Drying	73.9 ± 1.5 de	14.4 ± 1.8 a	45.7 ± 2.3 a	9.3
HHAH (70 °C) + Drying	72.7 ± 1.1 e	15.5 ± 0.4 a	46.6 ± 0.8 a	11.1

[#] Means with different letters in the same column indicate significant differences ($P < 0.05$).

[a] Control: Apple cubes without any pretreatments were dried in hot air at 90 °C for 70 min.

[b] AA (65 °C): Apple cubes were immersed in a 3.4% ascorbic acid solution (pH 2.47) at 65 °C for 90 s.

[c] AA (25 °C): Apple cubes were immersed in a 3.4% ascorbic acid solution (pH 2.47) at 25 °C for 10 min.

[d] HHAH (90 °C): Apple cubes were treated in the humidity chamber at 90 °C for 9 min.

[e] HHAH (70 °C): Apple cubes were treated in the humidity chamber at 70 °C for 16 min.

CRediT authorship contribution statement

Shuang Zhang: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ren Yang:** Writing – review & editing, Methodology. **Xu Zhou:** Writing – review & editing, Software, Data curation. **Yaohua Feng:** Writing – review & editing. **Juming Tang:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of Competing interest

To the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

Data availability

Data will be made available on request.

Acknowledgements

This research was funded by USDA-NIFA AFRI SAS grant 2020-68012-31822. The authors acknowledge the assistance from Huimin Lin and Dan Liu during microbial testing.

References

Almond Board of California. (2007). *Guidelines for validation of blanching processes.* Modesto, CA.

Association of Official Agricultural Chemists. (1996). *Official method of analysis.* Washington, DC.

Blackburn, C. de W., Curtis, L. M., Humpheson, L., Billon, C., & McClure, P. J. (1997). Development of thermal inactivation models for *Salmonella enteritidis* and *Escherichia coli* O157:H7 with temperature, pH and NaCl as controlling factors. *International Journal of Food Microbiology, 38*, 31–44. https://doi.org/10.1016/S0168-1605(97)00085-8

Burnham, J. A., Kendall, P. A., & Sofos, J. N. (2001). Ascorbic acid enhances destruction of *Escherichia coli* O157:H7 during home-type drying of apple slices. *Journal of Food Protection, 64*, 1244–1248. https://doi.org/10.4315/0362-028X-64.8.1244

Casulli, K. E., Garces-Vega, F. J., Dolan, K. D., Ryser, E. T., Harris, L. J., & Marks, B. P. (2018). Impact of process temperature, humidity, and initial product moisture on thermal inactivation of *Salmonella* Enteritidis PT 30 on pistachios during hot-air heating. *Journal of Food Protection, 81*, 1351–1356. https://doi.org/10.4315/0362-028X.JFP-17-439

Dipersio, P. A., Kendall, P. A., Calicioglu, M., & Sofos, J. N. (2003). Inactivation of *Salmonella* during drying and storage of apple slices treated with acidic or sodium metabisulfite solutions. *Journal of Food Protection, 66*, 2245–2251. https://doi.org/10.4315/0362-028X-66.12.2245

DiPersio, P., Kendall, P., Yoon, Y., & Sofos, J. (2007). Influence of modified blanching treatments on inactivation of *Salmonella* during drying and storage of carrot slices. *Food Microbiology, 24*, 500–507. https://doi.org/10.1016/j.fm.2006.09.004

DiPersio, P. A., Yoon, Y., Sofos, J. N., & Kendall, P. A. (2006). Inactivation of *Salmonella* during drying and storage of carrot slices prepared using commonly recommended methods. *Journal of Food Science, 70*, M230–M235. https://doi.org/10.1111/j.1365-2621.2005.tb07193.x

El-Shimi, N. M. (1993). Control of enzymatic browning in apple slices by using ascorbic acid under different conditions. *Plant Foods for Human Nutrition, 43*, 71–76. https://doi.org/10.1007/BF01088098

Finn, S., Condell, O., McClure, P., Amézquita, A., & Fanning, S. (2013). Mechanisms of survival, responses and sources of *Salmonella* in low-moisture environments. *Frontiers in Microbiology, 4*. https://doi.org/10.3389/fmicb.2013.00331

Grasso-Kelley, E. M., Liu, X., Halik, L. A., & Douglas, B. (2021). Evaluation of hot-air drying to inactivate *Salmonella* and *Enterococcus faecium* on apple pieces. *Journal of Food Protection, 84*, 240–248. https://doi.org/10.4315/JFP-20-167

Gurtler, J. B., Keller, S. E., Fan, X., Olanya, O. M., Jin, T., & Camp, M. J. (2020). Survival of *Salmonella* during apple dehydration as affected by apple cultivar and antimicrobial pretreatment. *Journal of Food Protection, 83*, 902–909. https://doi.org/10.4315/JFP-19-475

Jin, Y., Tang, J., & Zhu, M.-J. (2020). Water activity influence on the thermal resistance of *Salmonella* in soy protein powder at elevated temperatures. *Food Control, 113*, Article 107160. https://doi.org/10.1016/j.foodcont.2020.107160

Juneja, V. K., Eblen, B. S., & Ransom, G. M. (2001). Thermal inactivation of *Salmonella* spp. in chicken broth, beef, pork, Turkey, and chicken: Determination of *D*- and *Z*-values. *Journal of Food Science, 66*, 146–152. https://doi.org/10.1111/j.1365-2621.2001.tb15597.x

Krokida, M. K., Kiranoudis, C. T., Maroulis, Z. B., & Marinos-Kouris, D. (2000). Effect of pretreatment on color of dehydrated products. *Drying Technology, 18*, 1239–1250. https://doi.org/10.1080/07373930008917774

Li, K., Zhang, Y., Wang, Y. F., El-Kolaly, W., Gao, M., Sun, W., & Li, M. (2021). Effects of drying variables on the characteristic of the hot air drying for gastrodia elata: Experiments and multi-variable model. *Energy, 222*, Article 119982. https://doi.org/10.1016/j.energy.2021.119982

Liu, S., Tang, J., Tadapaneni, R. K., Yang, R., & Zhu, M.-J. (2018). Exponentially increased thermal resistance of *Salmonella* spp. and *Enterococcus faecium* at reduced water activity. *Applied and Environmental Microbiology, 84*, Article e02742-17. https://doi.org/10.1128/AEM.02742-17

Low, M., & Feng, Y. (2024). Content analysis of food safety information in dried apple recipes on YouTube, blogs, cookbooks and extension materials. *Foods, 13*, 778. https://doi.org/10.3390/foods13050778

Low, M., Scharff, R., Tang, J., Grasso-Kelley, E., & Feng, Y. (2022). Food handling practices for apple drying in home kitchens in the United States: A survey. *Journal of Food Protection, 85*, 1418–1430. https://doi.org/10.4315/JFP-22-106

Mujumdar, A. S. (Ed.). (2006). *Handbook of industrial drying* (p. 1279). CRC Press. https://doi.org/10.1201/9781420017618.

Olaimat, A. N., Osaili, T. M., Al-Holy, M. A., Al-Nabulsi, A. A., Obaid, R. S., Alaboudi, A. R., Ayyash, M., & Holley, R. (2020). Microbial safety of oily, low water activity food products: A review. *Food Microbiology, 92*, Article 103571. https://doi.org/10.1016/j.fm.2020.103571

Podolak, R., & Black, D. G. (Eds.). (2017). *Control of Salmonella and other bacterial pathogens in low moisture foods* (1st ed.). Wiley. https://doi.org/10.1002/9781119071051.

Saldivar, X., Wang, Y.-J., Chen, P., & Mauromoustakos, A. (2010). Effects of blanching and storage conditions on soluble sugar contents in vegetable soybean. *LWT - Food Science and Technology, 43*, 1368–1372. https://doi.org/10.1016/j.lwt.2010.04.017

Sun, S., Xie, Y., Zhou, X., Zhu, M.-J., Sablani, S., & Tang, J. (2023). Survival and thermal resistance of *Salmonella* in chocolate products with different water activities. *Food Research International, 172*, Article 113209. https://doi.org/10.1016/j.foodres.2023.113209

Syamaladevi, R. M., Tang, J., Villa-Rojas, R., Sablani, S., Carter, B., & Campbell, G. (2016). Influence of water activity on thermal resistance of microorganisms in low-moisture foods: A review. *Comprehensive Reviews in Food Science and Food Safety, 15*, 353–370. https://doi.org/10.1111/1541-4337.12190

Syamaladevi, R. M., Tang, J., & Zhong, Q. (2016). Water diffusion from a bacterial cell in low-moisture foods. *Journal of Food Science, 81*. https://doi.org/10.1111/1750-3841.13412

Velić, D., Planinić, M., Tomas, S., & Bilić, M. (2004). Influence of airflow velocity on kinetics of convection apple drying. *Journal of Food Engineering, 64*, 97–102. https://doi.org/10.1016/j.jfoodeng.2003.09.016

Xie, Y., Yang, R., Alshammari, J., Zhu, M.-J., Sablani, S., & Tang, J. (2021). Moisture content of bacterial cells determines thermal resistance of *Salmonella* enterica serotype Enteritidis PT 30. *Applied and Environmental Microbiology, 87*, Article e02194-20. https://doi.org/10.1128/AEM.02194-20

Xie, Y., Zhang, S., Sun, S., Zhu, M.-J., Sablani, S., & Tang, J. (2022). Survivability of *Salmonella* and *Enterococcus faecium* in chili, cinnamon and black pepper powders during storage and isothermal treatments. *Food Control, 137*, Article 108935. https://doi.org/10.1016/j.foodcont.2022.108935

Xu, J., Tang, J., Jin, Y., Song, J., Yang, R., Sablani, S. S., & Zhu, M.-J. (2019). High temperature water activity as a key factor influencing survival of *Salmonella* Enteritidis PT 30 in thermal processing. *Food Control, 98*, 520–528. https://doi.org/10.1016/j.foodcont.2018.11.054

Yam, K. L., & Papadakis, S. E. (2004). A simple digital imaging method for measuring and analyzing color of food surfaces. *Journal of Food Engineering, 61*, 137–142. https://doi.org/10.1016/S0260-8774(03)00195-X

Yang, R., Lombardo, S. P., Conway, W. F., & Tang, J. (2022). Inactivation of *Salmonella* Enteritidis PT 30 on black peppercorns in thermal treatments with controlled relative humidities. *Food Research International, 162*, Article 112101. https://doi.org/10.1016/j.foodres.2022.112101

Zhang, W., Tang, J., Liu, F., Bohnet, S., & Tang, Z. (2014). Chemical marker M2 (4-hydroxy-5-methyl-3(2H)-furanone) formation in egg white gel model for heating pattern determination of microwave-assisted pasteurization processing. *Journal of Food Engineering, 125*, 69–76. https://doi.org/10.1016/j.jfoodeng.2013.10.020

Zhou, X., Ramaswamy, H., Qu, Y., Xu, R., & Wang, S. (2019). Combined radio frequency-vacuum and hot air drying of kiwifruits: Effect on drying uniformity, energy efficiency and product quality. *Innovative Food Science and Emerging Technologies, 56*, Article 102182. https://doi.org/10.1016/j.ifset.2019.102182

Zhou, X., & Wang, S. (2019). Recent developments in radio frequency drying of food and agricultural products: A review. *Drying Technology, 37*, 271–286. https://doi.org/10.1080/07373937.2018.1452255

Zhou, X., Zhang, S., Tang, Z., Tang, J., & Takhar, P. S. (2022). Microwave frying and post-frying of French fries. *Food Research International, 159*, Article 111663. https://doi.org/10.1016/j.foodres.2022.111663