Heating of milk powders at low water activity to 95°C for 15 minutes using hot air-assisted radio frequency processing achieved pasteurization

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ABSTRACT

Salmonella persistence in milk powders has caused several multistate foodborne disease outbreaks. Therefore, ways to deliver effective thermal treatment need to be identified and validated to ensure the microbial safety of milk powders. In this study, a process of hot air-assisted radio frequency (HARF) followed by holding at high temperatures in a convective oven was developed for pasteurization of milk powders. Heating times were compared between HARF and a convection oven for heating milk powders to a pasteurization temperature, and HARF has been shown to considerably reduce the come-up time. Whole milk powder (WMP) and nonfat dry milk (NFDM) were inoculated with a 5-serotype Salmonella cocktail and equilibrated to a water activity of 0.10 to simulate the worst case for the microbial challenge study. After heating the sample to 95°C using HARF, followed by 10 and 15 min of holding in the oven, more than 5 log reduction of Salmonella was achieved in WMP and NFDM. This study validated a HARF-assisted thermal process for pasteurization of milk powder based on previously collected microbial inactivation kinetics data and provides valuable insights to process developers to ensure microbial safety of milk powders.

Key words: dielectric heating, low-moisture foods, Salmonella, whole milk powder, nonfat dry milk

INTRODUCTION

Milk powder is an important ingredient in various ready-to-eat (RTE) food products such as infant milk formula, chocolates, granola, drink mixes, seasonings, protein bars, and confectionery. In the industrial process, milk powder is produced by spray-drying of pasteurized liquid milk. Although pasteurization of milk inactivates pathogens, and milk powders are manufactured in a relatively clean environment, pathogens such as Cronobacter sakazakii and Salmonella are found to cross-contaminate the product at low levels. Often, these bacteria can survive through the spray-drying process (Osaili et al., 2009). Because pathogens such as Salmonella survive in low-moisture foods for a long period (Podolak et al., 2010; Keller et al., 2013; Chuang et al., 2020) and these products are often consumed as RTE or as ingredients in RTE foods by young infants and children, there is a need to pasteurize milk powders.

Recently, various outbreaks and recalls have been associated with milk powder (Brouard et al., 2007; Jourdan-da Silva et al., 2018; Marler, 2018). Currently, the microbial safety problems of milk powders are mainly due to lack of the key lethal treatment before consumption or use as ingredients (Carrasco et al., 2012; Silva and Gibbs, 2012). Therefore, an effective pasteurization process should be included in the production line, which uses milk powders as ingredients in RTE products. Thermal processing is one of the most common and effective methods for the inactivation of pathogens in food products. Currently, one challenge in the thermal processing of the milk powder is the increased thermal resistance of food pathogens at reduced water activity levels. Several studies (Liu et al., 2019; Wei et al., 2020a) reported that a higher D-value of Salmonella in nonfat dry milk (NFDM) was observed at a lower water activity. Similarly, increased D-values of Escherichia coli, Salmonella Typhimurium, and C. sakazakii were observed when the water activity decreased from 0.58 to 0.11 at different temperatures (Lang et al., 2017). When heating the milk powder, the water activity of the milk powder decreases due to moisture evaporation. This increases the difficulty of reducing the microbial population in milk powder and therefore requires a longer holding time at the specific treatment temperature. The other challenge for thermal
processing of milk powder is the difficulty of heating the milk powder using traditional thermal processing technologies, such as dry heat or the hot room method, because of the low thermal conductivity of milk powder (Muramatsu et al., 2005). The slow heating rate of milk powder using traditional thermal processing would require an extended treatment time and over-processing on edges, resulting in considerable quality deterioration (Karagül-Yüceer et al., 2001). The best way to preserve food quality during pasteurization is to heat the product to the maximum possible temperature uniformly (shortest come-up time) and rapidly, with the shortest holding time.

Radio frequency (RF) heating is a dielectric heating method, in which heat is generated within the food product by friction from the vibration of polar dielectric molecules or moving ions under the alternating electric field, similar to microwave heating (Chen et al., 2013, 2017; Pitchai et al., 2014). Radio frequency heating is independent of the product’s thermal conductivity, so it can provide a rapid heating rate to milk powder regardless of its low thermal conductivity. Compared with conventional heating, RF heating has the advantages of rapid and uniform heating and high energy efficiency (Zhao et al., 2000). Radio frequency preferentially vibrates bound water, whereas the microwave vibrates free water in food products (Awuah et al., 2014). Because of that, RF heating has been found to be suitable for pasteurizing various low-moisture foods such as wheat flour (Liu et al., 2018), black pepper (Wei et al., 2019), cumin seeds (Chen et al., 2020), basil leaves (Verma et al., 2021), almonds (Li et al., 2017), and walnuts (Wang et al., 2007). Recently, RF heating-assisted traditional thermal processing has been shown to effectively reduce the target food pathogen in infant formula milk, with a shorter processing time and lower lipid oxidation compared with the conventional thermal method (Lin et al., 2020). Similarly, Michael et al. (2014) reported that RF heating can be a post-process lethality treatment for inactivation of C. sakazakii and Salmonella in NFDM. However, in that study, RF heating validation was conducted only for NFDM, and the water activity of NFDM was not well controlled before the microbial challenge study, which is an essential process parameter for microbial inactivation. Because the thermal resistance of Salmonella increases with decreasing water activity, the initial water activity would considerably affect the microbial inactivation and should be considered as a critical control point. In addition, RF heating of NFDM (Michael et al., 2014) was conducted without the assistance of hot air, which could result in nonuniform heating. Radio frequency does not heat the air, and therefore the product can lose temperature to the air. After RF heating of low-moisture food products, the cold spot was usually found on the top center, and the edges were overheated. By heating the surrounding air to the desired temperature, uniformity of the heating can be increased. Several studies have showed that RF heating can improve the heating rate and uniformity for food products such as nuts (Wang et al., 2014; Chen et al., 2021), rice bran (Ling et al., 2018), and spices (Liu et al., 2021).

The Food Safety Modernization Act requires food producers to provide scientific proof that their established preventive controls can ensure the food safety of their products (FDA, 2015). Thus, process validation is usually conducted to demonstrate that the implemented pasteurization process can reduce target foodborne pathogens in the final products as intended.

Based on the results reported by Wei et al. (2020a), a higher thermal resistance of Salmonella in tested milk powders was observed at a lower water activity; natural water activities of both milk powders ranged from 0.18 to 0.20. During heating and holding of milk powders at high temperatures, the water activity of the product decreases due to moisture evaporation. In the current study, an extremely low water activity of 0.10 was selected, to evaluate the worst-case scenario for HARF heating of milk powders. The objectives of this study were to evaluate HARF processing for whole milk powder (WMP) and NFDM pasteurization at different holding temperatures, which can guide in-plant thermal process validation.

**MATERIALS AND METHODS**

**Milk Powder Samples**

Both WMP and NFDM were acquired from Mars Inc. and were held at ambient temperature (23 ± 2°C). Upon receiving the milk powder samples, the moisture content and water activity (25°C) were determined by a halogen moisture analyzer (HR73, Mettler Toledo Laboratory and Weighing Technologies) and a dew point water activity meter (Aqualab Series 4TE, Meter Inc. and were held at ambient temperature (23 ± 2°C). Upon receiving the milk powder samples, the moisture content and water activity (25°C) were determined by a halogen moisture analyzer (HR73, Mettler Toledo Laboratory and Weighing Technologies) and a dew point water activity meter (Aqualab Series 4TE, Meter Inc. and were held at ambient temperature (23 ± 2°C). Upon receiving the milk powder samples, the moisture content and water activity (25°C) were determined by a halogen moisture analyzer (HR73, Mettler Toledo Laboratory and Weighing Technologies) and a dew point water activity meter (Aqualab Series 4TE, Meter Inc. and were held at ambient temperature (23 ± 2°C). Upon receiving the milk powder samples, the moisture content and water activity (25°C) were determined by a halogen moisture analyzer (HR73, Mettler Toledo Laboratory and Weighing Technologies) and a dew point water activity meter (Aqualab Series 4TE, Meter Inc. and were held at ambient temperature (23 ± 2°C).
HARF of Milk Powders

We conducted HARF treatment of the milk powder in a pilot-scale parallel-plate RF heating system (6 kW, 27.12 MHz; model SO-6B, Monga Strayfield). Due to the difference in density, different amounts of WMP (400 ± 0.1 g) and NFDM (500 ± 0.1 g) were weighed and filled in a laminated paper tray (ConAgra Brands) and placed at the center of the bottom electrode (Figure 1a). Based on our preliminary experiments, the electrode gap between the top and bottom electrodes was set to 130 mm, which would provide a rapid heating rate as well as a good heating uniformity during HARF heating of milk powders. Two fan-forced heaters (1.5 kW, HHF370B, Honeywell) were placed separately at the 2 sides of the HARF heating system and were used to preheat the RF chamber to around 75°C, to minimize the heat loss from milk powders during HARF heating. During the HARF process, 6 fiber optic sensors (accuracy of 0.6°C; Neoptix) were inserted into the sample tray through predrilled holes and used to trace the temperature at different locations (Figure 1b) to determine the cold spot.

In this study, the inoculated pouch method was used as previously described in Wei et al. (2019) and Liu et al. (2018). In brief, inoculated sample (2.0 ± 0.1 g) would be packed into a paper bag (7 × 3 mm) and placed at the cold spot during HARF heating. The inoculated pouch separated the inoculated sample from the uninoculated sample in the paper tray and allowed for easier determination of microbial inactivation at the cold spot, with higher sensitivity. The use of the inoculated pouch method avoids overestimation of microbial inactivation and allows us to evaluate the worst-case scenario of microbial inactivation within the whole sample tray during HARF heating.
The 5 serotypes of *Salmonella enterica* used in this study were selected based on their implication in outbreaks and recalls related to low-moisture foods or high thermal resistance. The details of each *Salmonella* serotype are shown in Table 1. Each bacterial culture was stored in trypticase soy broth (Becton, Dickinson and Company) supplemented with 0.6% (wt/vol) yeast extract and 40% (vol/vol) glycerol (G31-1, Fisher Chemicals) in a cryogenic vial at −80°C.

The same inoculation method as described in Wei et al. (2020a) was followed in this study, as this method has been shown to provide a high and stable bacterial population in milk powders stored at low water activity. Briefly, each bacterial culture was thawed in an incubator at 37°C for 5 min and then transferred into a 10-mL tryptic soy broth tube with yeast extract, incubated at 37°C for 24 h for enrichment. The enriched bacterial culture was then streaked onto a TSAYE plate and incubated at 37°C for 24 h to obtain isolated colonies, which would be used as a working plate and stored at 4°C. Then, a sterilized loopful (10 µL) was used to transfer 1 bacterial colony from the working plate to a 10-mL tryptic soy broth tube with yeast extract, incubated at 37°C for 24 h for enrichment. The enriched bacterial culture was then streaked onto a TSAYE plate and incubated at 37°C for 24 h to obtain isolated colonies, which would be used as a working plate and stored at 4°C. Then, a sterilized loopful (10 µL) was used to transfer 1 bacterial colony from the working plate to a 10-mL tryptic soy broth tube with yeast extract, which was then incubated at 37°C for 24 h. The overnight culture (100 µL) was spread-plated onto a TSAYE plate and incubated at 37°C for 24 h to create bacterial lawns. Finally, the grown bacterial lawns were harvested by agitating the lawns with 3 mL of 0.1% BPW. An equal amount of each harvested *Salmonella* lawn was mixed in a 15-mL sterile conical tube (339650, Thermo Scientific) to prepare the *Salmonella* inoculum. The inoculum was used within 30 min for milk powder inoculation. New working cultures were used to inoculate different batches of the milk powder, which represented biological replication.

### Table 1. Bacterial serotypes used for inoculating milk powders

<table>
<thead>
<tr>
<th>Bacterial name</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Salmonella</em> Agona 447967</td>
<td>FDA, ORA Regional Laboratory (Jefferson, AR)</td>
</tr>
<tr>
<td><em>Salmonella</em> Montevideo 488275</td>
<td>FDA, ORA Regional Laboratory (Jefferson, AR)</td>
</tr>
<tr>
<td><em>Salmonella</em> Mbandaka 698538</td>
<td>FDA, ORA Regional Laboratory (Jefferson, AR)</td>
</tr>
<tr>
<td><em>Salmonella</em> Reading Moff 180418</td>
<td>FDA Culture Collection (Bedford Park, IL)</td>
</tr>
<tr>
<td><em>Salmonella</em> Tennessee K4643</td>
<td>University of Georgia (Athens, GA)</td>
</tr>
</tbody>
</table>

1US Food and Drug Administration, Office of Regulatory Affairs.

**Bacterial Cultures and Inoculum Preparation**

The 5 serotypes of *Salmonella enterica* used in this study were selected based on their implication in outbreaks and recalls related to low-moisture foods or high thermal resistance. The details of each *Salmonella* serotype are shown in Table 1. Each bacterial culture was stored in trypticase soy broth (Becton, Dickinson and Company) supplemented with 0.6% (wt/vol) yeast extract and 40% (vol/vol) glycerol (G31-1, Fisher Chemicals) in a cryogenic vial at −80°C.

The same inoculation method as described in Wei et al. (2020a) was followed in this study, as this method has been shown to provide a high and stable bacterial population in milk powders stored at low water activity. Briefly, each bacterial culture was thawed in an incubator at 37°C for 5 min and then transferred into a 10-mL tryptic soy broth tube with yeast extract, incubated at 37°C for 24 h for enrichment. The enriched bacterial culture was then streaked onto a TSAYE plate and incubated at 37°C for 24 h to obtain isolated colonies, which would be used as a working plate and stored at 4°C. Then, a sterilized loopful (10 µL) was used to transfer 1 bacterial colony from the working plate to a 10-mL tryptic soy broth tube with yeast extract, which was then incubated at 37°C for 24 h. The overnight culture (100 µL) was spread-plated onto a TSAYE plate and incubated at 37°C for 24 h to create bacterial lawns. Finally, the grown bacterial lawns were harvested by agitating the lawns with 3 mL of 0.1% BPW. An equal amount of each harvested *Salmonella* lawn was mixed in a 15-mL sterile conical tube (339650, Thermo Scientific) to prepare the *Salmonella* inoculum. The inoculum was used within 30 min for milk powder inoculation. New working cultures were used to inoculate different batches of the milk powder, which represented biological replication.

**Milk Powder Inoculation and Water Activity Equilibration**

Sample inoculation was conducted in a biological safety cabinet. Each milk powder sample (100 ± 0.1 g) was aseptically weighed and placed into a sterile Whirl-Pak bag (2.04 L, Nasco). A manually-operated spray head (ps20-410 natural, Midwest Bottles LLC) was used to spray the inoculum (10 mL) onto the milk powder sample. The inoculated sample was hand-massaged for 5 min to manually detach powders from the inner lining of the bag. Then, inoculated milk powder sample was homogenized in a paddle mixer for 6 min to achieve uniform distribution of bacterial cells in the sample. Subsequently, the inoculated sample (~5-mm thickness) was transferred onto a sanitized aluminum tray (230 × 300 × 15 mm) and placed into a custom-built environmental relative humidity chamber (Lau and Subbiah, 2020). The environmental relative humidity was set to 10% to equilibrate the inoculated milk powder samples to water activity of 0.10 for 5 d. This equilibration period also allowed the bacteria to acclimatize and adapt to the low-moisture environment before HARF treatment.

**HARF Microbial Inactivation Validation**

The inoculated milk powder (2 ± 0.1 g) was packed into a heat-sealable paper bag (7 × 3 mm) to prepare the inoculated pouch. One inoculated pouch was placed at the predetermined cold spot along with the remaining (398 and 498 g for WMP and NFDM) un inoculated milk powders in the paper tray. The tray was then placed at the center of the bottom electrode for HARF heating (Figure 1a). One fiber optic sensor was placed onto the pouch to measure the temperature of the cold spot during HARF treatment of milk powder. The samples were HARF heated to 85, 90, and 95°C before transferring to the hot air oven (preheated to target holding temperature) for subsequent holding. According to the previous study (Wei et al., 2021), the *D*-values of *Salmonella* in WMP (water activity = 0.10) at 85, 90, and 95°C were determined to be 7.98, 3.35, and 1.68 min, respectively. Similarly, the *D*-values of *Salmonella* in NFDM (water activity = 0.10) at 85, 90, and 95°C were found to be 10.98, 4.82, and 1.82 min, respectively. Initially, the maximum holding time at 85, 90, and 95°C were selected to be 60, 20, and 10 min (*D*-value > 5) to achieve more than 5 log reduction in this study. However, due to moisture loss during HARF
heating and oven holding, the thermal resistance of *Salmonella* increased dramatically. The maximum holding times were then extended to 120, 30, and 15 min at 85, 90, and 95°C, respectively. After holding in the oven, the inoculated pouch was immediately transferred into a sterile Whirl-Pak bag and immersed in an ice-water bath (0°C) to stop the thermal inactivation. After holding at 85°C for 120 min, 90°C for 30 min, and 95°C for 15 min, the water activity of WMP dropped from 0.100 to 0.064, 0.078, and 0.092, and moisture content of WMP dropped from 2.07% to 1.09, 1.43, and 1.74%, respectively.

The treated inoculated pack (2 ± 0.1 g) was diluted by adding 18 mL of 0.1% BPW and was homogenized for 1 min in a paddle mixer. Then, the homogenized sample was 10-fold diluted using 0.1% BPW and spread-plated onto TSAYE supplemented with 0.05% (wt/vol) ammonium iron citrate (Sigma-Aldrich), and 0.03% (wt/vol) sodium thiosulfate (Fisher Chemical) at 37°C for 24 h for *Salmonella* enumeration. The grown yellow colonies with black centers were counted as *Salmonella* survivors. All the HARF heating inactivation treatments were conducted in triplicate.

**RESULTS AND DISCUSSION**

**HARF of Milk Powder**

The WMP (water activity = 0.205 ± 0.004; moisture content = 3.07 ± 0.22 %) and NFDM (water activity = 0.220 ± 0.002; moisture content = 3.15 ± 0.05 %) were HARF heated for around 15 min to reach 95°C at the coldest location (Figure 2). As shown in Figure 2, the top center (1) was determined to be the cold spot among the 6 locations, which were measured during the HARF heating, for both WMP and NFDM. Within each layer, it can be observed that the heating rate of the edge was faster than the center. Similar observations have also been found during RF heating of other food products, such as infant formula milk (Lin et al., 2020), peanut kernels (Zhang et al., 2021a), wheat and corn flour (Ozturk et al., 2017; Villa-Rojas et al., 2017), and almonds (Li et al., 2017). The edges received more electromagnetic energy from multiple directions, in addition to the fringe effect of the electromagnetic field. In general, the dielectric properties increase with temperature, which leads to the hot spot heating at a faster rate than the cold spot. This is known as thermal runaway heating (Zhang et al., 2021b). The top layer of both milk powders had the slowest heating rate compared with the other 2 layers. Michael et al. (2014) conducted a case study and showed that RF heating could pasteurize NFDM without identifying the cold spot and RF heating profiles of milk powder, which would be important information for validation of this process. In this study, with the identification of cold spot and heating profiles, this framework could guide the dairy industry in conducting the process validation.

Because RF heating does not heat the air, the temperature gradient between the top layer of milk powder and air would result in considerable heat loss from the top layer. Thus, the fan-forced heater was used to preheat the RF chamber and reduce the thermal gradient in this study. The high environmental temperature minimized heat loss from the milk powder during RF heating and improved the heating uniformity. Previously, HARF has been shown to provide a faster heating rate and better heating uniformity for several low-moisture
The heating uniformity of milk powders can be further improved by establishing a continuous RF process or adding a mixing step between 2 RF units (Zhou and Wang, 2019). Additionally, recent studies (Chen et al., 2016, 2017; Huang et al., 2018; Zhang et al., 2021a) have shown that computer simulations can be used to design, scale up, and optimize the RF heating process to provide better heating uniformity.

The average heating rates for the cold spot temperature to reach 95°C were determined to be 6.4 and 6.2°C/min for WMP and NFDM, respectively. The WMP and NFDM were packed in the same tray, and the temperature of the cold spot (top center) was heated to 95°C using a convection oven preheated to 105°C. The temperature histories of both milk powders during oven heating are shown in Figure 3. The average heating rates for oven heating of WMP and NFDM were 0.42 and 0.32°C/min, respectively. Heating with HARF considerably shortened the amount of time required for heating the milk powder to 95°C. This shorter come-up time of HARF allowed for high-temperature short-time pasteurization, which has been shown to minimize quality deterioration. In this study, only small sample sizes (400 g for WMP and 500 g for NFDM) of milk powders were heated, whereas a much larger size sample would be needed for the industrial-scale processing. With a larger sample size, oven heating may require few days to heat the milk powder to the target pasteurization temperature, due to its poor thermal conductivity. For example, the traditional hot room pasteurization of egg white powder in commercial packages (9.07 kg) requires 15 d of holding time, which takes 4 to 7 d to heat the sample to a target temperature of 67°C (Baron et al., 2003; Boreddy et al., 2016; Wei et al., 2020b). Because RF heating can heat the milk powder volumetrically, the increase in come-up time would be relatively small with an increase in sample size. Longer heating time at high temperatures would result in greater loss of moisture and caking of milk powder. This may necessitate an additional unit operation to break the clumps. Also, a continuous RF heating process can be developed for the milk powder pasteurization, which could maintain a similar heating profile to that shown in this study and may provide better heating uniformity.

**Inactivation of Salmonella in Milk Powders During HARF**

The background microorganisms were determined to be <10 cfu/g in both WMP and NFDM. After inoculation and equilibration, the inoculation control samples had a *Salmonella* population of 6.47 ± 0.03 log and 6.54 ± 0.14 log cfu/g in WMP and NFDM. The inoculation method has been shown to significantly affect the *Salmonella* inactivation kinetics and subsequent thermal inactivation study (Hildebrandt et al., 2016). The lawn-based liquid inoculum method used in this study has been shown to be a suitable method for inoculation of low-moisture foods, which could provide a stable *Salmonella* population in different low-moisture foods (Hildebrandt et al., 2016; Verma et al., 2018; Chen et al., 2019).

Before the microbial challenge study, the inoculated samples were equilibrated to water activity at 0.10 and acclimated for 5 d for adaptation of bacteria to the low-moisture condition. The acclimation of inoculated samples before the microbial challenge study is essential for improving the external validity of the process validation (Allison and Fouladkhah, 2018). The fresh inoculated sample could be sensitive to the subsequent inactivation treatments, and acclimation would enhance the resistance of *Salmonella*, which simulates the real scenario (Piao et al., 2007; Lambertini et al., 2016; Lang et al., 2017). In the industrial process, milk powder could become contaminated during shipping or storage; thus, bacteria usually have sufficient time to adapt to the low water-activity environment before further processing. After inoculation, the thermal resistance of *Salmonella* has been shown to remain consistent during extended storage time up to 180 d (Sekhon et al., 2021; Wei et al., 2021). Thus, HARF heating of inoculated milk powder was conducted between 5 and 15 d after inoculation.

The survival curves of *Salmonella* in WMP and NFDM after HARF heated to 85, 90, and 95°C are shown in Figure 3. The thermal inactivation process for both milk powders is shown in Figure 4. The thermal death rates for WMP and NFDM were determined to be 7.98 and 7.94 log cfu/g/min, respectively. The *Salmonella* population in WMP and NFDM was significantly reduced by 7.98 and 7.94 log cfu/g/min, respectively.

**Figure 3.** Temperature histories of cold spots under hot air-assisted radio frequency (HARF) or oven heating (preheated to 105°C) of whole milk powder (WMP) and nonfat dry milk (NFDM).
shown in Figure 4. According to the US Food and Drug Administration (FDA, 2010), presence of pathogens such as *Salmonella* in dairy products indicates either inadequate pasteurization or post-pasteurization contamination. Because the contamination level of *Salmonella* in low-moisture food such as milk powder is low, the treatment process, which provides more than 5 log reduction of *Salmonella*, can be considered as a pasteurization process to ensure the safety of milk powders.

At time 0 (come-up time), 0.42, 0.50, and 0.54 log cfu/g reductions of *Salmonella* were achieved in NFDM at temperatures of 85, 90, and 95°C, respectively. The corresponding values for WMP were 0.43, 0.42, and 0.72 log cfu/g reduction of *Salmonella*. More than 5 log reduction of *Salmonella* was achieved in WMP after holding at 90 and 95°C for 30 and 10 min, respectively, although more than 5 log reduction of *Salmonella* was observed only after holding at 95°C for 15 min in NFDM. Thus, HARF-assisted thermal processing was demonstrated to be an effective pasteurization process for milk powder. Due to the presence of antimicrobial compounds (Tang et al., 2017), the thermal resistance of *Salmonella* in black pepper is low ($D_{75°C}$-value = 7.8 min at a natural water activity of 0.45) at a high temperature (Vasquez, 2018; Gautam et al., 2020). There is no need for additional holding time in RF heating of spice products such as black pepper (Wei et al., 2018), cumin seeds (Chen et al., 2019), and basil leaves (Verma et al., 2021). However, the thermal resistance of *Salmonella* is relatively high ($D_{75°C}$-value = 26.9 min at a natural water activity of 0.20) in NFDM (Liu et al., 2019; Wei et al., 2020a), which usually requires a holding process after RF heating to achieve the desired inactivation of *Salmonella* in powdered milk products (Michael et al., 2014; Lin et al., 2020). During the holding period, a large amount of moisture is lost due to evaporation. The thermal resistance of *Salmonella* was enhanced in this reduced water activity environment, resulting in an extended holding time requirement for achieving desired pasteurization. For instance, after holding at 85°C for 120 min, only 3.21 and 4.03 log reductions were observed in WMP and NFDM. According to Wei et al. (2020a), the determined $D_{85°C}$-values of *Salmonella* in WMP and NFDM were 10.1 and 9.6 min, respectively, at a water activity of 0.10. This indicated that a 5 log reduction of *Salmonella* was expected after holding the WMP and NFDM at 85°C for 50.5 and 45.0 min. The initial water activity and moisture content of inoculated WMP were found to be 0.10 and 2.07%, and the corresponding values decreased to 0.064 and 1.09%, respectively, after holding in the oven for 120 min at 85°C. The longer holding time was required to achieve the desired inactivation because of the considerably enhanced thermal resistance of *Salmonella*. Therefore, the *Salmonella* inactivation efficiency of HARF was low at 85°C, and a higher temperature (90 or 95°C) was recommended for pasteurization of milk powders. Even at the extremely low water activity of 0.10, HARF could provide a 5 log reduction of *Salmonella* in milk powders; this pasteurization process could be more effective for ensuring the safety of milk powders at the natural water activity (0.18–0.20).

Microbial inactivation kinetics of food pathogens in low-moisture foods have been collected extensively and modeled at different water activities, such as *Listeria monocytogenes* in cocoa powder (Tsai et al., 2019), *Salmonella* in black pepper powder (Gautam et al., 2020) and dried basil leaves (Verma et al., 2021), and *Escherichia coli* in confectionery and chicken meat powder (Daryaei et al., 2018). Those data will be very helpful for determining adequate thermal process conditions for pasteurization of low-moisture foods, considering
the dynamic moisture change during the process. In this study, because the microbial inactivation kinetics data of *Salmonella* in milk powders were not available at the extremely low water activity used here (<0.10), it is different to predict the *Salmonella* inactivation based on the thermal process data. To develop a reliable model, thermal inactivation kinetics data as a function of water activity, especially in the low range, are required.

Based on microbial inactivation data, a high temperature of 95°C is recommended for HARF heating of milk powders. In general, high-temperature short-time pasteurization results in a higher-quality product than low-temperature long-time processing for liquid milk and several other products. However, the quality of HARF-treated products needs to be further investigated. The holding of milk powder at high temperature could cause quality deterioration to the product. For example, Thomsen et al. (2005) reported that crystallization of lactose during storage at elevated temperatures was responsible for chemical changes in WMP, which triggers the development of Maillard reaction products such as melanoids and radicals. Also, crystallization of lactose can result in acceleration of nonenzymatic browning reactions, lipid oxidation, and other deteriorative chemical reactions (Roos and Drusch, 2015). Generally, the oxidation products of milk powder are responsible for off-flavor in oxidized WMP (Hall and Lingnert, 1984). Wang (2016) showed RF heating of NFDM could influence its color and whey protein nitrogen index. Therefore, future research could be done to analyze the quality of milk powders after HARF heating for optimization of process conditions for milk powder pasteurization.

**CONCLUSIONS**

This study showed that HARF heating considerably reduced the comp-up time compared with the hot air oven for heating of milk powder to the target pasteurization temperature, and the top center was identified as the cold spot. Use of HARF to preheat milk powders to target pasteurization temperatures, followed by holding in the hot air oven for the desired time has been shown to effectively pasteurize WMP and NFDM at a water activity of 0.10. More than 5 log reduction of *Salmonella* in WMP was achieved after HARF heated to 95°C and held for 10 min or HARF heated to 90°C and held for 30 min. For NFDM, more than 5 log reduction of *Salmonella* would require HARF preheating to 95°C and holding for 15 min in the oven. This study can guide the dairy industry in conducting industrial-scale process validation. Future work could focus on the quality evaluation of milk powder after HARF heating.

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