THERMAL INACTIVATION OF BACTERIAL PATHOGENS UNDER WIDELY CHANGING MOISTURE CONDITIONS IN COOKED BACON AND DRIED APPLE

By

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ABSTRACT

The overall goal of this thesis was to evaluate phenomenological similarity in bacterial pathogen inactivation under different thermal treatments of two very different food products (cooked bacon and dried apples) with similarly wide changes in moisture during processing. As ready-to-eat (RTE) products, both must comply with specific food safety regulations, under the United States (US) Department of Agriculture – Food Safety Inspection Service and the Food Safety Modernization Act Preventive Controls for Human Foods Rule, respectively. Therefore, there is a need for pathogen inactivation data to validate commercial pathogen control processes for both products. Both conventional and microwave oven cooking of bacon to the required 40% cooking yield achieved >6.5 log reduction of *Salmonella*. However, when humidity was reduced (dew point ≤25°C), microwave cooking of bacon yielded <6.5 log reduction. When drying apples to a standard moisture content (<24% wet basis), lower *Listeria monocytogenes* inactivation (1.8 and 2.8 log CFU) was achieved when drying at 60°C, under the studied air velocities (0.7 and 2.1 m/s) ($P < 0.05$), compared to 80°C, at which *Listeria* decreased by 5 log reduction by the end of drying. Despite the use of different pathogens, similar inactivation response patterns were observed during both apple drying and bacon cooking, especially microwave cooked bacon under dry conditions, reflecting the simultaneous counter-effects of dynamically increasing product temperature and decreasing product moisture. Therefore, results from this study suggest that it is theoretically possible to develop one model form for bacterial inactivation in widely changing moisture products.

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CHAPTER 1: INTRODUCTION

1.1 Foodborne Outbreaks from Ready-To-Eat (RTE) products

Foodborne illness is an ongoing global problem, annually affecting approximately 600 million people worldwide, according to the World Health Organization (*108*). In the United States (US), the Centers for Disease Control and Prevention (CDC) estimated that 48 million illnesses are annually associated with foodborne agents (*15*), in which fresh fruits and meat products, such as chicken, pork, beef, and turkey, are the top five food categories associated with outbreak-related illnesses (*31*). In those foodborne outbreaks, *Salmonella* and *Listeria* are among the most well-known bacterial agents, responsible for a total of 210 outbreaks between 2019 and 2020 (*26*). *Salmonell*a is a gram-negative bacterium naturally found in the intestinal tract of animals, which can contaminate foods through soil, water, and equipment (*5*, *12*, *46*, *50*, *58*, *63*, *74*), and then grow if conditions such as pH, temperature, and water activity (a_w) are favorable (*41*, *56*). Data from the CDC FoodNet show that *Salmonella* is the bacterial pathogen that causes the most foodborne infections and deaths in the US (*30*). While *Salmonella* foodborne outbreaks have been associated with various products, such as fruits and vegetables, low-moisture foods, and meat products, outbreaks related to meat are among the most common, accounting for an overall economic cost of $4.7 billion in pork and chicken alone (*67*). Foodborne outbreaks linked to *Listeria* are not as common as *Salmonella*. However, because of the high mortality rate of listeriosis (*104*), *Listeria* causes the second most deaths due to foodborne illnesses in the US (*30*). *Listeria*-related outbreaks have been most often traced to RTE meats (*27*, *28*, *29*), dairy products (*16*, *17*, *22*, *23*), fruits, and vegetables (*18*, *19*, *20*, *21*, *24*, *32*).

Given the persistent issue of foodborne illnesses, federal agencies, such as the US Food and Drug Administration (FDA) and the US Department of Agriculture Food Safety and Inspection

Service (USDA FSIS), recognize that food safety is a shared responsibility among stakeholders involved in the food supply chain. Therefore, in addition to recommending safe food handling practices for consumers (*91*, *95*), the FDA and USDA FSIS also require food processers to demonstrate and validate pathogen reductions in various food commodities. These specific regulations are governed by several federal acts, such as the Federal Meat Inspection Act for meat products, the Poultry Products Inspection Act for poultry products, the Egg Products Inspection Act for egg products, and the Food Safety Modernization Act for other food products (*89*, *96*).

1.2 *Salmonella* Lethality Requirement for RTE Meat

Food safety requirements for some RTE meat products have been codified and published in the Federal Register. For example, the Code of Federal Regulation 9 CFR 318.17(a)(1) requires that RTE beef processing, including cooked beef, roast beef, and cooked corned beef, must achieve a 6.5 log reduction of *Salmonella* (*34*). Moreover, for uncured meat patties, 9 CFR 318.23 provides a minimum internal temperature/minimum holding time combination under which fully cooked patties must be processed (*35*), in order to achieve a 5 log reduction of *Salmonella* and other pathogens, such as shiga toxin-producing *E. coli* (*90*). Lastly, for fully cooked poultry products, a 7-log reduction of *Salmonella* must be met according to 9 CFR 318.150(a)(1) (*36*). For other RTE meat products, such as cooked bacon, that were not covered by the described regulations, FSIS (*90*) recommended a 6.5 log reduction for *Salmonella* or a 5-log reduction with additional support or testing to meet the 9 CFR 417 requirements for hazard analysis and critical control points (*33*).

1.3 Food Safety Modernization Act (FSMA) for Other Foods

Adopted in 2011, FSMA codified a more integrated and preventative approach to food safety (*93*, *96*). To achieve this goal, FSMA was implemented by FDA as a series of different rules, such as the Preventive Controls for Human Foods Rule (*98*). This rule requires food processing facilities to have risk-based food safety plans for pathogen control (*98*). All food products belonging to categories regulated by FDA are subject to FSMA. These include fresh produce and low-moisture foods, such as dried fruits, but exclude meat, poultry, and fresh eggs, which are regulated by the USDA (*102*).

1.4 Microbial Safety of Bacon and Dried Apple: Knowledge Gap

Cooked bacon and dried apples are two very different products, but they undergo similarly wide moisture changes during processing. Both bacon and dried apple processing sufficiency are standardized based on the endpoint yield or moisture of the product, rather than time-temperature requirements. USDA labeling policy requires that bacon can only be labelled as fully cooked if cooked to a final yield of ≤ 40% (*88*, *92*). Similarly, for dried apples, the moisture content of the final product must not exceed 24% (wet basis (wb)) (*82*). In both bacon and apple, as long as the standards for yield and moisture content are met, industries can use a range of commercial processing methods and conditions. However, without appropriate process validation, this could result in food safety concerns.

For example, for apples, several methods, such as sun drying, microwave drying, or oven drying, are used, in which each processor, either small- or large-scale, uses different parameters (e.g., temperatures and air velocity) depending on their preference and capacity. Even though these various drying methods might result in a similar final moisture content of the apple

products, they might not yield similar pathogen reductions (*7*). As an illustration, when apples were previously dried at 104 or 135°C, >5 log reduction of *Salmonella* was achieved by the end of drying (*45*). However, in another study, only a 2.8-log reduction was achieved when apples were dried at 60°C to a similar a_w (*39*). Therefore, because the FSMA Preventative Controls Rule applies to dried apples, evaluating pathogen reductions under those different processing methods and conditions is critical for regulatory compliance.

Microwave cooking of bacon has become among the most common processing methods used by industries (*51*), in addition to moist-air convection-oven cooking. However, given the FSIS recommendation for *Salmonella* lethality in RTE meat products such as bacon (*90*), less scientific evidence is currently available regarding pathogen behavior under microwave cooking. Consequently, FSIS has recently identified *Salmonella* lethality in bacon undergoing microwave cooking as a specific knowledge gap and has encouraged performing challenge studies (*90*).

Another similarity between cooked bacon and dried apples is that they both undergo very wide changes in moisture during processing. During bacon cooking, moisture evaporates and fat is rendered out of the product, decreasing the cook yield, based on total mass. Similarly, in apple drying, moisture is removed as the drying process progresses, via mass convection at and diffusion to the surface. In both cases, the process starts with a high-moisture product and ends with a low-moisture product. As the temperature of the product increases, higher pathogen inactivation would be expected. However, because of the complex coupled heat and mass transfer processes, as the temperature increases, moisture content decreases. Studies have shown that pathogens such as *Salmonella* become more heat resistant in lower-moisture products (*2*, *4*, *43*, *49*, *52*, *66*, *72*, *76*, *78*, *107*, *109*, *110*). Consequently, when the process involves a dynamic decrease in moisture, such as in apple drying and bacon cooking, there is a constant tradeoff of

increasing temperature to inactivate pathogens, but also removing moisture and therefore simultaneously increasing the thermal resistance of pathogens (*7*). The question is how to identify the critical points where pathogen inactivation is sufficient when dealing with dynamic changes in moisture over time in a process. Previous studies working on the effect of moisture content or a_w on pathogen inactivation focused more on controlled systems, in which one variable at a time was assessed, such as in isothermal studies (*2*, *4*, *43*, *66*, *72*, *76*, *109*, *110*). Additionally, those studies were mostly done on products that already had low moisture, such as almond kernels, wheat flour, ground cinnamon, and protein powder, which is different from starting with a high-moisture product, such as freshly sliced apples or bacon. Therefore, although the insights from those prior studies are important to understanding pathogen thermal resistance in low-moisture foods, their applicability is limited when dealing with dynamic processes involving very wide changes in both temperature and moisture.

1.5 Goal and Objective

The goal of this study was to evaluate the phenomenological similarity between *Salmonella* and *Listeria monocytogenes* thermal inactivation across two very different food products (cooked bacon and dried apples) with similarly wide changes in moisture during processing. To achieve this goal, the objectives of this study were:

1) To quantify the thermal inactivation of *Salmonella* in bacon cooked in an impingement oven under industry-typical conditions.
2) To quantify the thermal inactivation of *Salmonella* in bacon cooked in a microwave oven to an industry-typical product endpoint.
3) To quantify the impact of air drying temperature and velocity on the inactivation of *Listeria monocytogenes* during drying of apple slices.

CHAPTER 2: LITERATURE REVIEW

2.1 Bacon

2.1.1 Bacon Processing

Pork products such as RTE bacon are the third most consumed meat in the US (*86*). With only two outbreaks reported between 1998 and 2015 (*68*), bacon has a long record of being a microbiologically safe product. Sliced bacon is cooked using pan frying, conventional oven, or microwave oven, in which the yield must be ≤ 40% to be labeled as fully-cooked (*88*, *92*). For microwave cooking, which is the most used method commercially, James et al. (*51*) showed that power-output, heating time, and position of the slices in the oven all affect the quality of RTE bacon. However, they assessed quality only subjectively, based on factors such as the degree of doneness and crispiness (*51*). An industrial microwave oven with a 2450 MHz frequency and 6 kW power output was used, and results showed that by using a 2.2 kg load of sliced bacon, optimal bacon quality was obtained around 115 s (*51*). Although such information may be useful to the industry in optimizing processes, validation for sufficient *Salmonella* lethality (6.5 log reduction) is needed, as indicated by scientific gaps identified in the recently revised USDA-FSIS Revised Appendix A (*90*).

2.1.2 Microbial Inactivation Studies for Bacon

Prior studies on bacon safety have used both thermal and non-thermal methods to evaluate pathogen inactivation (*8*, *10*, *11*, *37*, *70*, *77*). A methicillin resistant *Staphylococcus aureus* (MRSA) inactivation study in bacon under home-cooking conditions showed that grilling bacon slices at 177°C for 5 min resulted in ≥6.5 log reduction of MRSA (*11*). Results from that study can be useful to inform consumer practices on safe bacon handling and cooking. However,

from a regulatory perspective, MRSA is not the target pathogen in bacon (*90*), and a >6.5 log reduction of MRSA may not directly translate to a similar reduction of *Salmonella.* Additionally, grilling is not a common industrial, large-scale method, which restricts the applicability of the information. Other thermal inactivation studies focused more on bacon slab processing, which is traditionally a partially-cooked product obtained from slow heating and smoking of cured pork bellies (*77*). Smoked bacon slabs are usually then used to make raw bacon slices (*77*). Most survival studies on bacon slabs have investigated the behavior, growth, or inhibition of bacterial pathogens such as *Clostridium perfringens*, *Escherichia coli*, *Listeria monocytogenes*, MRSA, *Salmonella enterica*, and *Staphylococcus aureus* during cooking, smoking, or cooling (*8*, *11*, *37*, *70*, *77*). Because the endpoint of these processes results in a partially-cooked bacon slab or smoked raw bacon slices, none of these studies answer the question about pathogen reduction during subsequent cooking.

A non-thermal approach also has been investigated for its effectiveness on pathogen inactivation during bacon processing. By using non-thermal atmospheric pressure-plasma (NTAP), Calvo et al. (*10*) obtained only a 1.3 log reduction of *Salmonella* on sliced bacon after a 15 min treatment. Moreover, NTAP is currently not common in industry.

In summary, a significant knowledge gap exists in the literature, with no prior study having systematically evaluated *Salmonella* thermal reduction during cooking of RTE bacon in commercial-type conditions, which is essential for process validations as identified by the USDA-FSIS.

2.2 Dried Apple

2.2.1 Apple Drying

Apples are the most available fruit for consumption in the US (*85*), with an average annual production of 4.4 billion kg (*87*). Whereas some are distributed directly to consumers as fresh apples, 37% of harvested apples are further processed (*87*). Data from the US Department of Agriculture Economic Research Service (USDA ERS) show an average production of 113 million kg of dried apples (*87*), demonstrating the importance of the apple drying industry in the US. According to the US standards of identity, dried apples are defined as apples that undergo some drying process in which the final moisture content must not exceed 24% (wet basis (wb)) (*82*). Common drying methods include sun drying, conventional hot-air oven drying, microwave drying, and vacuum drying. In most of these methods, factors such as temperature and air velocity affect the rate of drying and therefore likely affect microbiological outcomes.

Unlike the regulation of RTE meats, where a specific log reduction of *Salmonella* is required (*42*), no specific target pathogen or reduction has been established for dried apples or other fruits. This might be because dried apples have had a long history of being a safe product without reported outbreaks. However, recent outbreaks and recalls in other dried fruits show the need for ensuring pathogen reduction during fruit drying. For example, a *Salmonella* outbreak associated with dried coconut was reported in 2018 (*25*), and freeze-dried sliced fruits (*100*) and dried apricots (*103*) were recalled due to potential contamination of *Salmonella* and *Listeria monocytogenes*, respectively. Additionally, listeriosis outbreaks from caramel apples in 2015 (*32*) and 2017 (*59*), along with several recalls of whole (*99, 101*) or sliced apples (*94, 97*), show that *Listeria monocytogenes* is an emerging pathogen of concern in apple products. The Food Safety Modernization Act (FSMA) final rule for Preventive Controls for Human Foods,

implemented by the US Food and Drug Administration (FDA), also requires food processing facilities, such as apple drying facilities, to have risk-based food safety plans for their processes (*98*). Therefore, there is a need to validate commercial practices for apple drying to ensure sufficient inactivation of key pathogens.

2.2.2 Microbial Inactivation Studies for Dried Apples

Previous apple drying inactivation studies have focused only on *Salmonella* and *E. coli* and did not include *Listeria*. These studies have shown that conditions such as temperature, pre-treatment method, and apple variety are critical factors in inactivation. When drying apples at 60°C for 6 h, Dipersio et al. (*39*) reported only up to a 2.8 log reduction of *Salmonella*. Likewise, drying apples at 57.2°C and 62.8°C for 6 h reduced *E. coli* population by 2.9 and 3.3 log, respectively (*9*). Similar *E. coli* reductions were reported in another study conducted at 62.8°C for 6 h (*38*). In contrast, at higher drying temperatures of 104 and 135°C, Grasso-Kelley et al. (*45*) reported > 5 log reduction of *Salmonella* in apples. In some of these studies, the final a_w of the apples was similar, but the log reduction was different because of the drying temperature. For example, in Grasso-Kelley et al. (*45*), the final a_w that corresponded to the > 5 log reduction of *Salmonella* was 0.247 ± 0.070 at 104°C. In Dipersio et al. (*39*), the final a_w was between 0.229 and 0.257 at 60°C; however, the *Salmonella* reduction was lower, as illustrated above. Therefore, pathogen inactivation during apple drying depends on the history of drying, such as temperature and drying time, not necessarily just the endpoint state, defined by the standard as moisture content. This means that following a standard moisture content for dried apples may not necessarily translate to sufficient pathogen inactivation.

Several studies on apple drying also assessed the use of various pre-treatment methods in which the use of acidic solutions was reported to have enhanced the reduction of *Salmonella* and *E. coli* due to their antimicrobial properties (*9*, *38*, *39*, *47*), whereas methods such as steam blanching were shown to have no effect (*9*). Only one of these prior studies controlled air velocity, where a low 0.4 m/s air velocity was used during drying. Given that air velocity is an important factor in drying kinetics of foods, especially in fruits and vegetables (*55*, *57*, *79*, *106*), and that air velocity has been shown to impact the inactivation of pathogens such as *E. faecium* and *Salmonella* in low-moisture foods (*44*, *64*), examining the impact of drying air velocity on bacterial survival during apple drying is also needed.

2.3 Effect of Moisture on Pathogen Inactivation

In food processing, there are two possible sources of moisture. Moisture can be intrinsic to the food product itself and is usually quantified in terms of a_w and/or moisture content. However, moisture can also be introduced during hot-air processing (e.g., water vapor / steam injection) as an extrinsic factor. Previous studies have shown that both forms of moisture can affect pathogen inactivation in food (*2*, *4*, *13*, *14*, *43*, *49*, *52*, *66*, *72*, *76*, *78*, *107*, *109*, *110*); however, for the purpose of this literature review, only the effect of product moisture and/or a_w on pathogen inactivation was investigated.

Studies on various low-moisture food products have shown that *Salmonella* becomes more thermally resistant when a_w is low. Although the mechanism of such resistance is not entirely understood, Spector and Kenyon (*73*) hypothesized that *Salmonella* initiates a stress response mechanism to persist under various environmental conditions, such as desiccation. When wheat flour was isothermally heated at 80°C, Smith et al. (*72*) reported a D-value of 1.27 ± 0.06 min at 0.582 a_w. However, when the a_w was reduced to 0.310, the D-value increased to 10.27 ± 0.65

min. Similar increased resistance of *Salmonella* was observed in other studies involving low-moisture foods, such as pistachios, almonds, and protein powder (*1*, *2*, *39*, *46*, *54*, *61*, *63*, *88*, *90*, *91*). Although *Salmonella* has been the most reported pathogen to exhibit increased resistance in low-moisture environments, studies have shown that *L. monocytogenes* can also develop similar resistance in low-moisture foods, such as cocoa powder. Tsai et al. (*80*) reported D-values of 3.4 ± 0.2 and 11.0 ± 0.5 min at 75°C in cocoa powder, at a_w 0.45 and 0.30, respectively. Similarly, another study investigating the thermal resistance of *Salmonella*, *E. coli,* and *Listeria* in pistachios demonstrated that although *Salmonella* showed the greatest resistance among those pathogens during drying, all of the pathogens showed similar thermal resistance in pistachios when exposed to hot water or hot oil at 80 and 121°C, respectively (*60*).

The effect of a_w on pathogen thermal resistance in low-moisture food may depend on other factors, such as the food composition. Jin et al. (*110*) reported a complex interaction of temperature, food components, and a_w on *Salmonella* thermal resistance in different food matrices. For instance, at a_w 0.9 and 52-90°C, D-values were larger in high-protein matrices than in high-fat matrices (*110*). However, at a_w 0.50 and > 77.4°C, the D-value was larger in high-fat matrices than in high-protein matrices (*110*). This shows product composition is another critical factor in understanding thermal resistance of pathogens in low a_w foods.

In most of the aforementioned studies, the effect of a_w was evaluated under isothermal heating. However, isothermal conditions are rarely consistent with commercial food processes, in which the temperature and moisture of the product may dynamically change over time. Additionally, the effect of a_w on pathogen inactivation was often investigated only at discrete a_w values and did not include changes in moisture during the entire process.

Additionally, most food products used in prior studies were already low-moisture products and did not account for raw products with high moisture content being processed to a low-moisture end-product. Casulli et al. (*14*) showed that increasing the initial moisture content of pistachios affected *Salmonella* resistance. In this study, by soaking pistachios in pure water or in 27% NaCl solution to a moisture content of up to 21.3 % (dry basis (db)), thermal treatment of the pistachios achieved a 4-log reduction 55 to 85% faster than when the pistachios contained 6% moisture (db) (*14*). This shows that initial product moisture content may need to be considered in pathogen inactivation. A subsequent part of that study also modeled *Salmonella* inactivation in pistachios under different temperature-humidity conditions and incorporated dynamic moisture and a_w in their models (*13*). Although that study included dynamic moisture in inactivation models, applicability may be limited for products with much higher moisture content, such as apples. Therefore, there is a need to evaluate inactivation of pathogens under widely changing moisture conditions in food products with high initial moisture content.

2.4 Summary

Although RTE bacon and dried apples are two very different products, the existing literature has shown that both products need process validations, given the food safety regulations established by USDA FSIS Appendix A and FSMA Preventive Controls Rules for Foods, respectively. For bacon, although microwave cooking can provide quality RTE bacon, FSIS has identified *Salmonella* lethality in bacon microwave cooking, where humidity is not controlled, as a scientific knowledge gap. For apples, recent *L. monocytogenes* outbreaks from caramel apples have demonstrated that this pathogen could be a potential concern in RTE apple products. However, current studies in apple drying have only focused on inactivation of *Salmonella* and *E. coli*. Thus, there is a need to assess *L. monocytogenes* reduction during apple

drying. Additionally, the effect of air velocity should be assessed, because it can affect both the drying and inactivation rate.

This literature review also has shown that product moisture can affect the inactivation of pathogens, such as *Salmonella* and *Listeria*, in low-moisture foods. As water activity decreases, pathogens become more heat resistant. Prior studies also have indicated that other factors such as the food matrix composition may play a role in this effect. However, in most of these studies, isothermal and iso-moisture conditions were used, which may not realistically reflect most industrial processes, in which moisture changes dynamically.

Therefore, there is a need to address this knowledge gap, of pathogen inactivation under widely changing moisture conditions, while assessing the thermal inactivation of *Salmonella* in commercial bacon processing and *L. monocytogenes* during apple drying, for purposes related to process validation, regulatory compliance, and an improved understanding of the dynamic moisture effects on pathogen thermal resistance.

CHAPTER 3: THERMAL INACTIVATION OF *SALMONELLA* DURING BACON PROCESSING

3.1 Materials and Methods

3.1.1 Overall Study Design

This study consisted of two main treatments: microwave and impingement oven cooking. In each treatment, bacon slices were cooked to a commercial target of 40% yield, and *Salmonella* lethality was assessed relative to a 6.5 log reduction target. Because large sample-to-sample variability was observed in *Salmonella* inactivation during microwave cooking, an additional experiment was conducted to determine whether this variability might be attributable to variability in lean and fat content. Therefore, *Salmonella* inactivation was compared in the lean and fat portions of the bacon under microwave cooking. Additionally, with microwave cooking being the most common industrial method for the production of RTE bacon, and the knowledge gap mentioned in USDA FSIS Revised Appendix A (*105*) on whether humidity is important in this case, a separate experiment was conducted to determine whether humidity influenced *Salmonella* inactivation in bacon cooked in a microwave oven.

3.1.2 Sample Preparation

Bacon slices 3.0 ± 0.5 mm thick (~ 30 g / slice) were prepared by the Michigan State University Meat Laboratory to replicate raw-smoked commercial bacon. Vacuum-packed bacon slices (0.5 kg per pack) were stored at -20°C and later thawed overnight at 4°C before each experiment. Slices with approximately the same lean and fat content by visual inspection and were selected to minimize variability of the treatments, especially in terms of microwave power distribution during cooking.

3.1.3 Culture Preparation and Inoculation

Eight strains of *Salmonella*, identical to the original cultures used to inform USDA FSIS Appendix A (*54*), were used in this study: *Salmonella* Typhimurium DT104 H3380, *S.* Hadar MF60404, *S.* Copenhagen 109 8457, *S.* Enteritidis 108 H3527, *S.* Enteritidis 108 H3502, *S.* Thompson FSIS 120, *S.* Montevideo FSIS 051, and *S.* Heidelberg F5038BG1. The cultures were stored in tryptic soy broth (TSB; Becton Dickinson, Sparks, MD) containing 20% glycerol (v/v) at -80°C. Working cultures were obtained by transferring each strain to TSB, followed by 24 h of incubation at 37°C. One milliliter of each working culture was then spread separately on tryptic soy agar plates (TSA; Difco, BD) for confluent growth. After 24 h of incubation, each strain was harvested in 10 mL of 0.1% buffered peptone water (Difco, BD, Franklin Lakes, NJ), combined in one centrifuge bottle, pelletized (3000 x *g* for 15 min), and the pellet was resuspended in 100 ml of 0.1% peptone water to obtain the inoculum.

Bacon slices were placed on a tray covered with aluminum foil. Each slice was inoculated by spreading 1 mL of inoculum on one side using a L-shaped spreader. After 20 min in a biosafety cabinet, the slices were flipped, and the other side was inoculated similarly. Inoculated slices were placed in sample bags and kept at 4°C until cooking (up to 2 h).

3.1.4 Microwave Oven Treatment

A 2450 MHz microwave oven (LMC2075XX , LG Electronics, Denver, CO, USA) with a maximum power output of 1200 W was set to 80% power to produce fully-cooked products (yield < 40%) at ~120 s, which matched a typical commercial-scale microwave cooking time (*51*). Samples were cooked in batches of 2 slices, for 30, 45, 60, 90, 120, and 150 s, with ≥6 biological replications and 2 subsamples per replication, in which the 2 subsamples were the 2

slices in a cooking batch. Two subsamples were used to quantify spatial variability in heating among the slices. Prior to cooking, each slice was weighed, and 2 slices were placed on a microwave tray (Microware Nordic Ware, Minneapolis, MN, USA) as one batch. Before cooking, each inoculated slice was weighed, and then a 4-cm piece of each slice in a batch was pre-cut for a_w and moisture content (MC) analysis later after cooking, and placed back in position with the rest of the full slice prior to cooking. After each time point during cooking, an infrared camera (TiR3FT Fluke, Everett, WA, USA) was used to immediately (< 30 s) capture a thermal image of each slice. The infrared camera was set up on a tripod next to the oven at a vertical distance of ~40 cm above the samples. Images were taken under room lighting 20-30 s after the samples were removed from the oven. Afterwards, the 4-cm pieces of the cooked slices were placed in sample bags for MC and a_w analysis, and the remaining portion of each slice was immediately submerged in 50 mL of chilled 0.1% peptone water to stop further *Salmonella* inactivation. Three inoculated, uncooked slices per run were used as untreated controls.

This specific microwave treatment is hereafter referred to as the "humid" condition, as humidity increased significantly inside the oven, due to water vapor leaving the product, and was not controlled or artificially reduced. In all treatments, cooking yield was measured as the mass of the bacon after cooking divided by the initial mass and multiplied by 100.

3.1.5 Impingement Oven Treatment

Another set of samples was cooked in a pilot-scale impingement oven (JBT FoodTech, Sandusky, OH), at 60% humidity (v/v) (corresponding to a dew point of 87.4°C), 0.7 m/s exit jet velocity (corresponding to 20% fan speed) and dry bulb temperature of 177°C or 232°C for up to 600 s, with 6 biological replications and 2 slices per replication. The cooking parameters were

chosen to approximate commercial oven conditions. Samples were cooked for 60, 120, 180, and 600 s at 177°C, or 60, 90, 120, and 360 s at 232°C. The different cook times at the two temperatures were chosen to achieve similar endpoint cooking yields. Two inoculated bacon slices per batch were put on a metal rack that was conveyed into the oven, with the same procedure as described above for microwave cooking followed for a_w and MC analyses. In terms of temperature measurement, one T-type temperature probe (32 gauge) was used to measure oven air temperature, and two T-type thermocouples (36 gauge) were each inserted just below the surface (1-2 mm depth) of the bacon – one into the lean portion, and the other into the fat portion. The thermocouples and probes were connected to a data logger covered by a thermal shield (Multipaq21, Fluke, Salem, NH), and temperature data were collected at a 5 s interval. Infrared images of the slices were also taken immediately (30-40 s) after the samples exited the oven, to compare the endpoint temperatures of the impingement-cooked and microwave-cooked samples.

3.1.6 Comparison of *Salmonella* Inactivation in the Lean and Fat Portions of Bacon

Bacon slices were inoculated as described above. The lean and fat portions were then manually separated using a sterile scalpel, and weighed to obtain ~30 g of each. One lean and one fat portion were placed together on a microwave tray and cooked for 30, 45, 60, and 90 s under similar microwave conditions as the baseline microwave experiment. The cook times 120 and 150 s were excluded from the comparison, because most samples cooked at those times had *Salmonella* survival below the limit of detection (LOD) of 0.6 log CFU/g. After cooking, a 4-5 g portion of each lean and fat sample was used for a_w and MC analysis, with the remaining portions immediately placed in 50 mL of chilled 0.1% peptone water.

3.1.7 Effect of Humidity on *Salmonella* Inactivation during Bacon Microwave Cooking

To reduce the humidity during microwave cooking, dry air was forced through a 1-cm diameter hole in the side wall of the oven, above the tray where the bacon slices were placed, and diagonally opposite the magnetron where the microwaves were propagated. Oven air then exited the oven cavity through a vent at the farthest point from the inlet (top and back of the opposite side wall). The flow rate was set at ~0.2 L/s by volume displacement. Humidity of the inlet and exit air was measured using a dew point sensor (Vaisala DMT346, Finland). The inlet air had a humidity ratio of 2 g of water / kg of air, which was equivalent to a relative humidity of 1.2% at ~25.6°C and a dew point of -29.7°C.

To measure oven air for humidity, a 1-cm diameter hole was made through the chamber top. A 60-cm siphon tube (0.75 cm i.d.) connected this hole to the inlet of a positive displacement pump (DOL-101-AA, Gast Manufacturing Inc, Harbor, MI), through which air was drawn in and then discharged through an outlet. Another siphon tube, 45-cm long, was used to move the discharged air from the pump outlet to a sealed box, referred to as the collector, containing the aforementioned dew point sensor. When tested, the sensor response time to a change in oven humidity was approximately 2-3 s. The air exiting the collector was passed through a column containing 75% ethanol to eliminate any *Salmonella* before being released to into the lab environment. The system is illustrated by the simplified diagram in Figure 1.

To maintain the dew point below 32°C inside the oven during cooking, both dry air purging as described above and a reduction in sample size was needed, which simultaneously reduced the amount of water vapor being evaporated into the oven air during cooking. Therefore, each bacon slice was divided into 4 pieces weighing ~7.5 g each, with two bacon pieces used per batch. Bacon slices were inoculated using the same procedures as described earlier. Two full-

sized inoculated slices were used as in the main microwave cooking experiments; however, instead of cooking the two full slices at once, pairs of quarter-sized slices were cooked separately. After cooking, an infrared thermal image was taken to record the temperature. The first three cooked pieces from each slice were immediately combined and added to 50 mL of chilled 0.1% peptone solution, for subsequent *Salmonella* enumeration with the fourth piece used for MC and aw analysis.

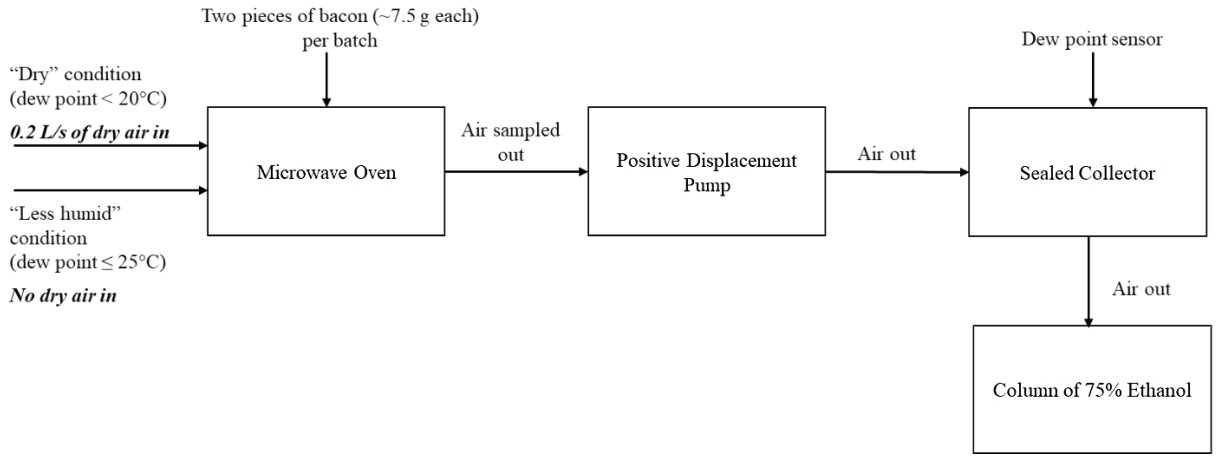


Figure 1: Diagram of the humidity control system during microwave cooking of bacon

Preliminary cooking trials again were conducted to determine the appropriate microwave power setting (30%) to achieve the target cooked product yield (< 40%) at a commercially relevant cooking time. Therefore, the experiment was conducted at 30% power for 45, 60, and 150 s. Two main treatments were used: (1) a dry condition with dry air pushed through the microwave at 0.2 L/s during cooking, and (2) a less humid condition using the smaller sized sample but with no dry air forced through the system. In both treatments, the dew point was recorded every 10 s during cooking. Before each experiment, the ambient conditions (dry bulb temperature, relative humidity, and dew point) were measured. The dew point in the collector also was checked by measuring the air inside the oven before each the experiment, with the oven

off and closed, using a handheld dew point meter (EXTECH Instruments, HD500, Nashua, NH). On average, the dew point measured by the meter was only 0.7°C higher than that of the air sampling / collector system.

3.1.8 *Salmonella* Enumeration, Moisture Content, and Water Activity Analyses

As mentioned above, when each bacon slice was divided into four equal pieces, three of the pieces were combined for *Salmonella* enumeration after cooking. The fourth piece, after undergoing each cooking treatment, was used for MC and a_w analysis.

After each treatment, samples were submerged in 50 mL pre-chilled 0.1% peptone solution, which corresponded to a dilution ratio of ~1:5 based on preliminary experiments. After homogenizing for 2 min (IUL Masticator Silver, 400 ml, IUL S.A., Barcelona, Spain), the samples were serially diluted in 0.1% peptone water and plated on a differential, non-selective medium composed of tryptic soy agar supplemented with 0.05% ammonium citrate, and 0.03% sodium thiosulfate (FTSA; Difco, BD), to enumerate both healthy and sublethally injured cells of *Salmonella*. All black colonies were counted as *Salmonella* after 48 h of incubation at 37°C. The limit of detection (LOD) was 0.6 log CFU/g.

Duplicate analyses were conducted for a_w (Aqualab 4TE, Pullman, WA, USA) and MC following AOAC method 950.46B (*3*).

3.1.9 Statistical Analyses

Temperature data from the infrared images were analyzed over time and across the bacon surface area (SmartView 7.0 software, Fluke Corporation, Everett, WA, USA). The area of each bacon slice was outlined using the visible-wavelength image, and temperature (average,

minimum, and maximum) was analyzed within those defined areas using the corresponding infrared image.

Assumptions for all data analyses, such as normality and equal variance, were verified (SAS 9.4, SAS Institute Inc., Cary, NC, USA), and ANOVA ($\alpha = 0.05$) was used to test the effect of the studied conditions (microwave cooking across different time points, impingement oven cooking at two temperatures across different time points, bacon fat vs. lean across different time points, and "humid" vs. "less humid" vs. "dry" conditions) on MC, a_w, yield, and *Salmonella* reduction. Tukey multiple means comparisons were conducted within each treatment across the corresponding cook times. T-tests ($\alpha = 0.05$) were also used to compare *Salmonella* lethality to the 6.5 log reduction target (*42*). In terms of bacterial enumeration, samples that had plates with nondetectable counts were replaced with the limit of detection (0.6 log CFU/g) before proceeding to data analysis. All the statistical analyses were performed in SAS 9.4 using the function PROC MIXED.

3.2 Results and Discussion

3.2.1 Microwave Oven Cooking

Moisture content, a_w, and yield decreased significantly in the bacon slices during cooking ($P < 0.05$), as expected (Table 1). Using microwave cooking, the 40% target yield was achieved at 150 s, which was similar to typical commercial processing. A t-test comparison showed that the final yield of 37.3% at 150 s was similar to the yield after 600 s of impingement cooking at 177°C ($P > 0.05$). However, the MC of the microwave-cooked slices was higher ($P < 0.05$) than that of the impingement-cooked slices (Table 2) ($P < 0.05$), due to the forced-air convection drying.

The population of the *Salmonella* inoculum was ~10 log CFU/mL, and after inoculation, 9.1 ± 0.3 log CFU/g initial population was obtained in the bacon slices. *Salmonella* lethality in the bacon slices increased during microwave cooking ($P < 0.05$) as expected, with the largest variability at 60 s. By 90 s, *Salmonella* decreased > 6.5 logs ($P < 0.05$), at which time the yield was 54% (Table 1), and not yet "fully cooked." The corresponding surface temperature was 89.6 ± 2.1°C (Figure 2).

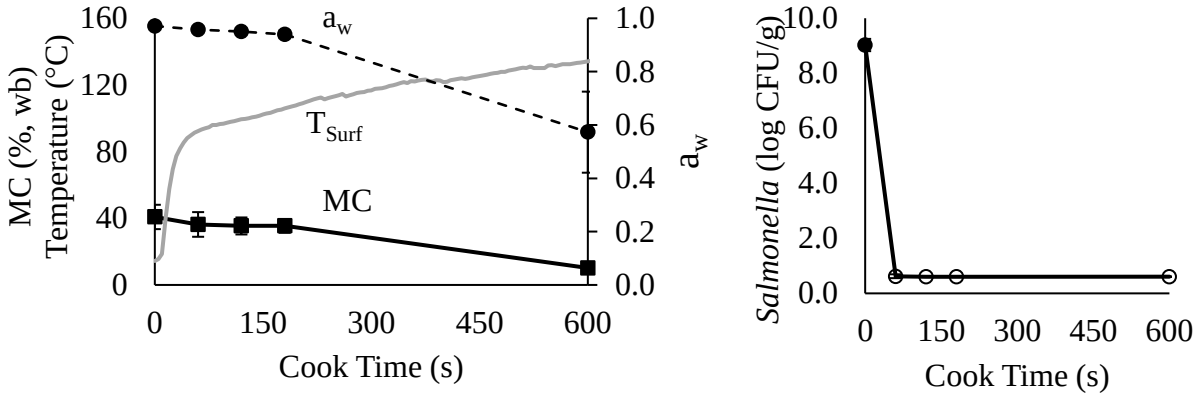
Table 1: Moisture content, water activity, cooking yield, and *Salmonella* reduction in bacon slices during microwave cooking

Cook Time (s)	Moisture Content (% water)	Water Activity	Cooking Yield (%)	*Salmonella* Reductions (log CFU/g)
0	41.5 ± 7.7** *a**	0.974 ± 0.006*a*	-	-
30	39.3 ± 9.0 *ab*	0.957 ± 0.028 *b*	85.9 ± 1.8 *a*	1.0 ± 0.2 *d*
45	35.5 ± 3.9 *b*	0.940 ± 0.015 *c*	72.9 ± 2.7 *b*	3.1 ± 1.1 *c*
60	36.1 ± 5.9 *b*	0.933 ± 0.018 *c*	64.6 ± 3.3 *c*	6.8 ± 1.7 *b*
90	32.0 ± 4.9 *c*	0.909 ± 0.029 *d*	54.1 ± 3.5 *d*	8.5 ± 0.6 *a*
120	25.9 ± 4.1 *d*	0.829 ± 0.054 *e*	44.5 ± 3.1 *e*	8.4 ± 0.6 *a*
150	18.9 ± 3.9 *e*	0.758 ± 0.079 *f*	37.3 ± 3.7 *f*	8.6 ± 0.1***

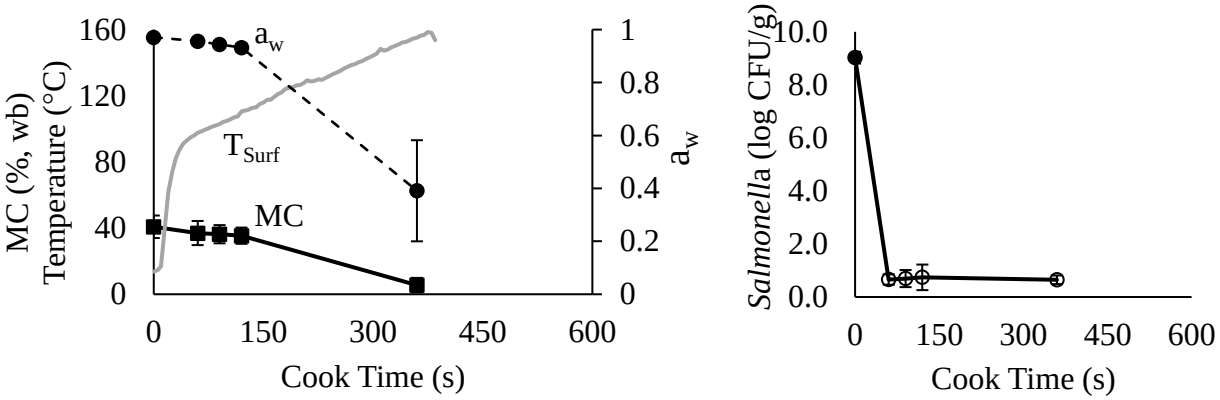
*Means followed by the same letter *within a column* are not significantly different ($\alpha = 0.05$)
** Mean ± standard deviation
*** ≥ 95% of plated samples were below the limit of detection (< 0.6 log CFU/g), therefore the '150 s' time point was excluded from the multiple comparison

By the time the microwaved bacon slices were fully cooked (150 s), the temperature was approximately 100°C, as recorded by the infrared camera (Figure 3). This temperature was similar to the temperature of the impingement oven cooked slices taken from the infrared images at the end of cooking (100.0 ± 5.6 °C after 600 s at 177°C cooking temperature and 105.4 ± 2.4 °C after 360 s at 232°C) (Figures 3B and 4). Additionally, heating across the two slices per batch was reasonably homogenous during both microwave and impingement cooking (Figure 3).

Impingement oven cooking (177°C, 0.7 m/s, 60% v/v, dew point 87.4°C)



Impingement oven cooking (232°C, 0.7 m/s, 60% v/v, dew point 87.4°C)



Microwave oven cooking ("humid" condition, dew point > 35°C)

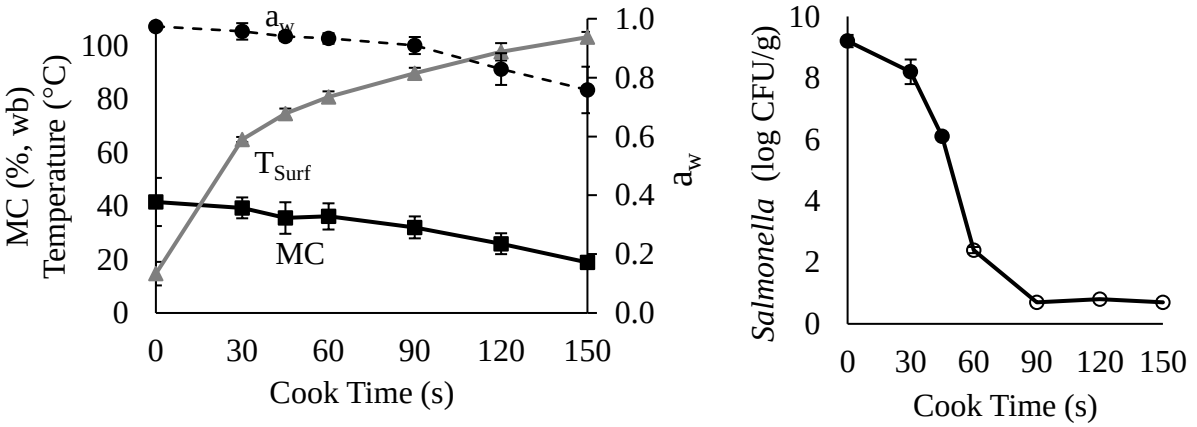


Figure 2: Water activity, moisture content, surface temperature, and *Salmonella* populations during impingement and microwave cooking of bacon. The open circles in the *Salmonella* population curves indicate that one or more samples were below the limit of detection (0.6 log CFU/g).

Figure 3A: Infrared images of microwave-cooked bacon slices

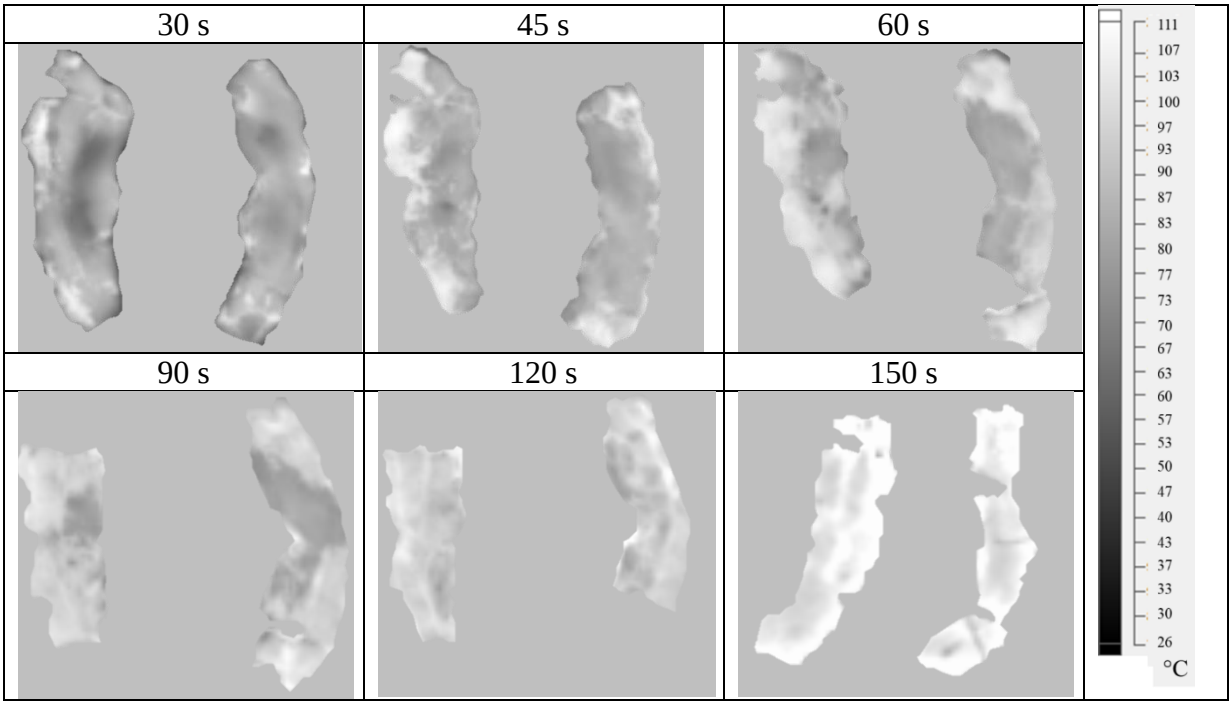


Figure 3B: Infrared images of bacon slices cooked in the impingement oven

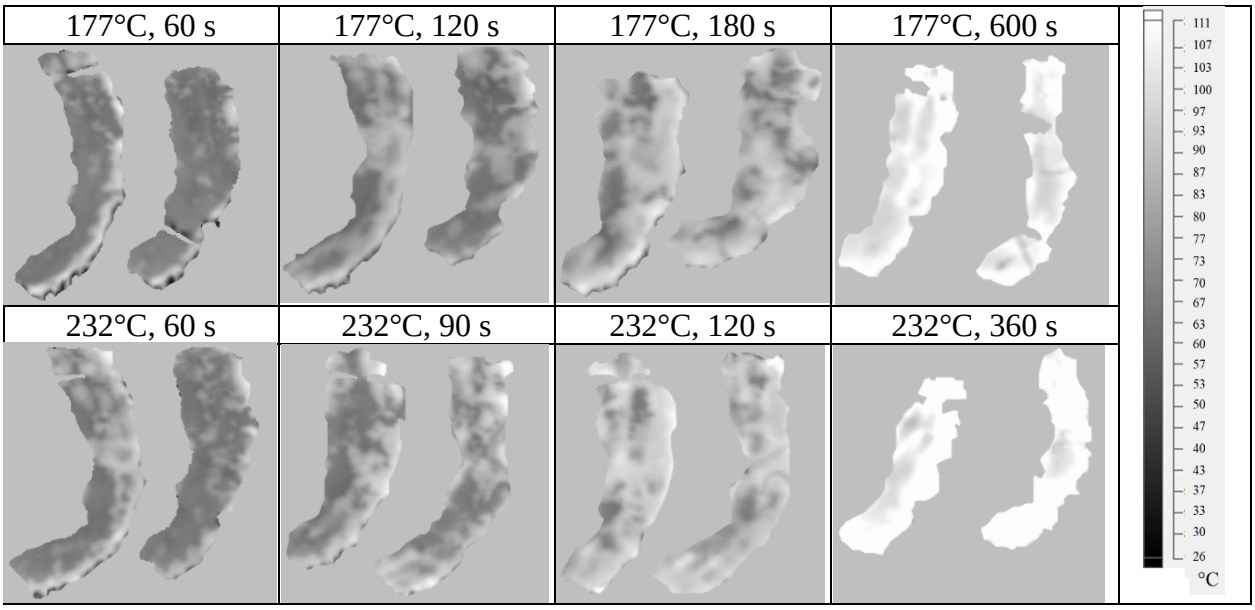


Figure 3: Infrared images of bacon slices A) during microwave cooking and B) during impingement oven cooking

3.2.2 Impingement Oven Cooking

The time to achieve the target cooking yield (< 40%) was, as expected, less at the higher oven temperature (Table 2); however, at similar yields (360 s for 232°C; 600 s for 177°C), the MC and a_w were lower for the higher oven temperature. With $a_w < 0.6$, these fully-cooked products met the characteristics of a low-moisture food (*40*). Overall, yield variability and a_w increased over time at both temperatures (Table 2), which could be due to rendering of fat and water evaporation over time.

Table 2: Moisture content, water activity, yield, and *Salmonella* reduction in bacon slices during impingement cooking

Cook Temp (°C)	**Cook Time (s)**	**Moisture Content (% water)**	**Water Activity**	**Cooking Yield (%)**	***Salmonella* Reductions (log CFU/g)**
Control	0	40.8 ± 6.8** *a, A**	0.971 ± 0.004 *a, A*	-	-
177	60	36.3 ± 7.3 *ab*	0.958 ± 0.009 *b*	84.9 ± 1.3 *a*	> 8.4 (11/12) ***
	120	35.4 ± 7.4 *b*	0.950 ± 0.008 *c*	77.1 ± 1.6 *b*	> 8.4 (12/12)
	180	35.4 ± 5.1 *b*	0.940 ± 0.015 *c*	70.3 ± 2.1 *c*	> 8.4 (12/12)
	600	10.2 ± 4.1 *c*	0.573 ± 0.152 *d*	35.6 ± 3.7 *d*	> 8.4 (11/12)
232	60	37.0 ± 7.3 *AB*	0.956 ± 0.009 *B*	80.5 ± 1.8 *A*	> 8.4 (11/12)
	90	36.3 ± 5.5 *AB*	0.944 ± 0.012 *C*	74.4 ± 2.3 *B*	> 8.3 (11/12)
	120	35.4 ± 4.9 *B*	0.932 ± 0.015 *C*	67.4 ± 3.4 *C*	> 8.3 (11/12)
	360	5.5 ± 4.4 *C*	0.391 ± 0.191 *D*	32.7 ± 4.9 *D*	> 8.4 (11/12)

*Means followed by the same lowercase or uppercase letter *within a column* for a given cook temperature are not significantly different ($\alpha = 0.05$)
** Mean ± standard deviation
***(11/12) means 11 of 12 plated samples were below the limit of detection of 0.6 log CFU/g

By 60 s, *Salmonella* decreased > 6.5 logs ($P < 0.05$) at both cooking temperatures. Such fast inactivation can be explained by the rapid condensation of water vapor on the bacon surface at the beginning of cooking until the bacon surface temperature exceeded the dew point temperature (87.4°C), which significantly enhances surface lethality (*49*). When compared to the temperature profile from infrared images (Figure 4), the continuous temperature profile obtained using thermocouples (Figure 2) was higher. This difference was due to the 20-30 s time lag necessary to transport the samples out of the oven before the infrared images could be taken. Additionally, the thermal images yielded spatial mean surface temperatures, compared to single point measurements using the thermocouples.

Overall, these results demonstrated that under the studied conditions in an impingement oven, the 6.5 log *Salmonella* lethality performance standard (*42*) was met before the bacon slices were fully cooked to a commercial yield of < 40%.

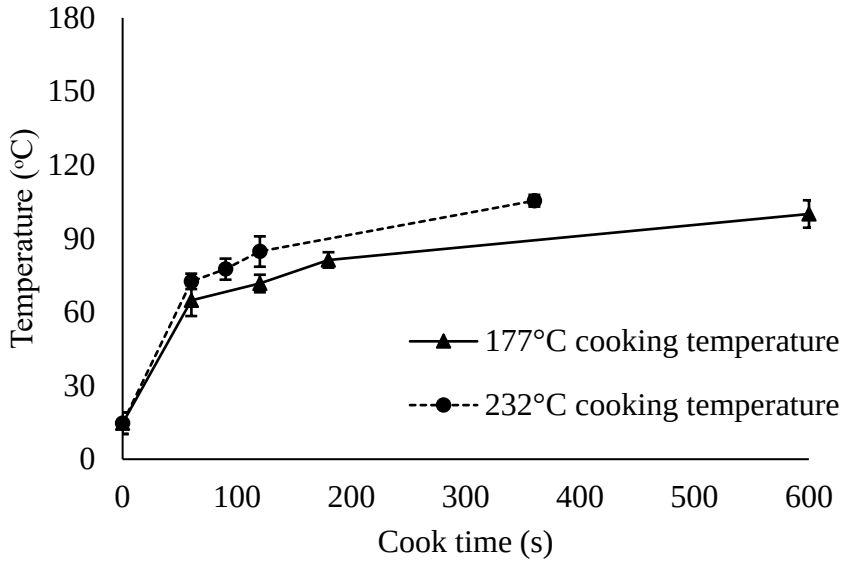


Figure 4: Surface temperature of bacon cooked in an impingement oven, measured using an infrared camera (~20-30 s after cooking as the samples were removed from the oven).

3.2.3 Comparison of *Salmonella* Inactivation in the Lean and Fat Portions of Bacon

The fat portion of the bacon had a lower a_w and MC ($P < 0.05$); the final MC at 90 s was 13% and 38% for fat and lean, respectively (Table 3). The initial *Salmonella* population was higher in the lean than in the fat ($P < 0.05$), indicating greater uptake in the lean, potentially because of the fibrous characteristics of the lean and the generally hydrophobic characteristic of the fat tissue. The temperature of the fat was consistently higher than the lean from 45 to 90 s (Figure 5). However, lower *Salmonella* reductions were observed in bacon fat ($P < 0.05$), even though the statistical interaction of fat vs. lean with cook time was not significant ($P > 0.05$). Similar observations have been reported in the literature, in which increased fat content was associated with higher bacterial pathogen survival (*1*, *53*). Possible explanations of such increased survival of bacterial pathogens in fat include the lower a_w of fat and the commonly reported protective effect of fat on bacteria, potentially due to some underlying physiochemical factors (*48*). Despite the difference in inactivation, *Salmonella* decreased > 6.5 logs in both bacon fat and bacon lean by 90 s, which was consistent with the results for microwave cooking of whole bacon slice (Tables 1 and 3). Therefore, the large variation observed for bacon slices after 60 s microwave cooking (Table 1, Figure 2) may be due to the variation in fat and lean content among the slices.

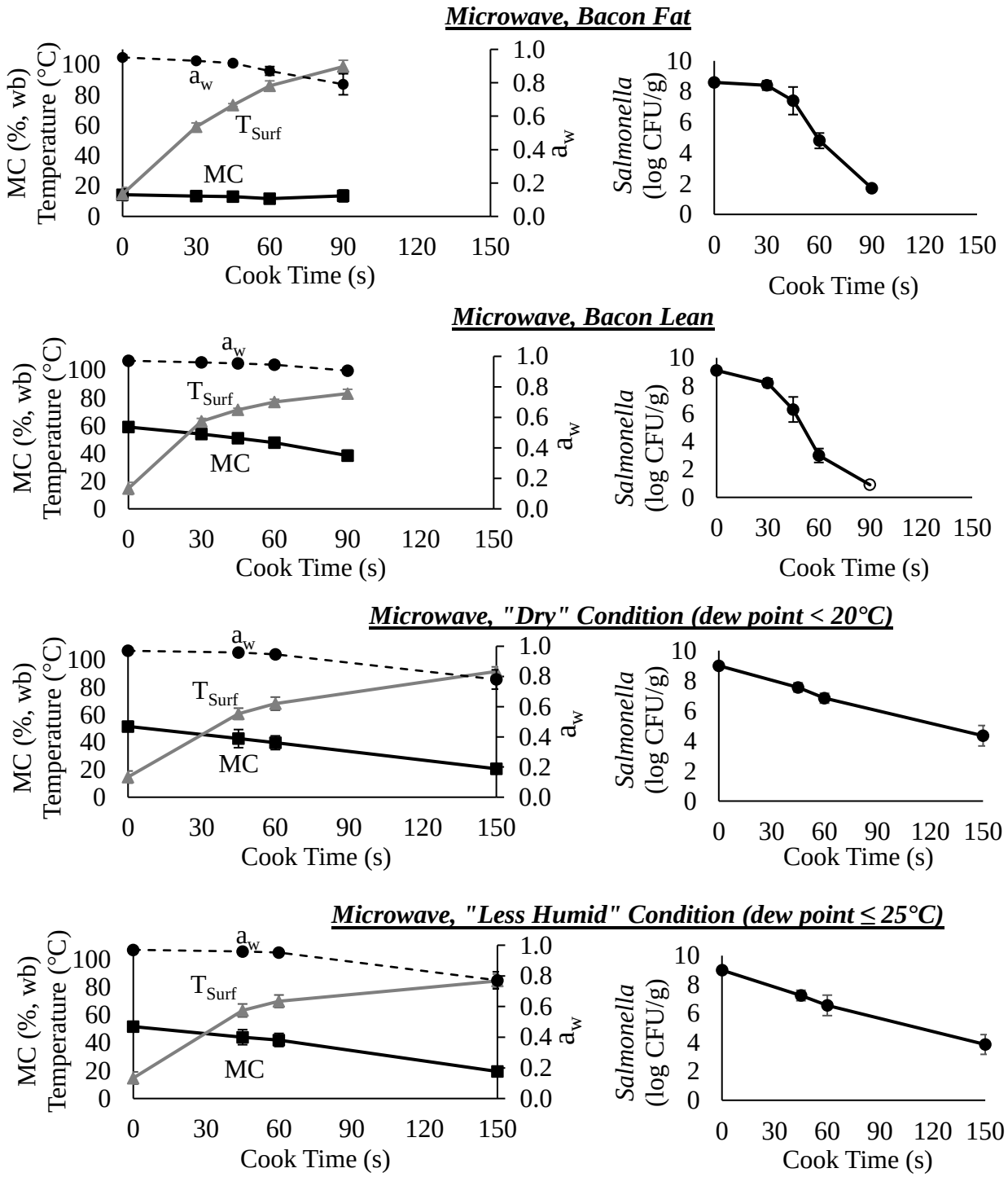


Figure 5: Water activity, moisture content, surface temperature, and *Salmonella* populations in bacon fat and lean portions of bacon and the effect of humidity during microwave cooking of bacon. Less humid conditions represent the scenario where no dry air was added into the system when cooking 2 bacon pieces per batch. Humid condition represents the condition of regular microwave cooking of bacon in which humidity was not controlled and 2 whole bacon slices were cooked per batch. Open circles in the *Salmonella* population curves indicate that one or more samples were below the limit of detection (0.6 log CFU/g).

Table 3: Moisture content, water activity, yield, and *Salmonella* reduction in bacon fat and bacon lean during microwave cooking

	Cook Time (s)	**Moisture Content (% water)**	**Water Activity**	**Cooking Yield (%)**	***Salmonella* Reductions (log CFU/g)**
Bacon fat	0	14.3 ± 3.8**e*	0.952 ± 0.014 b	-	-
	30	13.4 ± 3.1 e	0.931 ± 0.011 c	85.4 ± 1.7 b	0.4 ± 0.2 e
	45	13.1 ± 3.2 e	0.917 ± 0.013 c	68.2 ± 3.0 d	1.5 ± 0.3 d
	60	11.7 ± 2.0 e	0.871 ± 0.026 d	49.7 ± 5.6 f	4.1 ± 2.0 bc
	90	13.5 ± 3.9 e	0.791 ± 0.063 e	33.0 ± 2.5 g	7.2 ± 1.6 a
Bacon lean	0	59.0 ± 2.6 a	0.971 ± 0.005 a	-	-
	30	54.0 ± 3.2 b	0.960 ± 0.006 ab	89.5 ± 0.9 a	0.9 ± 0.5 ed
	45	50.9 ± 2.7 bc	0.954 ± 0.008 b	83.1 ± 1.5 b	2.8 ± 1.1 c
	60	47.7 ± 2.6 c	0.945 ± 0.021 bc	76.2 ± 1.3 c	6.2 ± 2.3 ab
	90	38.4 ± 3.9 d	0.906 ± 0.018 dc	64.4 ± 2.8 e	8.2 ± 0.7 a

*Means followed by the same letter *within a column* are not significantly different ($\alpha = 0.05$)
** Mean ± standard deviation

3.2.4 Effect of Humidity on *Salmonella* Inactivation in Microwave Cooked Bacon

On the days of experiments, the ambient environmental conditions in the lab were measured, in which the dew point was 12.2 ± 1.2°C, corresponding to a relative humidity of 48.3 ± 3.3% at a dry bulb temperature of 24.9 ± 0.4°C. Before cooking, the dew point inside the microwave oven was -0.8 ± 0.3°C and 10 ± 1.5°C for the "dry" and "less humid" conditions, respectively. No significant difference in MC, a_w, or yield ($P > 0.05$) was observed between the two main treatments – "dry" and "less humid" (Table 4). Within each treatment, MC and yield decreased with cook time ($P < 0.05$), as expected. The 40% target yield was achieved by 150 s. The surface temperatures for the "dry" and "less humid" conditions were similar (Figure 5). However, the final temperature at 150 s in both conditions were lower than in the "humid condition" (Figure 2), in which the surface temperature exceeded 100°C at the end of cooking.

Table 4: Moisture content, water activity, yield, and *Salmonella* reduction during microwave cooking under a dry and less humid conditions

	Cook Time (s)	**Moisture Content (% water)**	**Water Activity**	**Cooking Yield (%)**	***Salmonella* Reductions (log CFU/g)**
"Dry" condition *(dew point < 20°C)*	0	51.6 ± 3.7	0.970 ± 0.007	-	-
	45	42.7 ± 6.6** *a**	0.958 ± 0.007 *a*	75.8 ± 2.2 *a*	1.4 ± 0.4 *d*
	60	39.7 ± 5.0 *a*	0.947 ± 0.012 *a*	68.8 ± 2.1 *b*	2.2 ± 0.3 *bc*
	150	20.7 ± 3.8 *b*	0.780 ± 0.064 *a*	37.5 ± 2.6 c	4.7 ± 0.7 *a*
"Less humid" condition *(dew point ≤ 25°C)*	0	51.6 ± 3.7	0.970 ± 0.007	-	-
	45	44.0 ± 5.4 *a*	0.960 ± 0.007 *a*	75.2 ± 1.6 *a*	1.8 ± 0.4 *cd*
	60	42.0 ± 4.7 *a*	0.952 ± 0.007 *a*	67.8 ± 2.4 *b*	2.4 ± 0.7 *b*
	150	19.4 ± 2.3 *b*	0.771 ± 0.056 *a*	35.9 ± 3.0 *c*	5.1 ± 0.7 *a*

*Means followed by the same letter *within a column* are not significantly different ($\alpha = 0.05$)
** Mean ± standard deviation

The "dry" and "less humid" conditions were not significantly different from each other in terms of *Salmonella* inactivation ($P > 0.05$) (Table 4). However, when compared to the baseline microwave cooking of whole bacon slices (i.e., the "humid" condition, dew point > 35°C) (Table 1), both the "dry" and "less humid" conditions resulted in significantly lower *Salmonella* reductions ($P < 0.05$). In the "humid" condition, *Salmonella* decreased > 6.5 logs by 90 s (Table 1). However, only 4.7 and 5.1 log *Salmonella* reductions were achieved under the "dry" and "less humid" conditions, respectively, at 150 s (Table 4). Thus, humidity affected *Salmonella* lethality during microwave cooking of bacon.

Similar observations were made in previous studies on the effect of humidity on *Salmonella* inactivation during thermal processing of several foods, including meat products (*14*, *49*, *52*, *69*). Hildebrandt et al. (*49*) reported that an oven humidity ≥ 30 % (v/v) significantly increased *Salmonella* lethality on the surface of various chicken and beef products. Similar results were observed for sesame seeds (*69*), almonds (*52*), and pistachios (*14*), in which increased humidity was associated with higher *Salmonell*a inactivation. For the case of bacon in

this study, even though the dew point under the dry condition was lower than that of the less humid condition (Figure 6), the difference was not large enough to detect a significant difference in *Salmonella* inactivation. The oven dew point was highest when cooking two whole slices at a time (Figure 6, the "humid" condition), in which 6.5 log reductions of *Salmonella* were achieved before the 40% target yield was achieved. When cooking two full slices (the "humid" condition) the measured dew point was likely lower than the true process value because of the potential introduction of ambient air into the oven when the dew point meter was placed inside; however, the method nevertheless provided a consistent comparison across treatments. Overall, this supplemental experiment showed that humidity did affect *Salmonella* lethality during microwave cooking of bacon, and future studies should investigate the critical humidity threshold, and the humidity in typical commercial-scale, continuous microwave oven systems, to ensure compliance with USDA FSIS *Salmonella* lethality requirements.

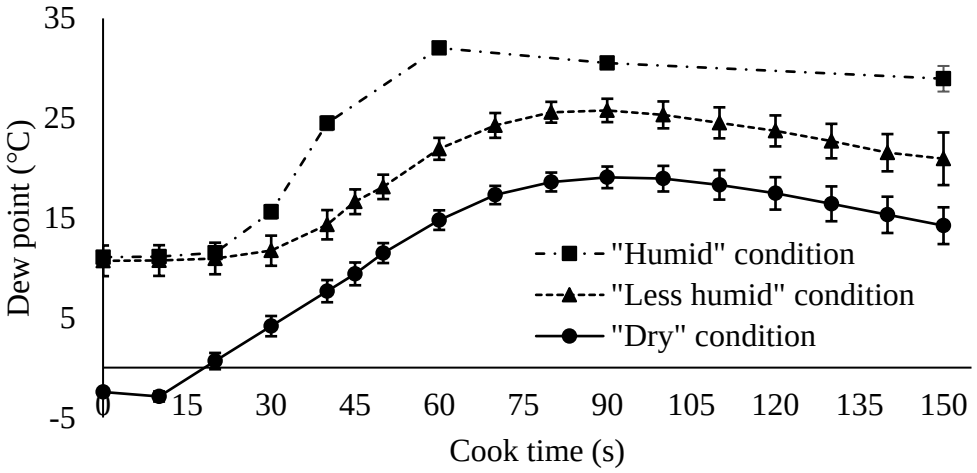


Figure 6: Dew point during microwave cooking of bacon. Dry condition represents the treatment in which dry air was pushed into the microwave during cooking of 2 bacon pieces. Less humid conditions represent the scenario where no dry air was added into the system when cooking 2 bacon pieces per batch. Humid condition represents the condition of regular microwave cooking of bacon in which humidity was not controlled and 2 whole bacon slices were cooked per batch.

3.3 Conclusions

In summary, one minute of impingement oven cooking at both the low and high commercial temperatures at a humidity of 60% (v/v) met the USDA-FSIS *Salmonella* lethality requirement long before the product reached the required yield to be labeled as fully cooked. For microwave cooking, *Salmonella* inactivation and compliance with USDA FSIS depended on oven humidity. Cooking whole bacon slices at a dew point > 35°C inside the oven achieved > 6.5 log reduction of *Salmonella* by 90 s, again prior to reaching the required endpoint yield for fully cooked product. However, reducing the humidity in the oven to a maximum dew point of 19°C or 25°C yielded results that did not ensure sufficient *Salmonella* lethality to meet the target 6.5 log reduction. Therefore, future studies should investigate the humidity threshold needed to meet required food safety standards in bacon processing.

CHAPTER 4: *LISTERIA MONOCYTOGENES* INACTIVATION DURING APPLE DRYING UNDER LOW OR MODERATE TEMPERATURE AND AIR VELOCITY

4.1 Materials and Methods

4.1.1 Study Design

To investigate *Listeria monocytogenes* inactivation during apple drying under conditions similar to industrial processes, this study included a full-factorial experiment (3 replicates) with multiple levels of temperature, air velocity, and drying time (detailed below). In each treatment, the apple slices were dried to a moisture content ≤ 24% (wb), as required by USDA standards defining dried apples (*82*, *84*). All the drying treatments were conducted in a pilot-scale industrial oven (JBT, Sandusky, OH, USA), in which apple surface and oven temperatures were measured over time. Colorimetric analysis was conducted to evaluate the effect of the studied conditions on the browning of the apples (*61*, *62*, *75*), which can vary with polyphenol oxidase (PPO) concentration, temperature, and oxygen availability (*6*). In addition to its effect on marketability of the product, browning can negatively impact the nutritional value (*65*).

4.1.2 Sample Preparation

Organic Gala apples (Rainier Fruit Co, Selah, WA) were acquired from a local retail store and stored at 4°C (up to 21 days) prior to the drying experiments. The apples were labeled “extra fancy,” implying various physical attributes, such as the absence of both internal and external damage based on USDA Agricultural Marketing Service standards (*81, 83*). After visual inspection for firmness and damage, the unpeeled apples were cored and sliced into 6-mm thick rings similarly to Burnham et al. (*9*), using a manual corer (19 mm diameter, Cuisipro, Markham,

ON, Canada) and a mechanical slicer (55200AN, Nemco, Hicksville, OH, USA). Apple rings with an average mass of 20 g and diameter of ~6 cm were used for the experiments.

For each experiment, four slices were used as controls to evaluate the native microflora of the apple slices. Each slice was weighed, diluted in 0.1% phosphate-buffered saline (PBS) (J.T. Baker, Center Valley, PA, USA) at a ratio of 1:5, and homogenized for 2 min (IUL Masticator Silver, 400 ml, IUL S.A., Barcelona, Spain). Appropriate serial dilutions in 0.1% PBS of two of the four slices were plated on a nonselective differential medium Tryptic Soy Agar (TSA) (Difco, Sparks, MD, USA) supplemented with 0.6% yeast extract (Bacto, BD, Sparks, MD, USA), 0.05% ammonium iron citrate (Sigma-Aldrich, St. Louis, MO, USA), and 0.025% esculin hydrate (Across Organics, Morris, NJ, USA) (ETSA). After 48 h of incubation at 37°C, all growing colonies were counted to evaluate the overall background microflora (aerobic mesophiles), and any black colonies would have been counted as presumed *Listeria*. To further confirm the presence or absence of *Listeria* in the apple slices before inoculation, the other two slices were plated on Oxford medium base (Difco, BD, Sparks, MD, USA) supplemented with Modified Oxford Antimicrobic Supplement (Difco, BD, Sparks, MD, USA) (MOX). After 48 h of incubation at 37°C, black colonies surrounded by black zone were counted as *Listeria*.

4.1.3 Culture preparation and sample inoculation

Eight strains of *L. monocytogenes* previously implicated in outbreaks were obtained from Dr. Sophia Kathariou at North Carolina State University: 4b1-GFP (clinical isolate, 1962), CFSAN048782-6 (apples, 2017), CFSAN023957-A10 (mung bean sprouts outbreak, 2014), 2014L-6695-5 (caramel apple outbreak, 2014-2015), 2014L-6680-7 (caramel apple outbreak, 2014-2015), F2365-2 (California cheese outbreak, 1985), 2010L-172304 (celery outbreak, 2010),

and H7858-1 (hot dog outbreak, 1998-1999). The methods of Sloniker et al. (*71*) were used to prepare the *Listeria* cultures and to obtain the inoculum as follows. All strains were stored at −80°C in tryptic soy broth (TSB; Difco, BD, Sparks, MD, USA) containing 20% glycerol (v/v). Working cultures were obtained by transferring each strain into 100 mL TSB, followed by 24 h incubation at 37°C. Each strain was harvested from TSB broth through centrifugation (3000 x *g*, 15 min). The pellets from two strains were then combined in one centrifuge bottle, and the mixture was diluted with 100 mL 0.1% PBS solution. After a gentle mixing using a sterile spatula, this mixture of two strains per centrifuge bottle was centrifuged for another 15 min. After centrifugation, all the pellets of all the eight-strains were combined and diluted into 30 mL 0.1% PBS solution to obtain an inoculum with a mean population of 10.0 ± 0.1 log CFU/mL.

Apple slices were placed on a sterile metal rack and spread with 0.5 mL of inoculum using a T-shaped spreader. After sitting 15 min in a biosafety cabinet, the slices were flipped, and 0.5 mL of inoculum was spread on the other side of each slice. After another 15 min, the inoculated slices were individually placed in sterile sample bags and kept at 4°C (≤ 1 h) until the start of oven drying. Preliminary work showed that post-inoculated samples were only 0.25 ± 0.01 g heavier than pre-inoculated samples (1.41% mass change), indicating a relatively negligible net moisture addition from the inoculum.

4.1.4 Apple Drying

The apple slices were dried at 60 or 80°C dry bulb, and an impingement air velocity of 0.7 or 2.1 m/s (corresponding to a 20 and 60% fan setting on the oven) (JBT, Sandusky, OH, USA). The air flow was perpendicular to the surface of apple slices (from an array of round jet nozzles) with a turbulent regime. The total drying time at 60°C was 180 min (sampling at 30, 60,

90, 120, 150, and 180 min), and at 80°C was 150 min (sampling at 30, 60, 90, 120, and 150 min). Different total drying times were used for each temperature to achieve < 24% (wb) moisture content at the end of each treatment. Apples slices were dried in batches of 10 or 12, at 80 and 60°C, respectively. The slices were placed in a single layer on a metallic mesh tray, and arranged in two columns, adjacent to each other, following the position of the air jets inside the oven, with each column containing 5 or 6 apple slices. To better mimic a commercial process with a full load on a dryer belt, ~240 g of additional, non-inoculated apple slices were placed on either side of the two columns of inoculated slices during each drying test.

To measure the temperature of the inoculated apple slices during drying, two T-type thermocouples (36 gauge) were inserted just below the surface of two slices that were situated diagonally across from each other on the belt. The experiment was conducted such that these two slices with the thermocouples were the last to be sampled in each drying trial, in order to record the surface temperature during the entire drying process. The thermocouples were connected to a data acquisition system (Multipaq21, Fluke, Salem, NH, USA), which transferred the temperature data to a computer via radio frequency telemetry, at an interval of 5 s. Two thermocouples were used to capture the variability across the slices. A T-type temperature probe (32 gauge) was also attached to the conveyor belt with the thermocouple junction measuring the oven air dry bulb temperature near the samples on the belt over time.

At each 30-min sampling point, the tray was briefly removed from of the oven (~1 min), during which one apple slice was randomly taken from each of the two columns, prior to immediately putting the tray back into the oven. One slice was immediately placed in a sample bag, cooled in an ice bath, and used for *Listeria* enumeration. The other slice was used for colorimetry measurement followed by a_w and MC analyses as described below.

The colorimetry analysis was performed on one randomly chosen side of the slice using a handheld colorimeter (CR-400, Konica Minolta, Ramsey, NJ, USA). $L^*a^*b^*$ color values were recorded at three different random locations across the slice, in which L^* indicated the lightness of the slice, a^* the redness or greenness, and b^* the yellowness or blueness. The $L^*a^*b^*$ color values of the slice were measured at room temperature in a biosafety hood. Immediately after the measurement, which took approximately 1 to 2 min, the slice was put in a sealed sample bag. The browning index (BI) (*61*, *62*, *75*) was computed based on the measured color values and then used to compare the impact of the different drying conditions over time.

The same slice that was used for color analysis also was used for a_w measurement. The maximum time lag between removal of the sample from the oven and a_w analysis was 3-4 h, during which all samples were kept in sealed sample bags at 4°C, except during the colorimetry analysis. To prepare samples for a_w measurement, apple slices were cut into small pieces ($\leq$ 50 mm^2), then placed in the a_w cup (~3-5 g). Water activity was measured twice for each sample at an ambient temperature of ~25°C (Aqualab 4TE, Pullman, WA, USA), and the average of the two values was reported. After a_w analysis, AOAC method 950.46B (*3*) was used to measure the MC of the slice gravimetrically after drying at 100-102°C for ~16 h.

4.1.5 *Listeria* Enumeration

One whole slice from each drying time was diluted 1:6 in 0.1% PBS solution. Diluted samples were then homogenized for 2 min (IUL Masticator Silver, 400 ml, IUL S.A., Barcelona, Spain), serially diluted in 0.1% PBS solution and plated on ETSA. *Listeria* colonies (black with black halos) were enumerated after 48 h incubation at 37°C.

4.1.6 Statistical Analyses

After checking for normality and equal variance assumptions using graphical and statistical methods, such as Levene's test, the effect of temperature and air velocity over time on *Listeria* inactivation, MC, and a_w was evaluated using ANOVA ($\alpha = 0.05$) (SAS 9.4, SAS Institute Inc., Cary, NC, USA). In order to have the same number of levels for the 'time' factor, the 180 min time point for 60°C drying temperature was removed for the ANOVA and mean comparisons. Multiple pair-wise comparisons of the means of the responses over the drying times were then conducted using Tukey's test ($\alpha = 0.05$).

4.2 Results and Discussion

4.2.1 Moisture Content and Water Activity

Starting at a MC of approximately 85% (wb), the apple slices met the standard of ≤ 24% (wb) MC for dried apples by the end of the studied drying time (Figure 7, Table 5). When dried at 60°C, the target 24% (wb) moisture was achieved after 150 min at an air velocity of 0.7 m/s, compared to 120-150 min at 2.1 m/s. Similarly at 80°C, 24% MC was achieved by 90 min at 0.7 m/s and between 60-90 min at 2.1 m/s.

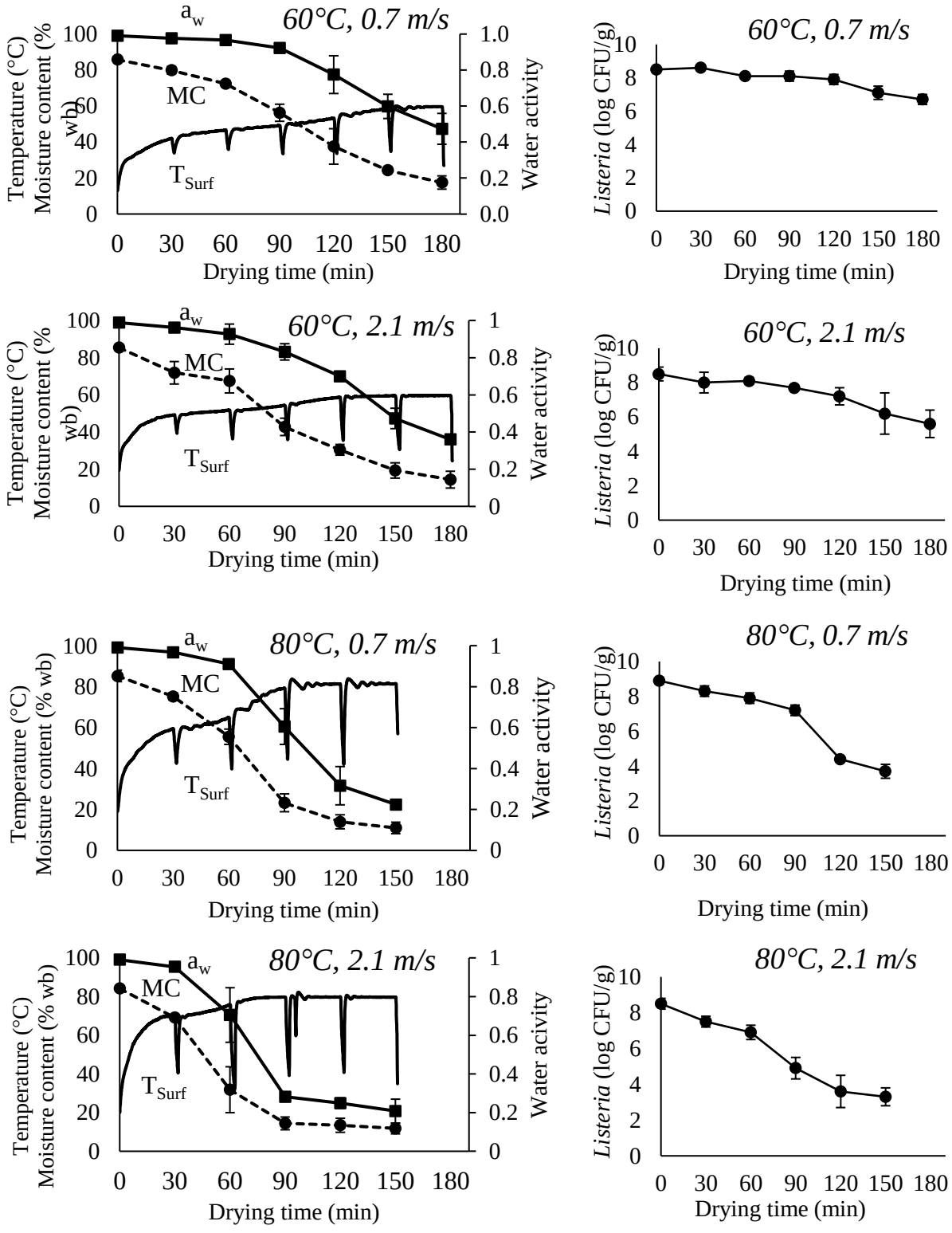


Figure 7: Moisture content, water activity, surface temperature, and *Listeria* populations during apple drying.

Table 5: Multiple comparisons of the moisture content, water activity, surface temperature, and *Listeria* population during apple drying across the studied conditions.

Temp (°C)	Air Velocity (m/s)	Drying Time (min)	Moisture Content (% water)	Water Activity	*Listeria* Reductions (log CFU/g)
60	0.7	0	85.78 ± 0.74** *a**	0.990 ± 0.006** *a**	-
		30	79.82 ± 2.14 *ab*	0.976 ± 0.001 *a*	-0.1 ± 0.3 *g*
		60	72.40 ± 1.82 *bcd*	0.966 ± 0.005 *a*	0.4 ± 0.2 *fg*
		90	56.26 ± 4.74 *e*	0.922 ± 0.018 *a*	0.5 ± 0.5 *fg*
		120	37.51 ± 9.84 *fg*	0.775 ± 0.105 *cd*	0.6 ± 0.3 *f*
		150	24.29 ± 1.53 *ih*	0.598 ± 0.067 *e*	1.4 ± 0.5 *cde*
		180	17.50 ± 3.73	0.473 ± 0.086	1.8 ± 0.3
	2.1	0	85.42 ± 0.37 *a*	0.989 ± 0.003 *a*	-
		30	71.92 ± 6.07 *cd*	0.962 ± 0.010 *a*	0.4 ± 0.4 *fg*
		60	67.50 ± 6.45 *d*	0.927 ± 0.054 *a*	0.4 ± 0.3 *fg*
		90	42.74 ± 4.64 *f*	0.832 ± 0.044 *bc*	0.8 ± 0.4 *ef*
		120	30.42 ± 2.86 *gh*	0.700 ± 0.009 *d*	1.3 ± 0.1 *cdef*
		150	19.34 ± 4.15 *ij*	0.473 ± 0.055 *f*	2.3 ± 1.1 *c*
		180	14.40 ± 4.53	0.360 ± 0.021	2.8 ± 0.7
80	0.7	0	85.25 ± 2.80 *a*	0.991 ± 0.004 *a*	-
		30	75.28 ± 1.78 *bc*	0.968 ± 0.010 *a*	0.6 ± 0.2 *f*
		60	55.55 ± 3.74 *e*	0.911 ± 0.014 *ab*	0.9 ± 0.3 *ef*
		90	23.24 ± 4.31 *ih*	0.605 ± 0.087 *e*	1.7 ± 0.3 *cd*
		120	13.96 ± 3.48 *kj*	0.316 ± 0.093 *g*	4.4 ± 0.2 *a*
		150	10.97 ± 2.77 *k*	0.224 ± 0.025 *h*	5.2 ± 0.5 *a*
	2.1	0	84.20 ± 0.87 *a*	0.991 ± 0.001 *a*	-
		30	69.17 ± 1.33 *cd*	0.954 ± 0.007 *a*	0.9 ± 0.5 *def*
		60	31.78 ± 11.87 *g*	0.705 ± 0.141 *d*	1.6 ± 0.7 *cde*
		90	14.43 ± 3.25 *kj*	0.282 ± 0.023 *gh*	3.6 ± 0.8 *b*
		120	13.44 ± 3.61 *kj*	0.249 ± 0.027 *gh*	4.9 ± 0.8 *a*
		150	11.81 ± 2.80 *k*	0.208 ± 0.062 *h*	5.2 ± 0.5 *a*

*Means followed by the same letter *within each entire column* are not significantly different (Tukey's LSD, $\alpha = 0.05$)
** Mean ± standard deviation

The higher fan speed and drying temperature resulted in faster moisture removal ($P < 0.05$), as expected, because of increased mass convection and heat transfer. For example, at either drying temperature, the apple surface temperature rose to within ~1-2°C of the air temperature almost 30 min sooner at the higher air velocity (Figure 7). Similarly, the change in apple temperature was faster at 80°C (Figure 7). The brief dips in the temperature profiles

(Figure 7) were due to the short period during which the samples tray was removed from the oven for sample collection. Overall, the mean absolute difference (± standard deviation) between the temperatures measured by the two thermocouples on two concurrently dried slices was 1.48 ± 1.80°C, indicating fairly low surface temperature variability during drying. The measured air temperature was, on average, 0.33 ± 3.33°C below the set temperature across all treatments, indicating adequate control of the process temperature.

Consistent results also were observed for the change in moisture over time, with the higher drying temperature associated with a faster decrease in moisture beginning as soon as 30 min into the drying period. Air velocity only significantly affected the MC at 30 and 90 min at 60°C and at 60 min at 80°C ($P < 0.05$), with the lower air velocity associated with slower change in moisture (Figure 7). Previous studies on the drying kinetics of fruits and vegetables confirmed that higher drying temperatures and air velocities result in faster drying rates and moisture diffusion (*57*, *79*, *106*), as would be expected. However, if the temperature and air velocity are too high, shrinkage and/or "case hardening" can occur, preventing moisture loss from the food matrix (*57*, *79*). In this study, by visual inspection, shrinkage did not occur until the later phase of drying, after 90 min, depending on the drying temperature and air velocity.

In this study, temperature had a greater effect on moisture removal during drying than did air velocity, as shown by the difference in the slopes of the moisture plots. Similar findings were reported in a previous study (*57*) that examined the drying kinetics of various vegetables. These researchers attributed the lower effect of air velocities to the range of air velocity used, which was considered relatively high (1.5-2.6 m/s) (*57*). In contrast, our air velocity of 0.7 m/s was much lower, with no apparent shrinkage until later in the drying. Therefore, the lower effect of air velocity on MC may be due to lower heat and mass convection.

In terms of a_w, the apples slices started at 0.99, and, depending on the drying conditions used, a_w only decreased significantly during the later stage of drying (Table 5). At 60°C and 0.7 m/s, a_w only changed after 120 min of drying, whereas, at 80°C and 2.1 m/s, a similar change occurred after 60 min ($P < 0.05$).

4.2.2 Colorimetric Results

Apple browning during drying was affected by the time-temperature-air velocity interaction ($P < 0.05$). Some of the slices had a browning index significantly greater from the raw inoculated slices ($P < 0.05$). The average browning index of the raw inoculated apple slices was 29.88 ± 3.33, whereas that of the dried apples was 36.95 ± 5.39; however, mean browning was not significantly different across the drying treatments ($P > 0.05$).

4.2.3 *Listeria* Inactivation

Gala apples were chosen for this study, as this specific variety had been widely used in previous apple drying studies (*9*, *38*, *39*, *45*). Gurtler et al. (*47*) reported that survival of *Salmonella* in Gala apples during drying was higher compared to other varieties, such as Granny Smith, Pink Lady, and Fuji. The initial *Listeria* population after inoculation was 8.6 ± 0.3 log CFU/g across all the treatments. Among the negative controls that were plated on ETSA, all the samples, except 2, had total counts below the limit of detection (LOD) of 1.7 log CFU/g. Those two samples had an average total plate count of 2.7 log CFU/g, but none of the colonies resembled *Listeria*. All the negative controls had counts below the LOD on MOX.

Temperature and air velocity significantly impacted the inactivation of *L. monocytogenes* during drying ($P < 0.05$), with the higher temperature and air velocity resulting in greater

reductions. At 60°C and air velocity of 0.7 m/s, the initial *Listeria* population decreased only 0.6 ± 0.3 log at 120 min, in which the MC was 38% (wb). At that same drying time and temperature, increasing the air velocity to 2.1 m/s decreased *Listeria* by 1.3 ± 0.1 log, at a MC of 30% (wb). After 180 min of drying, the overall *Listeria* reduction was 1.8 ± 0.3 and 2.8 ± 0.7 log CFU/g at 0.7 and 2.1 m/s respectively, when the oven was set at 60°C. When the higher drying air temperature of 80°C was used, greater *Listeria* reduction occurred. By the time the MC was less than 24% (wb) at 90 min, the initial population was reduced by 1.7 ± 0.3 and 3.6 ± 0.8 log CFU/g respectively at 0.7 and 2.1 m/s. At the same drying temperature, both air velocities resulted in similar *Listeria* reductions of 5.2 ± 0.5 log CFU/g after 150 min. Overall, temperature, air velocity, and drying time each had a significant effect on *Listeria* inactivation *(P* < 0.05), with the interaction between temperature, air velocity, and time being significant (*P* < 0.05).

During apple drying in this study, a dynamic change of water activity was observed in all the treatments, even though the rates were different (Table 5). Such different changes in a_w are important because they could be important control factors for *L. monocytogenes* survival in the apple slices. Previous studies have shown that a_w has a significant impact on the thermal inactivation of bacteria such as *Salmonella* in low-moisture products (*2*, *43*, *78*, *107*, *109*, *110*).

The results from this study are generally consistent with what those from previous investigations of bacterial inactivation under similar drying conditions. When studying *Salmonella* survival in various apple varieties during drying, Gurtler et al. (*47*) reported a 2.0 log reduction in Gala apples when no pre-treatment was applied to apples dried at 60°C for 5 h. Similarly, Dipersio et al. (*39*) achieved a 2.7 to 2.8 log reduction of *Salmonella* during drying of Gala apples at 60°C for 6 h. In two other studies where Gala apple slices were inoculated with *E.*

coli, the overall reductions were 2.5 log CFU after 6 h at 57.2 °C (*9*) and 2.5 (*38*) or 3.3 (*9*) log CFU after 6 h at 62.8 °C. In all these studies, drying was conducted in a food dehydrator, and the air velocity was not controlled. Nevertheless, the log reductions reported were similar to what was seen in the present study, in which using 60°C drying temperature decreased *Listeria* by 1.8-2.8 logs, depending on the air velocity. Therefore, within in the ranges tested, the effect of air velocity appears to be minimal at lower drying temperatures.

In another study using higher temperatures (104 and 135°C) and a relatively low air velocity (0.4 m/s), > 5 log reduction of *Salmonella* was achieved in apple pieces by the end of drying (*45*). A similar reduction in *Listeria* was seen in the present study at 80°C at both the lower and higher air velocities. Though the total drying times differed, these two studies show that moderate (80°C) to high drying temperatures (≥104°C) are potentially effective in decreasing both *Listeria* and *Salmonella* in apples during drying, compared to 60°C, which is common for home-scale dehydrators.

4.3 Conclusions

In summary, temperature and air velocity both affected apple drying, in terms of moisture removal and a_w over time, with temperature having a greater impact. Similar effects were also observed for *L. monocytogenes* inactivation. Drying at 60°C yielded only a 1.8 to 2.8 log reduction in *Listeria*, whereas a 5 log reduction was achieved at 80°C. These results suggest that drying at 80°C under the studied air velocities might be sufficient for pathogen control in apple drying industry. Although the higher air velocity resulted in greater *Listeria* reduction, the effect was independent of drying time and temperature. Therefore, future studies should investigate a wider range of temperatures and air velocities to support the validation of various commercial practices for producing dried apple products.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Overall Findings

This thesis investigated *Salmonella* and *L. monocytogenes* inactivation under widely changing moisture conditions in RTE bacon and dried apples. For bacon, the following conclusions were made.

1. During impingement oven cooking, *Salmonella* decreased > 6.5 logs before the product was fully-cooked (40% yield).
2. During microwave oven cooking, *Salmonella* decreased > 6.5 logs in the absence of humidity control (dew point ≥ 35°C) before the end of cooking (40% yield).
3. However, when the dew point in the microwave oven was kept below 25°C, *Salmonella* decreased < 6.5 log, indicating that humidity enhances *Salmonella* inactivation during microwave cooking of bacon.
4. Additionally, *Salmonella* was shown to be more resistant in the fat portion of the bacon than in the lean portion during microwave cooking.

For apple drying, the following conclusions were drawn:

1. Higher air velocities and higher temperatures contributed to greater *L. monocytogenes* inactivation.
2. At a drying temperature of 60°C, *Listeri*a decreased < 5 logs by the end of the drying.
3. However, at 80°C, a 5 log reduction of *Listeria monocytogenes* was achieved, regardless of the air velocity.

Despite obvious compositional differences between bacon and apples, and their complex and different coupled heat and mass transfer mechanisms, similar pathogen inactivation trends were seen in both products (Table 6). In both bacon and apple, the MC and a_w decreased during drying to a low-moisture state. Similarly, both bacon and apples showed a continually dynamic product surface temperature during processing. Additionally, both product processes yielded generally similar patterns of pathogen reduction over time (nominally "linear") for the low-humidity cases. For bacon cooked in an impingement oven, the observed rapid inactivation of *Salmonella* likely resulted from the high process humidity (60% v/v) and subsequent rapid condensation of water vapor on the product surface, creating a significant advantage for pathogen lethality. For apple drying, inactivation of *L. monocytogenes* was slower because of the countereffects on lethality of simultaneously increasing the temperature and decreasing moisture over time. Additionally, the apple slices were thicker, which impeded moisture removal and lengthened the processing time.

Table 6: Comparison of bacon cooking and apple drying described in this study

Product	Treatment	Moisture Content (%, wb)		Water Activity		Maximum Surface Temperature (°C)	Overall Pathogen Reduction (log CFU/g)
		Initial	Final	Initial	Final		
bacon	Impingement oven cooking: 177°C, 60% (v/v) humidity	40.8 ± 6.8	10.2 ± 4.1	0.971 ± 0.004	0.573 ± 0.152	~ 138.9	> 8.4 (*Salmonella*)
	Impingement oven cooking: 232°C, 60% (v/v) humidity	40.8 ± 6.8	5.5 ± 4.4	0.971 ± 0.004	0.391 ± 0.191	~ 171.2	> 8.4 (*Salmonella*)
	Microwave cooking: 80% power, (1200W max); humid condition	41.5 ± 7.7	18.9 ± 3.9	0.974 ± 0.006	0.758 ± 0.079	~ 103.1	> 8.4 (*Salmonella*)
apple	Drying: 60°C, 0.7 m/s	85.78 ± 0.74	17.50 ± 3.73	0.990 ± 0.006	0.473 ± 0.086	~ 60	1.8 ± 0.3 (*Listeria*)
	Drying: 60°C, 2.1 m/s	85.42 ± 0.37	14.40 ± 4.53	0.989 ± 0.003	0.360 ± 0.021	~ 60	2.8 ± 0.7 (*Listeria*)
	Drying: 80°C, 0.7 m/s	85.25 ± 2.80	10.97 ± 2.77	0.991 ± 0.004	0.224 ± 0.025	~ 80	5.2 ± 0.5 (*Listeria*)
	Drying: 80°C, 2.1 m/s	84.20 ± 0.87	11.81 ± 2.80	0.991 ± 0.001	0.208 ± 0.062	~ 80	5.2 ± 0.5 (*Listeria*)

5.2 Summary

Although RTE bacon and dried apples are two completely different products, they both exhibit similar phenomenological changes in MC, a_w, and pathogen inactivation (Figures 2, 5, and 7). Under non-isothermal, dynamic temperature conditions, product MC, a_w , and pathogen populations all declined. During impingement oven cooking of bacon, *Salmonella* decreased

rapidly very early in the cooking process due to the effect of vapor condensation, which facilitated rapid inactivation before the product started losing moisture. For bacon cooked in the microwave oven where humidity was not controlled, the target lethality also was achieved before obtaining a RTE product. When humidity was controlled (held below 25°C dew point) in the microwave, *Salmonella* decreased over time, even though the rate of inactivation was slower. In contrast to bacon, the apple drying treatment was conducted under dry conditions. Therefore, product moisture loss over time influenced the inactivation rate of *L. monocytogenes*. Nevertheless, a gradual *Listeria* reduction was observed over time. Both dry microwave cooking and apple drying showed similar pseudo-linear bacterial inactivation curves due to the low humidity. These observations demonstrate that despite obvious differences in product composition and processing methods, bacterial inactivation followed a similar trend, with thermal inactivation influenced by the counter-effects of dynamically and simultaneously increasing temperature and decreasing moisture. Thus, it may be possible to represent bacterial pathogen inactivation under such widely changing moisture conditions using one model form that accounts for these multiple factors, and their possible interactions. A previous study modeled *Salmonella* inactivation in pistachios incorporating dynamic moisture change (Equation 1) (*13*). Even though the product in that study was already a low-moisture product, their model form could a starting point to predict *Salmonella* and other pathogen inactivation in food undergoing dynamic wide moisture change over time.

$$D_{T,T_d,MC}(t) = D_{ref} \times 10^{\frac{T_{ref}-T_S(t)}{z_T}+\frac{(T_{d,ref}-T_d)-(T_{ref}-T_S(t))}{z_M}+\frac{MC_{ref}-MC(t)}{z_{MC}}}$$ (Equation 1) (*13*)

- $D_{T,T_d,MC}$: D-value in function of dynamic temperature and MC over time (min)
- D_{ref} : D-value at a specific reference condition (min)

- T_{ref} : Reference temperature (°C)
- $T_{d,ref}$: Reference dew point (°C)
- T_d : Dew point (°C)
- $T_s(t)$: Product surface temperature over time (°C)
- MC_{ref} : Reference moisture content (% MC, db)
- $MC(t)$: Moisture content over time (% MC, db)
- Z_T : Parameter defining the effect of product surface temperature changes on $D_{T,T_d,MC}$ (°C)
- Z_M : Parameter defining the effect of dew point changes on $D_{T,T_d,MC}$ (°C)
- Z_{MC} : Parameter defining the effect of product moisture content changes on $D_{T,T_d,MC}$ (% MC, db)

5.3 Future Work

Given the existing FSIS and FSMA regulations for bacon and dried apples, respectively, this thesis has shown that more research is needed to ensure full compliance. For bacon, because humidity influenced *Salmonella* inactivation during microwave cooking, future studies should focus on the threshold humidity needed to meet the FSIS 6.5 log *Salmonella* reduction requirement in an industrial setting. It is therefore also important to characterize the humidity in actual commercial, continuous microwave systems, to confirm that typical commercial processes (as expected) operate at humidity levels sufficient to ensure compliance with FSIS expectations for process lethality. For apples, this study and previous literature have demonstrated that pathogen lethality depends on the drying conditions used, including drying air temperature and velocity. Given the limited literature on pathogen inactivation during apple drying or fruit drying in general, and the wide range of parameters and processing methods used by apple drying

industry, future work is needed to further understand and predict bacterial pathogen inactivation under such widely changing moisture conditions. In this case, potential research ideas include the following.

1. Evaluating pathogen inactivation during apple drying as affected by product geometry, such as thickness.
2. Assessing the effect of a wider range of air velocities (very low to very high) on pathogen inactivation.
3. Investigating the effects of a wider range of temperatures on inactivation, based on the full range of temperature used by the apple drying industry (e.g., 60 and 190°C).
4. Modeling *Salmonella* and other pathogen inactivation during apple drying under wide moisture changes over time, as a function of product temperature, MC (and/or a_w), and perhaps process humidity and air velocity.
5. Evaluating the effect of anti-browning pre-treatment methods in apple drying and integrating the effect in an inactivation model.
6. Combining existing drying technologies, such as microwave-convective drying, and evaluating the hurdle effect on pathogen inactivation.
7. Imitating the industrial practice of multistage drying in apple and evaluating pathogen inactivation during the process.

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APPENDIX A: Collected Data from Bacon Cooking Study

Table 7: Collected data from *Salmonella* inactivation during microwave cooking of bacon

Cooking Time (s)	Replication	Subsample	*Salmonella* Population (log CFU/ g)	Water Activity	MC (%, wb)	Yield (%)
0	1	A	9.1	0.9704	33.21	
0	1	B	9.1	0.9732	28.99	
0	1	C	9.1	0.9807	16.62	
0	1	A	9.6	0.9772	47.76	
0	1	B	9.7	0.9725	46.54	
0	1	C	9.6	0.9814	42.89	
0	1	A	9.1	0.9761	48.58	
0	1	B	9.0	0.9778	56.08	
0	1	C	9.1	0.9737	45.34	
0	1	A	9.2	0.9746	46.37	
0	1	B	9.3	0.9605	35.49	
0	1	C	9.0	0.9689	42.04	
0	1	A	9.0	0.9533	26.92	
0	1	B	9.1	0.9707	36.79	
0	1	C	9.1	0.9652	38.49	
0	1	A	9.1	0.9808	37.40	
0	1	B	9.1	0.9769	43.76	
0	1	C	9.0	0.9734	44.64	
0	2	A	9.6	0.9666	38.41	
0	2	B	8.8	0.9690	41.49	
0	2	A	8.8	0.9809	47.57	
0	3	B	9.7	0.9698	38.68	
0	3	A	9.1	0.9617	41.53	
0	3	B	9.6	0.9716	34.00	
0	4	A	9.2	0.9770	49.01	
0	4	B	9.2	0.9779	48.57	
0	4	A	9.0	0.9725	34.72	
0	5	B	9.4	0.9744	43.77	
0	5	A	9.3	0.9697	49.14	
0	5	B	9.3	0.9730	49.35	
0	6	A	9.3	0.9738	39.15	
0	6	B	9.3	0.9693	42.86	
0	6	A	9.3	0.9731	43.07	
30	1	A	7.7	0.9603	40.28	83.67

Table 7 (cont'd)

Cooking Time (s)	Replication	Subsample	*Salmonella* Population (log CFU/ g)	Water Activity	MC (%, wb)	Yield (%)
30	1	B	8.4	0.9635	36.31	88.46
30	1	A	8.4	0.9650	46.35	87.06
30	1	B	8.1	0.9625	36.92	87.08
30	1	A	8.0	0.9647	40.97	84.82
30	1	B	8.4	0.9649	38.26	88.85
30	1	A	8.4	0.9541	46.08	87.47
30	1	B	8.2	0.9597	23.96	86.79
30	1	A	8.4	0.9677	48.47	86.91
30	1	B	8.2	0.9555	35.05	84.73
30	1	A	7.9	0.9749	31.68	85.78
30	1	B	8.2	0.9753	30.42	85.94
30	2	A	8.2	0.9642	38.57	84.24
30	2	B	7.7	0.9598	26.17	85.15
30	3	A	7.8	0.9656	69.33	85.46
30	3	B	8.4	0.8299	37.83	88.24
30	4	A	8.4	0.9559	34.62	88.66
30	4	B	8.0	0.9514	39.09	85.53
30	5	A	7.9	0.9642	44.08	83.11
30	5	B	8.2	0.9524	29.95	85.15
30	6	A	8.4	0.9676	43.39	83.22
30	6	B	8.5	0.9705	44.22	84.16
30	7	A	8.4	0.9638	38.30	84.45
30	7	B	8.5	0.9500	38.07	87.63
45	1	A	4.1	0.9473	39.54	68.84
45	1	B	7.3	0.9308	35.07	75.63
45	1	A	7.0	0.9052	24.86	69.98
45	1	B	5.7	0.9413	33.41	72.97
45	1	A	4.7	0.9430	39.03	70.24
45	1	B	7.0	0.9374	34.81	75.77
45	1	A	4.5	0.9366	38.88	69.67
45	1	B	6.8	0.9368	34.68	76.27
45	1	A	5.8	0.9300	34.80	68.35
45	1	B	7.6	0.9431	39.74	76.43
45	1	A	4.6	0.9422	31.45	73.22
45	1	B	6.0	0.9005	28.46	71.06
45	2	A	5.6	0.9578	38.28	70.35
45	2	B	7.1	0.9466	37.35	72.99

Table 7 (cont'd)

Cooking Time (s)	Replication	Subsample	*Salmonella* Population (log CFU/ g)	Water Activity	MC (%, wb)	Yield (%)
45	3	A	7.3	0.9590	35.71	71.43
45	3	B	6.1	0.9430	36.10	75.09
45	4	A	6.7	0.9412	35.77	76.01
45	4	B	5.1	0.9160	34.28	72.79
45	5	A	5.2	0.9582	29.64	69.14
45	5	B	6.5	0.9390	33.69	75.94
45	6	A	5.5	0.9591	41.68	71.41
45	6	B	6.7	0.9528	34.95	76.31
45	7	A	6.5	0.9481	38.94	74.31
45	7	B	7.5	0.9327	34.90	74.64
60	1	A	3.4	0.9376	37.78	66.06
60	1	B	3.8	0.9233	31.20	54.34
60	1	A	1.3	0.9245	31.59	58.28
60	1	B	3.0	0.9502	42.17	66.81
60	1	A	1.1	0.9237	55.59	62.61
60	1	B	1.2	0.9395	35.45	61.01
60	1	A	0.6	0.9245	33.13	65.53
60	1	B	1.1	0.9516	41.86	64.46
60	1	A	0.8	0.9513	45.47	69.55
60	1	B	4.6	0.9358	39.86	64.91
60	1	A	4.1	0.9608	38.83	66.53
60	1	B	1.9	0.9507	40.31	67.39
60	2	A	3.9	0.9520	39.90	61.21
60	2	B	2.9	0.9120	33.29	66.40
60	3	A	<LOD	0.9537	34.40	62.05
60	3	B	<LOD	0.9169	34.66	65.50
60	4	A	<LOD	0.9237	31.31	66.56
60	4	B	5.4	0.8872	30.51	64.48
60	5	A	<LOD	0.9276	29.13	64.30
60	5	B	5.5	0.9440	37.93	66.90
60	6	A	<LOD	0.9386	38.38	65.01
60	6	B	5.0	0.9272	31.59	65.88
60	7	A	3.0	0.9343	35.65	65.11
60	7	B	2.8	0.9074	33.35	68.01
90	1	A	3.1	0.9393	36.13	53.93
90	1	B	1.3	0.8907	29.82	46.98
90	1	A	<LOD	0.9070	32.13	56.92

Table 7 (cont'd)

Cooking Time (s)	Replication	Subsample	*Salmonella* Population (log CFU/ g)	Water Activity	MC (%, wb)	Yield (%)
90	1	B	<LOD	0.9128	32.74	46.95
90	1	A	<LOD	0.9202	39.43	56.69
90	1	B	<LOD	0.8982	32.12	51.47
90	1	A	<LOD	0.9141	33.25	58.89
90	1	B	<LOD	0.9262	30.07	54.19
90	1	A	-0.4	0.9476	44.96	61.52
90	1	B	0.2	0.9214	35.12	54.77
90	1	A	1.4	0.9520	38.96	59.08
90	1	B	<LOD	0.9492	39.98	57.40
90	2	A	<LOD	0.9333	35.17	51.29
90	2	B	<LOD	0.8955	30.12	56.89
90	3	A	<LOD	0.8797	26.90	52.58
90	3	B	<LOD	0.9332	35.03	51.46
90	4	A	<LOD	0.8779	26.58	54.05
90	4	B	<LOD	0.8345	24.16	54.09
90	5	A	<LOD	0.8994	29.08	55.21
90	5	B	<LOD	0.9130	32.09	54.09
90	6	A	0.3	0.9090	35.21	52.97
90	6	B	<LOD	0.9097	30.78	51.34
90	7	A	1.5	0.9035	33.99	52.10
90	7	B	<LOD	0.8543	25.53	54.89
120	1	A	0.8	0.8607	31.98	44.50
120	1	B	<LOD	0.7337	27.30	49.77
120	2	A	<LOD	0.7849	18.97	41.41
120	2	B	<LOD	0.8856	29.66	38.93
120	3	A	<LOD	0.8403	23.92	45.18
120	3	B	<LOD	0.7360	19.45	42.21
120	4	A	<LOD	0.8281	24.53	47.58
120	4	B	2.3	0.8611	27.67	43.79
120	5	A	1.1	0.8756	28.69	45.54
120	5	B	<LOD	0.8989	30.21	48.35
120	6	A	<LOD	0.8245	23.55	42.49
120	6	B	<LOD	0.8188	24.75	43.94
150	1	A	<LOD	0.6311	13.53	34.79
150	1	B	<LOD	0.6687	14.64	32.77
150	1	A	<LOD	0.7002	13.84	36.82
150	1	B	<LOD	0.7042	16.25	34.01

Table 7 (cont'd)

Cooking Time (s)	Replication	Subsample	*Salmonella* Population (log CFU/ g)	Water Activity	MC (%, wb)	Yield (%)
150	1	A	<LOD	0.7219	17.75	42.61
150	1	B	<LOD	0.7064	15.47	39.00
150	1	A	<LOD	0.7814	18.89	47.21
150	1	B	<LOD	0.7541	18.15	39.12
150	1	A	<LOD	0.7207	17.07	38.40
150	1	B	<LOD	0.8551	25.06	39.61
150	1	A	<LOD	0.8621	25.93	40.08
150	1	B	<LOD	0.6832	15.48	38.11
150	2	A	<LOD	0.9132	25.23	35.13
150	2	B	<LOD	0.8741	17.33	35.74
150	3	A	<LOD	0.8240	19.49	30.22
150	3	B	<LOD	0.8369	22.36	32.10
150	4	A	<LOD	0.7346	16.44	39.87
150	4	B	<LOD	0.6400	14.32	36.96
150	5	A	0.6	0.6674	13.94	36.57
150	5	B	<LOD	0.7166	15.76	34.23
150	6	A	<LOD	0.8104	24.58	38.48
150	6	B	<LOD	0.8128	20.90	34.74
150	7	A	<LOD	0.8000	20.96	39.14
150	7	B	<LOD	0.7779	21.71	40.30

Table 8: Collected data from comparison of *Salmonella* inactivation in bacon fat and bacon lean

Bacon characteristic	Cook Time (s)	Replication	*Salmonella* Population (log CFU/g)	Water Activity	Moisture Content (% wb)	Yield (%)
Fat, control	0	1	8.8	0.9463	10.18	
Fat, control	0	2	8.7	0.9274	13.78	
Fat, control	0	3	8.9	0.9563	12.56	
Fat, control	0	4	9.0	0.9506	12.67	
Fat, control	0	5	8.9	0.9669	15.37	
Fat, control	0	6	8.8	0.9642	21.11	
Lean, control	0	1	9.1	0.9639	54.50	
Lean, control	0	2	9.1	0.9671	57.96	
Lean, control	0	3	9.3	0.9738	60.66	
Lean, control	0	4	9.0	0.9736	58.83	
Lean, control	0	5	9.1	0.9729	61.86	
Lean, control	0	6	9.0	0.9761	60.10	
Fat	30	1	8.6	0.9310	9.43	87.40
Fat	30	2	8.2	0.9161	12.37	84.90
Fat	30	3	8.7	0.9342	17.22	84.76
Fat	30	4	8.4	0.9230	11.99	85.24
Fat	30	5	8.5	0.9370	11.98	87.06
Fat	30	6	8.1	0.9470	17.09	82.76
Fat	45	1	7.5	0.9221	11.67	66.90
Fat	45	2	7.1	0.9131	14.65	64.19
Fat	45	3	7.8	0.9171	8.86	69.81
Fat	45	4	7.2	0.8951	14.88	71.00
Fat	45	5	7.6	0.9247	17.59	65.73
Fat	45	6	7.4	0.9312	10.76	71.53
Fat	60	1	5.8	0.8708	11.41	46.41
Fat	60	2	5.3	0.8667	11.67	43.80
Fat	60	3	5.1	0.9059	11.02	55.98
Fat	60	4	4.1	0.8265	9.12	53.39
Fat	60	5	1.5	0.8861	15.19	43.91
Fat	60	6	7.1	0.8702	11.97	54.86
Fat	90	1	1.6	.	.	29.41
Fat	90	2	<LOD	0.7022	8.21	35.22
Fat	90	3	<LOD	0.8489	18.00	34.87
Fat	90	4	<LOD	0.7723	10.90	33.67
Fat	90	5	4.7	0.8546	15.97	30.25
Fat	90	6	1.9	0.7781	14.29	34.29

Table 8 (cont'd)

Bacon characteristic	Cook Time (s)	Replication	*Salmonella* Population (log CFU/g)	Water Activity	Moisture Content (% wb)	Yield (%)
Lean	30	1	7.7	0.9502	55.16	88.59
Lean	30	2	8.7	0.9673	57.37	91.11
Lean	30	3	8.0	0.9611	57.33	88.72
Lean	30	4	8.6	0.9633	52.95	89.34
Lean	30	5	8.1	0.9604	51.65	89.48
Lean	30	6	8.4	0.9587	49.63	89.64
Lean	45	1	4.3	0.9410	48.58	81.18
Lean	45	2	6.4	0.9548	50.58	84.58
Lean	45	3	6.1	0.9635	53.93	82.54
Lean	45	4	7.4	0.9624	54.26	82.36
Lean	45	5	6.7	0.9525	49.81	85.07
Lean	45	6	7.1	0.9517	48.01	82.73
Lean	60	1	<LOD	.	.	75.10
Lean	60	2	4.6	0.9376	44.45	74.79
Lean	60	3	6.7	0.9508	50.31	77.11
Lean	60	4	<LOD	0.9454	48.31	76.36
Lean	60	5	2.7	0.9390	45.52	78.25
Lean	60	6	2.6	0.9513	49.85	75.82
Lean	90	1	<LOD	0.8979	34.72	59.86
Lean	90	2	<LOD	0.8739	34.50	64.16
Lean	90	3	2.5	0.9103	44.99	64.91
Lean	90	4	<LOD	0.9010	37.39	67.63
Lean	90	5	<LOD	0.9368	40.49	66.69
Lean	90	6	<LOD	0.9146	38.48	63.19

Table 9: Collected data for *Salmonella* inactivation during bacon microwave cooking where humidity was controlled.

Condition	Cook time (s)	Replication	Slice	*Salmonella* Population (log CFU/g)	Moisture Content (% wb)	Water activity
Dry	0	1	A	9.1	56.2	0.971
Humid	0	1	B	9.1	54.3	0.973
Dry	0	2	A	8.9	49.1	0.948
Humid	0	2	B	8.9	54.7	0.968
Dry	0	3	A	9.0	48.4	0.972
Humid	0	3	B	9.1	56.7	0.968
Dry	0	4	A	9.0	51.2	0.974
Humid	0	4	B	9.1	50.2	0.974
Dry	0	5	A	8.8	47.3	0.973
Humid	0	5	B	9.0	47.2	0.976
Dry	0	6	A	9.0	56.2	0.975
Humid	0	6	B	9.0	48.2	0.970
Dry	45	1	A	7.3	35.6	0.948
Dry	45	1	B	6.9	47.7	0.947
Dry	60	1	A	6.7	46.8	0.950
Dry	60	1	B	6.6	35.5	0.931
Dry	150	1	A	3.9	16.8	0.711
Dry	150	1	B	4.1	16.7	0.731
Humid	45	1	A	7.2	47.9	0.956
Humid	45	1	B	6.7	50.0	0.957
Humid	60	1	A	6.5	47.7	0.950
Humid	60	1	B	6.8	43.8	0.955
Dry	45	2	A	7.9	49.0	0.956
Dry	45	2	B	7.6	50.2	0.954
Dry	60	2	A	7.2	37.2	0.931
Dry	60	2	B	6.6	37.1	0.937
Dry	150	2	A	2.7	14.7	0.668
Dry	150	2	B	4.7	18.4	0.729
Humid	45	2	A	7.4	48.8	0.954
Humid	45	2	B	6.5	41.8	0.945
Humid	60	2	A	6.8	48.3	0.952
Humid	60	2	B	4.5	40.1	0.935
Humid	150	2	A	4.5	22.1	0.781
Humid	150	2	B	3.1	14.5	0.644
Dry	45	3	A	7.8	48.6	0.964
Dry	45	3	B	7.3	35.1	0.956
Dry	60	3	A	6.7	41.0	0.957

Table 9 (cont'd)

Condition	Cook time (s)	Replication	Slice	*Salmonella* Population (log CFU/g)	Moisture Content (% wb)	Water activity
Dry	60	3	B	6.5	44.2	0.951
Dry	150	3	A	4.9	22.5	0.787
Dry	150	3	B	5.4	19.7	0.761
Humid	45	3	A	7.0	42.2	0.968
Humid	45	3	B	7.4	45.5	0.957
Humid	60	3	A	7.3	44.7	0.956
Humid	60	3	B	6.5	42.1	0.948
Humid	150	3	A	3.9	19.6	0.735
Humid	150	3	B	4.2	20.6	0.762
Dry	45	4	A	7.7	44.2	0.961
Dry	45	4	B	7.7	28.6	0.965
Dry	60	4	A	7.2	43.9	0.957
Dry	60	4	B	7.1	35.7	0.960
Dry	150	4	A	4.8	20.3	0.822
Dry	150	4	B	4.5	21.0	0.838
Humid	45	4	A	7.8	39.8	0.962
Humid	45	4	B	7.6	31.3	0.971
Humid	60	4	A	6.8	41.0	0.963
Humid	60	4	B	6.8	38.9	0.947
Humid	150	4	A	5.2	22.0	0.841
Humid	150	4	B	4.3	19.1	0.810
Dry	45	5	A	7.7	45.4	0.956
Dry	45	5	B	7.6	43.7	0.967
Dry	60	5	A	7.0	33.3	0.960
Dry	60	5	B	6.6	42.9	0.935
Dry	150	5	A	4.0	20.6	0.756
Dry	150	5	B	4.3	24.2	0.849
Humid	45	5	A	7.5	50.3	0.960
Humid	45	5	B	7.1	41.9	0.965
Humid	60	5	A	6.7	44.9	0.954
Humid	60	5	B	7.0	32.0	0.950
Humid	150	5	A	3.4	18.0	0.751
Humid	150	5	B	3.9	17.8	0.783
Dry	45	6	A	7.9	42.2	0.959
Dry	45	6	B	7.3	42.6	0.964
Dry	60	6	A	7.4	46.3	0.957
Dry	60	6	B	6.5	32.9	0.934
Dry	150	6	A	4.4	27.9	0.870
Dry	150	6	B	4.5	25.0	0.841

Table 9 (cont'd)

Condition	Cook time (s)	Replication	Slice	*Salmonella* Population (log CFU/g)	Moisture Content (% wb)	Water activity
Humid	45	6	A	7.4	46.2	0.968
Humid	45	6	B	7.4	42.0	0.959
Humid	60	6	A	6.9	-7.6	0.957
Humid	60	6	B	6.3	38.4	0.951
Humid	150	6	A	3.2	19.3	0.767
Humid	150	6	B	3.1	21.1	0.832

Table 10: Collected data for *Salmonella* inactivation during impingement oven cooking of bacon

Cook Temperature (°C)	Cook Time (min)	*Salmonella* Population (log CFU/g)	Water Activity	Moisture Content (% wb)	Yield (%)
232	0	9.3	0.974	37.53	
232	0	9.2	0.965	37.26	
232	0	8.8	0.970	46.07	
232	0	9.2	0.969	31.21	
232	0	9.3	0.968	34.15	
232	0	9.1	0.965	48.51	
232	0	9.2	0.973	48.33	
232	0	9.3	0.973	47.79	
232	0	9.1	0.976	47.02	
232	0	8.8	0.969	39.30	
232	0	8.5	0.972	40.51	
232	0	8.7	0.972	45.82	
232	0	9.1	0.970	23.17	
232	0	9.0	0.971	43.74	
232	0	9.0	0.967	45.21	
232	0	8.9	0.981	42.30	
232	0	8.9	0.974	37.28	
232	0	8.9	0.973	39.25	
232	1	<LOD	0.949	33.92	79.6
232	1	<LOD	0.966	42.81	82.7
232	1	<LOD	0.941	28.23	77.4
232	1	<LOD	0.961	42.96	82.6
232	1	<LOD	0.956	36.10	79.8
232	1	<LOD	0.968	43.31	80.6
232	1	<LOD	0.949	36.44	81.9
232	1	<LOD	0.960	42.01	80.9
232	1	<LOD	0.945	19.09	77.2
232	1	<LOD	0.957	38.35	81.5
232	1	<LOD	0.958	42.62	81.5
232	1	1.3	0.965	38.28	80.7
232	1.5	<LOD	0.935	38.58	76.9
232	1.5	<LOD	0.951	42.25	76.0
232	1.5	<LOD	0.916	26.51	70.9
232	1.5	<LOD	0.949	40.32	76.1
232	1.5	<LOD	0.948	33.52	73.3
232	1.5	<LOD	0.961	41.49	72.6

Table 10 (cont'd)

Cook Temperature (°C)	Cook Time (min)	*Salmonella* Population (log CFU/g)	Water Activity	Moisture Content (% wb)	Yield (%)
232	1.5	<LOD	0.933	34.53	74.9
232	1.5	<LOD	0.949	38.91	74.5
232	1.5	<LOD	0.947	25.34	73.6
232	1.5	<LOD	0.936	36.83	70.6
232	1.5	<LOD	0.954	40.58	77.7
232	1.5	1.7	0.945	36.25	75.8
232	2	<LOD	0.934	36.00	70.3
232	2	<LOD	0.949	40.60	70.2
232	2	<LOD	0.893	25.20	65.6
232	2	<LOD	0.948	37.35	70.7
232	2	<LOD	0.932	36.07	64.1
232	2	<LOD	0.943	39.67	67.5
232	2	<LOD	0.926	36.53	68.5
232	2	<LOD	0.940	36.72	65.4
232	2	<LOD	0.922	25.95	64.6
232	2	<LOD	0.923	35.44	60.3
232	2	<LOD	0.941	39.79	71.2
232	2	2.3	0.936	35.17	69.8
232	6	<LOD	0.379	4.65	30.8
232	6	1.2	0.537	7.23	32.6
232	6	<LOD	0.321	2.61	36.4
232	6	<LOD	0.506	6.32	31.6
232	6	<LOD	0.119	0.66	30.1
232	6	<LOD	0.479	6.61	30.7
232	6	<LOD	0.274	3.62	36.8
232	6	<LOD	0.462	6.53	31.9
232	6	<LOD	0.173	0.57	26.6
232	6	<LOD	0.131	1.79	25.0
232	6	<LOD	0.715	16.20	43.1
232	6	<LOD	0.590	9.21	36.4
177	0	9.3	0.974	37.53	
177	0	9.2	0.965	37.26	
177	0	8.8	0.970	46.07	
177	0	9.2	0.969	31.21	
177	0	9.3	0.968	34.15	
177	0	9.1	0.965	48.51	
177	0	9.2	0.973	48.33	

Table 10 (cont'd)

Cook Temperature (°C)	Cook Time (min)	*Salmonella* Population (log CFU/g)	Water Activity	Moisture Content (% wb)	Yield (%)
177	0	9.3	0.973	47.79	
177	0	9.1	0.976	47.02	
177	0	8.8	0.969	39.30	
177	0	8.5	0.972	40.51	
177	0	8.7	0.972	45.82	
177	0	9.1	0.970	23.17	
177	0	9.0	0.971	43.74	
177	0	9.0	0.967	45.21	
177	0	8.9	0.981	42.30	
177	0	8.9	0.974	37.28	
177	0	8.9	0.973	39.25	
177	1	<LOD	0.952	34.89	84.1
177	1	<LOD	0.967	44.37	85.5
177	1	<LOD	0.948	28.05	84.0
177	1	<LOD	0.969	41.24	84.5
177	1	<LOD	0.959	34.57	84.5
177	1	<LOD	0.975	42.99	81.8
177	1	<LOD	0.951	31.27	86.0
177	1	0.8	0.964	43.75	86.1
177	1	<LOD	0.943	19.56	85.7
177	1	<LOD	0.954	38.80	85.3
177	1	<LOD	0.959	38.23	86.7
177	1	<LOD	0.959	37.48	84.1
177	2	<LOD	0.938	34.73	75.8
177	2	<LOD	0.958	42.10	75.6
177	2	<LOD	0.939	29.62	73.9
177	2	<LOD	0.956	41.26	79.7
177	2	<LOD	0.952	24.32	76.7
177	2	<LOD	0.962	41.06	77.5
177	2	<LOD	0.945	38.22	78.2
177	2	<LOD	0.954	39.23	78.0
177	2	<LOD	0.937	18.70	76.1
177	2	<LOD	0.951	38.32	77.3
177	2	<LOD	0.954	40.31	77.1
177	2	<LOD	0.952	36.32	78.8
177	3	<LOD	0.938	35.68	71.5
177	3	<LOD	0.953	41.02	70.9

Table 10 (cont'd)

Cook Temperature (°C)	Cook Time (min)	*Salmonella* Population (log CFU/g)	Water Activity	Moisture Content (% wb)	Yield (%)
177	3	<LOD	0.903	26.32	67.5
177	3	<LOD	0.957	38.08	71.7
177	3	<LOD	0.936	36.93	65.9
177	3	<LOD	0.943	39.21	71.4
177	3	<LOD	0.934	33.76	71.7
177	3	<LOD	0.948	35.24	70.1
177	3	<LOD	0.926	24.36	69.3
177	3	<LOD	0.942	37.26	70.0
177	3	<LOD	0.946	39.90	73.8
177	3	<LOD	0.953	36.98	70.0
177	10	<LOD	0.533	9.60	33.0
177	10	0.6	0.608	10.61	33.7
177	10	<LOD	0.530	7.00	37.7
177	10	<LOD	0.689	12.87	32.7
177	10	<LOD	0.389	4.56	35.5
177	10	<LOD	0.721	15.76	33.7
177	10	<LOD	0.625	11.19	40.4
177	10	<LOD	0.669	12.03	35.9
177	10	<LOD	0.221	2.51	32.8
177	10	<LOD	0.486	8.47	29.9
177	10	<LOD	0.687	12.57	39.4
177	10	<LOD	0.723	15.71	42.5

APPENDIX B: Collected Data from Apple Drying Study

Table 11: Collected data for *Listeria monocytogenes* inactivation during apple drying

Temperature (°C)	Air velocity (m/s)	Drying time (min)	Replication	*Listeria* Population (log CFU/g undried_mass)	Moisture content (%wb)	Water activity
60	0.7	0	1	8.3	.	.
60	0.7	0	1	8.4	85.25	0.994
60	0.7	30	1	8.7	78.85	0.976
60	0.7	60	1	8.0	71.05	0.971
60	0.7	90	1	8.3	50.93	0.901
60	0.7	120	1	7.6	26.19	0.655
60	0.7	150	1	7.0	22.55	0.528
60	0.7	180	1	6.4	15.08	0.379
80	0.7	0	1	8.9	.	.
80	0.7	0	1	8.8	84.28	0.991
80	0.7	30	1	8.1	73.24	0.973
80	0.7	60	1	7.6	51.50	0.909
80	0.7	90	1	6.8	18.59	0.507
80	0.7	120	1	4.5	12.04	0.310
80	0.7	150	1	3.4	9.69	0.231
60	2.1	0	1	8.9	.	.
60	2.1	0	1	8.4	85.74	0.989
60	2.1	30	1	8.6	64.92	0.956
60	2.1	60	1	8.3	74.91	0.976
60	2.1	90	1	7.7	45.61	0.843
60	2.1	120	1	7.5	33.44	0.704
60	2.1	150	1	7.5	24.14	0.414
60	2.1	180	1	6.5	19.58	0.383
80	2.1	0	1	8.3	.	.
80	2.1	0	1	8.4	84.12	0.990
80	2.1	30	1	7.8	70.66	0.961
80	2.1	60	1	7.3	44.67	0.857
80	2.1	90	1	5.5	17.73	0.282
80	2.1	120	1	2.6	17.39	0.260
80	2.1	150	1	2.7	14.01	0.254
80	0.7	0	2	9.1	.	.
80	0.7	0	2	9.1	88.40	0.994
80	0.7	30	2	8.6	76.09	0.974
80	0.7	60	2	8.1	58.87	0.926
80	0.7	90	2	7.4	27.10	0.673

Table 11 (cont'd)

Temperature (°C)	Air velocity (m/s)	Drying time (min)	Replication	*Listeria* Population (log CFU/g undried_mass)	Moisture content (%wb)	Water activity
80	0.7	120	2	4.3	17.98	0.411
80	0.7	150	2	3.6	14.15	0.245
80	2.1	0	2	8.3	.	.
80	2.1	0	2	8.3	85.11	0.991
80	2.1	30	2	7.3	68.73	0.947
80	2.1	60	2	6.8	29.37	0.681
80	2.1	90	2	4.7	14.32	0.305
80	2.1	120	2	4.2	12.63	0.269
80	2.1	150	2	3.7	12.75	0.232
60	0.7	0	2	8.6	.	.
60	0.7	0	2	8.3	85.47	0.983
60	0.7	30	2	8.6	78.33	0.976
60	0.7	60	2	8.2	71.69	0.962
60	0.7	90	2	8.1	60.02	0.934
60	0.7	120	2	8.2	42.35	0.850
60	0.7	150	2	7.5	25.40	0.661
60	0.7	180	2	7.0	15.62	0.490
60	2.1	0	2	8.5	.	.
60	2.1	0	2	8.9	85.01	0.987
60	2.1	30	2	8.0	75.07	0.956
60	2.1	60	2	8.1	64.45	0.869
60	2.1	90	2	7.6	45.23	0.869
60	2.1	120	2	7.4	30.08	0.707
60	2.1	150	2	5.4	16.86	0.523
60	2.1	180	2	5.3	11.23	0.358
80	0.7	0	3	8.8	.	.
80	0.7	0	3	8.7	83.06	0.987
80	0.7	30	3	8.1	76.52	0.957
80	0.7	60	3	8.0	56.29	0.898
80	0.7	90	3	7.4	24.03	0.636
80	0.7	120	3	4.4	11.87	0.226
80	0.7	150	3	4.1	9.07	0.197
80	2.1	0	3	8.9	.	.
80	2.1	0	3	8.9	83.37	0.992
80	2.1	30	3	7.5	68.12	0.955
80	2.1	60	3	6.6	21.31	0.578
80	2.1	90	3	4.4	11.23	0.260
80	2.1	120	3	3.9	10.31	0.219

Table 11 (cont'd)

Temperature (°C)	Air velocity (m/s)	Drying time (min)	Replication	*Listeria* Population (log CFU/g undried_mass)	Moisture content (%wb)	Water activity
80	2.1	150	3	3.5	8.66	0.138
60	0.7	0	3	8.7	.	.
60	0.7	0	3	8.9	86.63	0.993
60	0.7	30	3	8.5	82.27	0.977
60	0.7	60	3	8.2	74.47	0.965
60	0.7	90	3	7.8	57.82	0.930
60	0.7	120	3	8.0	44.00	0.820
60	0.7	150	3	6.8	24.92	0.606
60	0.7	180	3	6.9	21.80	0.549
60	2.1	0	3	7.8	.	.
60	2.1	0	3	8.2	85.51	0.992
60	2.1	30	3	7.4	75.76	0.974
60	2.1	60	3	7.9	63.15	0.936
60	2.1	90	3	7.7	37.39	0.784
60	2.1	120	3	6.6	27.75	0.690
60	2.1	150	3	5.6	17.03	0.482
60	2.1	180	3	5.1	12.39	0.340