Recieved: 08/08/2023 Revised: 04/09/2023

Accepted article published: 14/09/2023

Published online: 14/09/2023

Thermal and Nonthermal Inactivation of Foodborne Pathogens on Low-Moisture Foods: A Systematic Review

Norfaziey Aini Sukarno¹, Arthika Kalaichelvan⁴, Pichamon Limcharoenchat⁵, Noor Azira Abdul Mutalilb^{1,3}, Nurul Hawa Ahmad^{1, 2, 3*}

¹Faculty of Food Science and Technology, University Putra Malaysia, 43300 UPM Serdang, Selangor, Malaysia

²Halal Products Research Institute, Putra Infoport, University Putra Malaysia, 43300 UPM Serdang, Selangor, Malaysia

³Institute of Tropical Agriculture and Food Security, University Putra Malaysia, 43300 UPM Serdang, Selangor, Malaysia

⁴Faculty of Livestock, Fisheries, and Nutrition, Wayamba University of Sri Lanka, Makandura, 60170 Gonawila, Sri Lanka

⁵Faculty of Science, Maejo University, 50290 Chiang Mai, Thailand

*Correspondence; Nurul Hawa Ahmad E-mail: nurulhawa@upm.edu.my ORCID No: 0000-0001-5786-6655



Licensee Food Analytica Group, Adana, Turkey. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license

(https://creativecommons.org/licenses/by/4.0). DOI: https://doi.org/10.57252/jrpfoods.2023.5

Abstract

Low-moisture foods (LMF) are generally regarded as safe because microbes typically do not survive in water activity less than 0.85. Previous studies have shown that pathogens are capable to persist in dry conditions for an extended period and may acquire resistance to subsequent killing steps. As a result, there are major foodborne outbreaks and product recalls associated with LMF causing hospitalizations and even death. Given that the persistence of the foodborne pathogens in LMF is not widely understood. The objective of this review is to provide the current knowledge of thermal and nonthermal treatments of foodborne pathogens in LMF and discuss the effectiveness of thermal and nonthermal treatments for LMF processing. A total of 137 articles were used after inclusion and exclusion criteria were applied. Many parameters affect the effectiveness of the treatments such as water activity, temperature, time, product formulation. Predictive models for instance Bigelow, Weibull, and Kopelman model can be used to design the inactivation steps in LMF. Different treatments are needed to inactivate different pathogens of LMF products thus food manufacturers should implement the most effective way to kill the pathogen according to the food produced.

Keywords: Low-moisture food, Thermal processing, Nonthermal processing, Predictive model, Foodborne pathogens

1.INTRODUCTION

Low moisture foods (LMF) are food that contains water activity (aw) less than 0.85 (Codex, 2018). Some examples of low moisture foods are cereals, chocolate, cocoa powder, dried fruits and vegetables, egg powder, fermented dry sausage, flour, meal and grits, and condiments, spices hydrolyzed vegetable protein powder, meat powders, dried meat, milk powder, pasta, peanut butter, peanuts, tree nuts, powdered infant formula (PIF), grains and seeds such as sesame, melon, pumpkin, linseed (Beuchat et alet al., 2013). These past years many foodborne outbreaks have been related to low moisture foods, and caused severe illnesses and deaths

(Alshammari et al., 2020a; Beuchat et al., 2013; Mondal et al., 2014; Shah et al., 2017; Van Doren et al., 2013). In low water activity and dry food processing and preparation conditions, some of these foodborne pathogens can survive for months, even years. They are higher resistant to heat and other treatments than high water activity products/conditions (Beuchat et al., 2013). The main foodborne pathogens that cause outbreaks in low moisture foods such as flour, cake mix, cereals, ginger powder, and herbal teas around the globe are Listeria monocytogenes (Taylor et al., Escherichia coli (CDC, 2019; CDC, 2021), and Salmonella (CDC, 2018; Falkenstein, 2017;

Keller et al., 2015). While most strains of E. coli are harmless, others can cause illness and some E. coli strains can cause diarrhea, while others can cause urinary tract infections, respiratory illness, pneumonia, and other illnesses (CDC, 2022). Listeria can cause fever and diarrhea in the same way that other foodborne germs do, but this type of Listeria infection is uncommon (CDC, 2022). The symptoms of invasive listeriosis, which means the bacteria has spread beyond the gut, vary depending on whether the person is pregnant (CDC, 2022). There are few ways to inactivate foodborne pathogens in foods for example thermal and nonthermal treatments.

Thermal processing is the combination of temperature and time needed to reduce the microbial load in the food. There are a few examples of thermal processing technologies for example extrusion, radiofrequency, and steam (Wason et al., 2021a). Thermal processing is also one of the most effective ways and is commonly used to kill harmful germs in food (Pan et al., 2017; Silva and Gibbs, 2012a). Proper time and temperature exposure can eliminate most of the microbial load present in the food. Heat is used to kill pathogens as well as develop the flavor, aroma, texture, and color of a cooked dish (Silva and Gibbs, 2012b). However, pathogens are difficult to eliminate from foods with low water activity using techniques like mild heat treatment, which works well for foods with high water activity which is concerning since some of the foodborne pathogens such as Salmonella and Escherichia coli O157:H7 only need a few cells to survive and cause further outbreaks (Beuchat et al., 2013). In a dehydrated condition, the metabolism of the pathogens is greatly reduced thus there is no growth, but the vegetative cells and spores may remain viable for several months or even years (Beuchat et al., 2013). Thermal processing also causes some undesirable changes and may form a byproduct that will negatively affect the flavor, texture, nutritional value of the final product (Pan et al., 2017). This may adversely affect the sales of the product since people are getting conscious about the nutritional value present in their food thus prefer more natural and less processed food.

Nonthermal methods are gaseous technologies that are being used to eliminate the microbial load present in food (Wason et al., 2021a). Nonthermal technologies are based on an electromagnetic field which includes pulsed electric fields, high voltage arc discharge, pulsed light, ionizing radiation, microwave and cold plasma (Pan et al., 2017). Nonthermal inactivation is significant to reduce the negative impact on the food and increase the shelf life of the products. The benefit of using the nonthermal method is the ability of the gaseous to diffuse through the air spaces and pores thus allowing the gaseous to eliminate the microbial load even with irregularly shaped food (Wason et al., 2021a). Furthermore, combining these approaches with thermal treatment can lower the treatment temperature while still achieving large microbe reductions in food (Pan et al., 2017). Some of the nonthermal processing is not applicable for low moisture food for example chlorine dioxide (ClO2), hydrogen peroxide (H2O2), and high-pressure processing (HPP) (Wason et al., 2021b).

LMF's are commonly assumed as safe food from microorganisms, however, there are many recorded outbreaks regarding LMF particularly caused by Salmonella. Mountain Mel's is recalling herbal teas, including those that are intended for babies and toddlers, due a risk of Salmonella infection of ingredients (Food and Drug Administration, n.d.). Salmonella can survive for a long time, and because low-moisture foods are long-lasting and have a long shelf life, Salmonella can harm customers for years by causing subsequent infections. Thus, more studies about the inactivation of the foodborne pathogen in low moisture need to be conducted to improve food safety around the

globe. The expected outcome of this review is to cover the effective ways to reduce or kill the foodborne pathogens that survive in LMF. The objective of this review is to provide the current of thermal and nonthermal treatments of foodborne pathogens in LMF and discuss the effectiveness of thermal and nonthermal treatments for LMF processing..

2. Materials and Methods Literature Search and Search Strategy

A literature search was conducted through Scopus and Science Direct databases using keywords searches for low-moisture foods, thermal inactivation, and non-thermal inactivation. The keywords used for the Scopus search engine were "low-moisture foods" and ("thermal inactivation" or "non-thermal inactivation") while for Science Direct search engines were "low-moisture foods" AND ("thermal inactivation" OR "non-thermal inactivation"). No restrictions were placed on the subject area of the searches. Restrictions are only placed on the date published, document type and language. The date of publications was restricted between 2000 to the present; the last search was conducted on 1st September 2021. This review only included the research articles document type that has been written in English. After removing duplicates and reviewing papers, the remaining articles were screened based on inclusion and exclusion criteria (Table 1), by three researchers independently to minimize bias

Table 1. Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
Study on thermal inactivation or nonthermal	Review paper
inactivation on LMF	Research articles on animal feed, antimicrobial
Tested on foodborne pathogens.	agent of the LMF, only storage or survival of
Surrogate study of the foodborne pathogen	microbes, surveys, RSM without microbes, study on
	inoculation only or sanitizing solution.

Inclusion and Exclusion Criteria

Acceptability criteria are research articles that evaluates the effectiveness of thermal inactivation or nonthermal inactivation step for LMF. All articles in the study focused on LMF as the primary outcome. Data compilation from original articles provided adequate discussion to meet the objectives of this review. As primary data needed were not always available from review articles, they were excluded in the article selection. Studies that were focusing on the efficacy of antimicrobial agent and optimization processing of parameters in LMF were also excluded as these studies are more relevant to food product development.

Studies that were focusing only on the pathogen behaviour under multiple stresses including dry environment, were included although without the present of LMF, as these studies would provide an in-depth explanation on the mode of pathogen inactivation when subjected to newly developed kill step protocol. Studies utilizing that were surrogate microorganisms are included because selecting appropriate surrogate microorganism for intended pathogen is critical for process validation as the use of pathogenic microorganism is not recommended in the food processing operations. The summary of article selection process is illustrated in Figure 1.

Figure 1

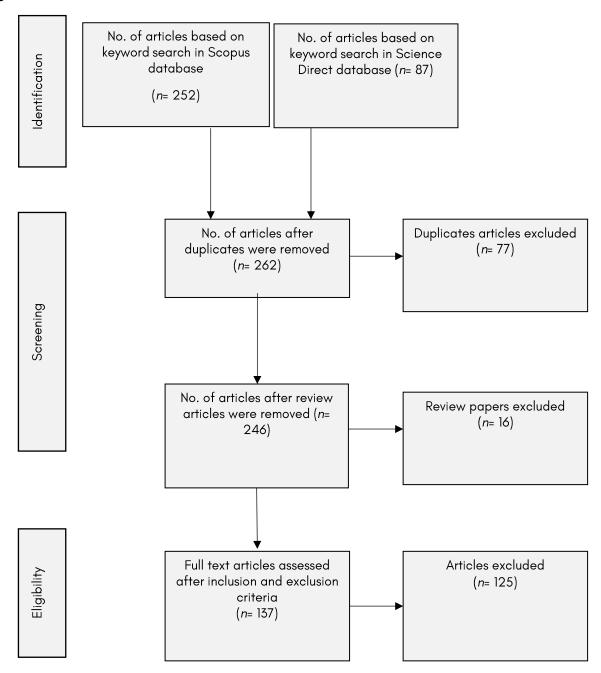


Fig 1 Flowchart of the article selection process

Results and Discussion

The food industry has a vital task to mitigate or controls the inactivation of foodborne pathogens in low-moisture foods. Preventative control may include additional treatments to ensure the safety and verification of these treatment methods. Currently, there is a lack of tools and methods for process validation in LMF processing. The treatment and product factors selected are one of the key parameters that determine the validation of the pasteurization process. The development of verification protocols for LMF processing technologies also requires the identification of appropriate surrogate microorganisms.

Overall, 137 articles were selected from a total of 262 articles derived from Scopus and ranging 2000-2021. Science Direct Information regarding the target microorganisms, food samples, processing parameters, log reduction or/and D- and Zvalues, inactivation models used to obtain the D- and z-values, and the summary of significant findings were reported in Table 2 and Table 3. for thermal treatment and nonthermal treatment, respectively.

Thermal Inactivation

Thermal inactivation is widely used to reduce microbial loads in LMFs all over the world. While thermal treatments can eliminate or reduce microbial load, choosing the best processing method to maintain product quality are considerate validation (Wason et al., 2021b). Most of the industrial-scale technologies are used to eliminate or reduce the microbial loads in food processing. Thermal processing is the common technology applied and approved by regulatory and international agencies, to inactivate spoilage and pathogenic bacteria, while also providing food with adequate stability during storage. The intensity of the treatments will determine the stability of the product during storage conditions for the suggested time frame (Bermúdez-Aguirre and Corradini, 2012).

The microbial cell's DNA, RNA, ribosome, cell envelope, and proteins can all be destroyed by thermal inactivation. By using treatment, the magnitude of microbial damage is as follows: protein, RNA, cell wall, and lastly DNA. The microbial cell's DNA, RNA, ribosome, cell envelope, and proteins can all be destroyed by thermal inactivation. The magnitude of microbial damage after infrared treatment is as follows: protein is followed by RNA, then the cell wall, and finally DNA (Rifna et al., 2019). However, mild, and high heat treatment that works well for foods with high water activity might not eliminate all foodborne pathogen in LMFs. Pathogens such as Salmonella and Escherichia coli O157:H7 only need a few cells to survive and cause further outbreaks. The vegetative cells and spores may remain viable for several months or even years (Beuchat et al., 2013). The review also states that the heat is transferred differently in conventional thermal treatment, processing times are reduced, and heat-food contact is reduced thus significantly reducing the negative effect of heat on food characteristics. In this section, different thermals treatments and their' efficacies are reviewed to reduce the microbial loads in low-moisture foods.

Liquid-heated bath

The water bath, ethylene glycol bath, and oil bath were used as liquid medium in thermal inactivation of foodborne pathogens and surrogates such as Salmonella, monocytogenes, and Enterococcus faecium. Types of bath liquids impact thermal efficiency. Oil bath was used when the inactivation temperature was above 100°C. The water bath is laboratory equipment that is used to incubate samples at a certain temperature for an extended time (Baths, 2020). According to the results, most studied low-moisture foods are powder milk, flours, nuts (such as almonds and pecans) with a temperature range of between 60 to 90°C. The common primary models used are the Weibull model and the Bigelow model.

Water bath thermal treatment shows a significant reduction of foodborne pathogens in LMF (Sekhon et al., 2021). Few factors affect the effectiveness of water baths in reducing the microbial load for instance fat content, moisture content, inoculation method, temperature, time and water activity (Daryaei et al., 2020; Limcharoenchat et al., 2018; Quinn et al., 2021). Lower moisture content and water activity may cause lower microbial reduction, thus higher temperature and longer time exposure is needed to achieve the same log reduction as high moisture content and water activity food (Daryaei et al., 2020). High carbohydrates content in food may result in higher thermal resistances in storage and heat treatments (He et al., 2011). The findings also suggested that contamination events during prefabrication may be more concerning in process validation (Limcharoenchat et al., 2018). Additional tests are being carried out to quantify Salmonella thermal resistance in various product structures at different aw levels, to model Salmonella behavior in a variety of LMF. Future research on secondary inactivation models to apply for process validation, must account for dynamic moisture during processing.

For example, a study was conducted by Quinn et al., (2021) shows that Salmonella spp. in powder infant formula had the highest thermotolerance Listeria among monocytogenes, Salmonella spp. and E. faecium in peanut butter, powder infant formula and wheat flour. Salmonella was also tested in dry and dehydrated non-fat dry milk and whole milk powder using water bath (80 to 90°C), resulting low inactivation rate (Sekhon et al., 2021). Additionally, the sorption state LMF products should be considered prediction of bacterial inactivation kinetics, developing models and validation processes (Garces-vega et al., 2019).

The ethylene glycol bath is a promising thermal treatment that can reduce the microbial load up to 5 log reduction in LMF. Some studies

have been conducted to test the microbial inactivation using ethylene glycol baths in cocoa powder, non-fat dairy milk, and wheat flour. Some of the pathogens studied are Listeria monocytogenes, Salmonella spp., and Enterococcus faecium with the temperature range from 70 to 80°C. Water activity is a significant factor for reducing Salmonella loads in cocoa powder (Tsai, et al., 2019a). The log reduction of Listeria monocytogenes was more than 4 log CFU/g when tested on the same food sample which cocoa powder with the same parameters. (Tsai et al., 2019b). monocytogenes was reduced up to 5 log reduction when tested in non-fat dry milk under the parameters of water activity is 0.30, the temperature of 80°C and 60 min of treatment time (Ballom et al., 2020). However, the most significant impact of milk powder pasteurization is browning, which is caused by the formation of melanoidins in the final stage of the Maillard reaction which happens during heating if the heat is very high (Wei et al., 2020a).

The most studied food samples in oil bath are wheat flour and some other food such as confectionary, seasoning, chicken meat powder, peanut oil, and almonds. The most studied foodborne pathogens are Salmonella spp. and Enterococcus faecium. The oil bath treatment is more effective compared to hot water treatment for Salmonella Enteritidis PT 30 in almonds due to higher inactivation rate at the same temperature (Mohammad et al., 2020). Other than that, a study confectionary, seasoning, and chicken meat powder was conducted and highlighted that 5reduction of Salmonella. log Listeria monocytogenes, and Enterococcus faecium can be inactivated with the temperature of 111.2, 105.3 or 111.8°C respectively with the time ranging from 1.5 to 2 min (Rachon et al., 2016). A correlation between temperature and water activity based on the fat and protein content and indicate that these parameters must be considered predicting in the thermal

inactivation in foods (Yuqiao et al., 2018). Moreover, a study of Enterococcus faecium in peanut oil resulting in less than 1 log reduction concluded that oil acts as a barrier to moisture diffusion is another mechanism that will cause oil's protective effect on bacteria from thermal inactivation (Amninder et al., 2021).

Steaming and vacuum steam pasteurization

Steaming is one of the methods studied that effectively reduce the microbial load in black peppercorns, almonds and pistachios and maintains the product quality and the temperature used are between 70 - 200°C (Ban and Kang, 2016; Zhou et al., 2019). The steam process direct raises the temperature of the food, the mechanism for microbial inactivation is like that of the thermal process. The structure of proteins, nucleic acids, and lipids is harmed by these high temperatures and causes protein and nucleic acid denaturation, which disrupts cell metabolism. Lipids melt within the cell membrane to maintain cellular content. resulting in cell lysis microorganism inactivation (Wason et al., 2021). However, there is a limitation in superheated steaming which is ineffective towards high moisture content food (Ban et al., 2018).

Ban and Kang (2016) tested E. coli, Salmonella and Listeria spp. in almonds and pistachios with the temperature of 100 - 200°C and the treatment time is between 1- 30s. The log reduction are $3.0 - 6.2 \log CFU/g$ for E. coli, 2.7 – 6.5 log CFU/g for Salmonella spp. and 2.7 - 5.7 log CFU/g for Listeria spp. and D100 $^{\circ}$ C = 5.28 - 9.88, D100°C = 4.87 - 11.15, D100°C = 6.68 – 11.12, respectively. The finding from this study is that superheated steaming is an effective method for inactivation foodborne pathogens in almonds and pistachios while maintaining the quality of the products. More than 5 log reduction was able to achieve targeting E. faecium in peanut butter with temperature used 125 - 250°C and water activity 0.19 - 0.80 (Park et al., 2021). The D values and Z value recorded are D125 $^{\circ}$ C = 129.70 - 6.33s, D175°C = 32.41 - 3.38s, D225°C= 24.62 - 1.93s, D250°C= 18.49 - 3.22s and Z value = 194.66°C (Park et al., 2021). The highlight of this study is the inactivation results are applicable to environmental surfaces for effective inactivation of the pathogens. Salmonella spp. was tested in black peppercorns, pecans, and almond by using superheated steaming with temperature ranging from 100 - 180°C and the log reduction recorded was more than 6 log CFU/g. The D100°C = 4.65 - 9.2 while the Z-value = 47.06 - 146.26°C (Ban et al., 2018).

Other than that, vacuum steam pasteurization is a heat treatment process that kills pathogenic microorganisms in specific foods and beverages (Pasteur and States, n.d.). Most studies using pasteurization are flaxseed, quinoa, sunflower kernels, black peppercorns, macadamia, raisins, and many more using the Weibull model and Geeraerd-tail model. The temperature range used are between 60 -105°C. Short time exposure of vacuum steam pasteurization in spices can effectively reduce the microbial load up to 5 log reduction (Newkirk et al., 2018; Shah et al., 2017). Vacuum steam pasteurization has proven to effectively reduce the total aerobes, yeast, and moulds and the chemical properties are not significantly affected by this treatment (Malekmohammadi et al., 2020; Shah et al., 2018). It is a method for improving the safety of dried fruits and nuts in a short time, depending on the temperature exposed (Acuff et al., 2020).

Salmonella Enteritidis PT30, Enterococcus faecium NRRL B-2354 ATCC 8459 and Escherichia coli O157:H7 are tested in flaxseed, quinoa, sunflower kernels, and black peppercorns with the temperature of 75 – 105°C within the time of 0.5 to 5.0 mins able to reduce ~7 to 8 log CFU/g of the microorganisms. The significant findings from this study is that the pathogens were reduced by more than 5 logs in whole flaxseed, sunflower kernels, and peppercorns at 75°C and milled flaxseed and quinoa at 85°C (Shah et al., 2017).

A study conducted by Acuff et al. (2020) by targeting Salmonella, E. coli, Listeria monocytogenes, and Pediococcus acidilactici in apricot, macadamia and raisins, by using vacuum steam pasteurization with temperature of 62 - 82°C and O -5 mins able to achieve more than 5 log reduction with the D value recorded D72 $^{\circ}$ C = 0.8 – 7.5, D72 $^{\circ}$ C = 0.8 -5.4, D72°C = 0.7 -7.3, and D72°C = 1.1 -10.3, respectively. The findings from the study is that depending the temperature, on lowtemperature, vacuum-assisted pasteurisation provides a strategy for improving the safety of dried fruits and nuts in relatively short time periods. Salmonella was tested in flaxseed with the processing parameters of 71°C and 0.5 water activity and the D value recorded is D71°C = 1.0 to 1.5 with the significant finding that the time stored before the heat treatment would have a small impact on the time required inactivate Salmonella in flaxseeds to (Malekmohammadi et al., 2020). Salmonella and E. faecium was tested in whole peppercorns and cumin seed with the temperature of 177°C, the log reduction recorded are 1.92 - 1.93 and 1.64 - 2.3 log CFU/ respectively (Newkirk et al., 2018). The findings from this article is that vacuum assisted steam pasteurization of spices was effective in reducing Salmonella and Enterococcus faecium may be used as a surrogate for inactivation on whole peppercorns and cumin seeds (Newkirk et al., 2018). The conclusions and recommendations for thermal pasteurization can be extended to non-thermal pasteurisation processes, as it is necessary to determine microbial D- and z-values, or nonthermal resistance parameters of other models, concerning the new technologies (Silva and Gibbs, 2012). Future studies need to conduct with different parameters to confirm the effectiveness of vacuum steam pasteurization. Roasting

Roasting usually been done for LMF such as cocoa beans, sunflower seeds, etc. between the temperature range 90 - 150°C.

Salmonella is proven to be inactivated over 5 log reduction using roasting using the right exposure and time (Yan et al., 2021). Salmonella that survives during the heat treatment may survive in room temperature storage (Zhang et al., 2017). Heat resistance data obtained under specific experimental conditions, on the other hand, cannot be used to validate thermal cocoa and chocolate processes by manufacturers. A study was conducted by Yan et al., (2021) found that the log reduction is 2.8 - more than 5 log CFU/g for Salmonella Oranienburg in cocoa beans with the treatment temperature (100 - 150°C) and time (2- 100 mins). The D-value recorded are D100°C: 33.34, D110°C: 18.7, D115°C: 12.92, D120°C: 10.50, D130°C: 4.20, D140°C: 1.9 with the Z-value: 32.0°C; the study indicates that 10 mins of roasting at 150°C able to reduce 5 log reduction of Salmonella. Similarly, few strains of Salmonella (Salmonella Typhimurium, Salmonella Newport, Salmonella Enteritidis and Salmonella Tennessee) were tested sunflower seeds and the log reduction is more than 4 log CFU/g (Kottapalli et al., 2020). The temperature used are 107.2 - -135°C with the treatment time of 5 -45 mins and it claims that after roasting the sunflower seeds for 45 minutes at 135°C have saleable water activities, resulting in a.7-log reduction in Salmonella (Kottapalli et al., 2020). Zhang et al., (2017) demonstrated that more than 4 log CFU/g of Salmonella can be reduce in tahini after the storage time of 119 days with the temperature of 95-130 °C and time between 0-90 mins. The D value recorded are D90°C = 24.7 and D130°C = 15.0; this study mentioned that there are no changes in Salmonella population after 119 days of storage (Zhang et al., 2017). These findings highlight the critical importance of aw during the roasting step, and Salmonella that survives roasting is likely to survive the tahini's in RT.

A risk assessment analysis is required to determine the level of safety for Salmonella contamination in this type of product and, as a result, the parameters of its thermal processes. Environmental conditions such as temperature and humidity, which have been linked to Salmonella outbreaks linked to almond consumption or the presence of Salmonella in almonds, require further research.

TDT Sandwich

The TDT Sandwich was created as an open-source, free alternative that uses dry heat. The system can heat samples to 140°C and keep them within ±0.2°C of the target temperature (Lau and Subbiah, 2020). Most studies conducted the TDT sandwich with the temperature range of 60 to 95°C with food samples such as whole black peppercorns, wheat flour, almond meal, skim milk powder, desiccated shredded coconut and some types of sugar. The log reduction of foodborne pathogen ranges from 0.2 to more than 8 log CFU/g. The almond flour would need to be fully exposed to 80°C for 120 minutes to achieve a 6-log reduction of Salmonella Enteritidis PT30 (Xu et al., 2019). Mild thermal treatments can be used to control Salmonella in cinnamon powder, as well as possibly other antimicrobialcontaining spices or herbs, for better product quality retention (Xie et al., 2021). Water activity had a strong influence on the D-values of Salmonella and Enterococcus faecium in ground black pepper. Lower water activity increased the thermal resistance of Salmonella and Enterococcus faecium in ground black pepper (Wei, Vasquez, et al., 2021a).

Recently, Salmonella spp. in whole black peppercorns was tested using TDT cells and the log reduction achieved was 0.41 - 2.19 log CFU/g and the D75°C = 106 - 198 mins with the temperature used of 60 - 85°C. The study highlighted that modifying the food water activity may be an effective way to achieve the required level of pathogen activation in a relatively short period of time at low treatment temperatures (Marco et al., 2021). Similar to study conducted by Tsai et al., (2019a), more than 5 log of Salmonella spp. in soy protein

powder was reduce by using temperature ranging from 60 - 95°C (Tsai et al., 2019a). The study concluded that Salmonella thermal resistance are affected by the temperature and the water activity of the food. Recently, Salmonella spp., Listeria spp. and Enterococcus faecium was tested in desiccated shredded coconut and the log reduction recorded is more than 5 log CFU/g with the processing temperature of 75 - 90°C with the water activity between 0.25 - 0.45 (Dhowlaghar et al., 2021). The D-value for Salmonella spp. is D80°C = 38.7 - 53.2, Listeria spp. is 14.2 - 40.2 and Enterococcus faecium NRRL B-2354 is D80°C = 49.6 - 85.5 and the significant finding is Listeria monocytogenes has less thermal resistance than Salmonella. The study focuses on thermal for inactivation strategies controlling Salmonella and Listeria monocytogenes during the desiccated shredded coconut post-drying process (Dhowlaghar et al., 2021). Similarly, E. coli ATCC 25922 in almond powder were reduced up 2.55 log CFU/g and the D75 $^{\circ}$ C = 12.6 - 20.5 when treated with 75°C and the highlight of this study is that the effects of storage environment on reducing bacterial populations and D75°C of E. coli became more noticeable as storage temperature increased Cheng and Wang, 2018). More than 6 log CFU/g and more than 7 log CFU/g of Salmonella spp. and Enterococcus faecium, respectively, were able to reduce in egg powder (Pérez-Reyes et al., 2021). The temperature used are between 20 -80°C, time ranging from 0 - 150 mins with water activity from 0.3 - 0.74 (Pérez-Reyes et al., 2021). The D-value recorded for Salmonella is D80 $^{\circ}$ C = 5.1 – 25.9 and Enterococcus faecium is $D80^{\circ}C = 10.4 - 43.8$ and concluded the D value had a linear relationship with water activity and the composition differences (Pérez-Reyes et al., 2021).

Desiccation

Desiccation known as drying or dehydration has been used for a long time to preserve fruits such as prunes, raisins. Most studies use desiccation for food samples for instance flour, almond meal, and peanuts. A study was conducted on wheat flour to test the survival of Salmonella Enteritidis PT30 under different water activities (0.3 and 0.6) and the result shows that the responses are negligible (Smith and Marks, 2015). Biofilm producing strain of Salmonella was tested on wheat flour using desiccation and the finding are the thermal resistance of Salmonella in LMF are influenced by the strain that produces biofilm (Villa-Rojas, Zhu, Paul, et al., 2017a). A study was conducted to test the thermal resistance of E. coli O121 in wheat flour with a temperature of 70 - 80°C and found that E. coli O121 is the least thermally resistant compared to Salmonella Enteritidis PT30 when tested under the same condition. The log reduction ranged from 0.64 -6.95 log CFU/g and the D80 $^{\circ}$ C = 4.58 min while the Z- value = 14.57°C (Suehr et al., 2019). Enterococcus faecium was tested in peanut oil using desiccation with the water activity around 0.33 to 0.93 and the log reduction was a range between O to 5 log CFU/g. The significant findings of this study are that the key factor of thermal resistance of bacteria in oil is the equilibrium of water activity and oil in the system (Yang et al., 2020).

A study conducted by Villa-Rojas et al., (2017a), found that 0.59 - 1.49 log CFU/g of Salmonella spp. were able to reduce in wheat flour by using desiccation. The study justified that the thermal resistance of Salmonella in LMF was influenced by the preformed biofilm and the D80 $^{\circ}$ C is 3.1 – 21.7. Similarly, 2.5 – 4.3 log CFU/g of Salmonella Enteritidis PT30 in wheat flour were able to reduce with the D80°C ranging from 1.33 - 7.32 mins (Smith and Marks, 2015b). The study concluded that when applying thermal resistance data to industrial pasteurization validations, the response period to new water activity is negligible (Smith and Marks, 2015). Then again, 0.64 – 6.95 log CFU/g of E. coli O121 in wheat flour were able to reduce with the temperature used of 70 - 80°C. The D

value recorded are D70°C = 18.16, D75°C = 6.47, D80°C = 4.58 with the Z- value = 14.57°C and the study highlighted that E. coli O121 was found to be least thermally resistant than Salmonella Enteritidis PT30 when assessed under the same environments and using the same methodology (Suehr et al., 2019).

Drying

Drying is one of the techniques to draw the water of the food thus reducing the water activity in it. Most studies conducted this thermal treatment with temperatures between 60 to 100°C. The effectiveness of drying was tested on Salmonella spp. in almonds and the log reduction ranged from 0.17 to more than 6.54 log CFU/g. The study concluded that the combination of dry heat and vacuum packaging can significantly inactivate Salmonella without affecting the color of the products (Song and Kang, 2021). Enterococcus faecium and Salmonella in dried basil leaves was tested using a dry heating method and the D-value recorded is 6.53 to 14.07 min and 3.30 to 9.14 min, respectively. The study found that Enterococcus faecium is a suitable surrogate for Salmonella to perform validation of the thermal process (Verma, et al., 2021a). Salmonella and Cronobacter sakazakii in milk powder was tested with the temperature range of 90 to 100°C resulting in the log reduction of up to 1.12 log CFU/g. The percentage of uncultivable cells are strongly related to the loss of respiratory activity and weakly with the membrane permeability (Lang et al., 2018). Lastly, Enterococcus faecium in almonds are studied using a drying column resulting in less than 1 log reduction thus the study highlight that the harvested almonds need to be sorted and dehulled before drying to increase the efficiency and moisture uniformity (Chen et al., 2021a).

Extrusion

Extrusion cooking is a time-honoured method that has been widely used in the food industry for decades (Wason et al., 2021). Because of the high temperature, pressure, and shear applied to

the product, the extrusion process reduces the microbial load on food commodities. Extrusion processing was assumed to eliminate biological hazards from food due to the use of high temperatures and high moisture, even though the final product contains low moisture. However, the food industries are required to validate their process as a killing step such that it will effectively control the identified hazard. In that case, twin-screw extrusion can be used as an effective process intervention step for the inactivation of Salmonella spp. in whole grain oat flour (Verma and Subbiah, 2019). Whole grain oat flour with an initial fat content of 5-15% and moisture content of 14-26% was subjected to treatment. About 0.0 to 9.0 log reduction was achieved at a temperature of 55-85°C, and a screw speed of 75-225 rpm.

Nonthermal Inactivation

Thermal treatments play a major role in the inactivation of pathogenic bacteria in lowmoisture foods. But nowadays non-thermal inactivation methods are gaining importance as potential alternatives to thermal operations in food processing. Non-thermal methods allow the processing of foods in such a way as to preserve flavors, essential nutrients, and vitamins. In addition, Salmonella exhibits increasing thermal resistance at decreasing aw during heat treatment (Wei et al., 2018). So, this major challenge is expected to be overcome non-thermal inactivation with radiofrequency, irradiation, extrusion and many more.

Types of inactivation in high frequency heating the type of heat transfer is radiation, where the energy delivered is directly absorbed by the microbial DNA and essential proteins, resulting in physical changes in the microbial cell structure and function. Therefore, it can be concluded that the effect of radio-frequency treatment on reducing microbial logs in food depends on the species of the target organisms and cell wall structure of them, the RF frequency

used, and the uniformity of heating (Rifna et al., 2019). The mode of pulsed light inactivation was destructing cellular structure and caused the microbial DNA damage and was thought to be a key contributor to the fatal effects. Microbial destruction begins with the absorption of UV light emitted by pulsed light, followed by the formation of cross-linked pyrimidine nucleotide bases that cause mutations in the DNA (Rifna et al., 2019).

The following section discusses non-thermal methods such as radiofrequency heating, gaseous chlorine dioxide technology, pulsed light, X-ray, and high-pressure carbon dioxide for the elimination of pathogenic bacteria in various foods. Many parameters affect the effectiveness of the treatments such as water activity, temperature, time, product formulation and more. Predictive models for instance Bigelow, Weibull and Kopelman models can be used to design the inactivation steps in LMF. So those were discussed accordingly.

Radiofrequency heating

Radiofrequency (RF) heating is a novel non-thermal processing method that has gained the interest of the scientific community for the pasteurization of various food products. RF heating is a dielectric heating method operating in the range of 3 kHz–300 MHz. Friction caused by ionic conduction and dipole rotation of water molecules ended up in the formation of heat needed for the inactivation of pathogenic bacteria. Unlike irradiation and other treatment methods, RF treatment is certified organic, natural, and can be used on an FDA approved clean label (Lin *et al.*, 2020).

Aspergillus flavus, which can produce aflatoxins, is a major problem in peanut production worldwide. A study by Zhang et al., (2021) pointed out the effectiveness of radiofrequency heating in eliminating Aspergillus flavus in peanut kernels using the Kopelman model. Between the treatment

temperature of 65-70°C, 3 to 7 log reduction of *Aspergillus flavus* was observed and the D value at 68°C with the water activity of 0.74 was 8.3 minutes. Although it is successful in inactivation, the problem observed was the non-uniformity of RF treatment causes the least *Aspergillus flavus* death at cold spots. And that study recommends the use of "COMSOL" software in the development of effective RF.

Similarly, a study by Zhang et al., 2020 effectiveness of the has found the radiofrequency against Salmonella Typhimurium in red pepper powder. In treatment under the water activity between 0.44 - 0.70, there was a 4-log reduction of Salmonella Typhimurium. Further, findings confirmed the absence of Salmonella Typhimurium sublethal injury cells (SICs) in red pepper powder with an initial aw of 0.44 after the RF treatment. Same as for red pepper powder Jiao et al., 2019 has researched to find out the effectiveness of RF treatment in eliminating Bacillus cereus spores. B. cereus endospores are resistant to heat, radiation, disinfectants, and desiccation, and their adhesive characters facilitate their attachment to processing equipment and resistance to cleaning procedures. Jiao et al., 2019 has used the Weibull model in water activity of 0.70 at a temperature of 90°C to predict the log reduction and they reported a 4-log reduction and D value of 5.8 min and the Z value is 64.3°C. And the study highlighted that the RF inactivation effects could be improved by manipulating the sample initial water activity level. Another study has been done for Salmonella Typhimurium in red powders using the Weibull model at a temperature of 70°C with a water activity of 0.71. It has resulted in a more than 5 log reduction (Hu et al., 2018). It has also suggested that the increasing initial aw could first increase log reductions and then decrease the log reductions, optimum aw level was 0.71 for RF

inactivation of *Salmonella* in red pepper powders.

In addition to that RF, treatments could be considered as an effective method to control pathogens in in-shell walnuts as well. There was a 4-log reduction of Staphylococcus aureus ATCC 25923 in in-shell walnuts with a 15.01% of moisture (Weight basis) after RF treatment (Zhang et al., 2019). The effectiveness of radiofrequency heating against Aspergillus parasiticus in corn grains was studied by Zhang et al., 2017. About 5 to 6 log reduction was achieved at the temperature of 70°C in moisture content of 15.0% (Weight basis). RF treatments can provide an effective and rapid heating method control Aspergillus to parasiticus and maintain acceptable corn quality.

In general, RF heating is a propitious non-thermal technique rather than conventional techniques to inactivate foodborne pathogens but there is an urgent need to find out the appropriate surrogate for the target pathogen and it is needed to be validated for different food matrices. Therefore, the identification of a surrogate for different food products is crucial to help the food industry conduct the in-plant validation studies. In this perspective, Ballom et al., 2021 has studied the suitability of Enterococcus faecium NRRL B2354 and Listeria innocua as surrogates for *Salmonella* and Listeria monocytogenes respectively using the Bigelow model in cocoa powder. About 4.6 log reduction was observed at the temperature of 75°C in water activity of 0.45. D value at 90°C was observed as 2.5 minutes for Salmonella and 2.3 minutes for Enterococcus faecium. Enterococcus faecium and L. innocua were appropriate surrogate strains for controlling Salmonella and L. monocytogenes, respectively, during processing of cocoa powder. Verma et al. (2021b) explored the inactivation of Salmonella and Enterococcus faecium NRRL B-2354 in

dried basil leaves. At 100°C of cold spot temperature, a 4.8 log reduction was observed in *Salmonella* and the case of *Enterococcus faecium* about 2.7 log reduction. So, *Enterococcus faecium* was validated as a suitable surrogate for *Salmonella* in dried basil leaves under radiofrequency treatment. Furthermore, RF processing results in rapid heating of the dried basil leaves enhancing food safety with an insignificant impact on quality.

According to Tingyu et al., 2021, RF heating could effectively inactivate *E. coli* O157: H7 and Salmonella Typhimurium ATCC 14028 without significant influence on the quality of black pepper kernels. It was reported that the E. coli O157: H7 was reached more than 6 log reductions after 7.0 min when heating to 90°C and in contrast Salmonella Typhimurium ATCC 14028 reached more than 6 log CFU/g reduction after 8.0 min when reaching 100°C. RF holds great potential for the industrial pasteurization of cumin seeds as well. In continuous radiofrequency heating of cumin seeds with a belt speed of 28.2 m/h and at a cold-spot temperature of 99.6°C, Salmonella enterica showed more than 5.52 log reduction and Enterococcus faecium showed more than 6.52 log reduction (Chen et al., 2020). Another study was also done to validate the inactivation of RF in cumin seeds by Chen et al., 2019. According to them, at a water activity of 0.74, Salmonella achieved a 5.8 log reduction and Enterococcus faecium achieved more than 6.4 log reduction. Thus, Enterococcus faecium is a suitable surrogate of Salmonella in cumin seeds for RF microbial inactivation. One consideration pointed out by the above-mentioned study is batch variation requires stricter process control parameters for RF microbial inactivation.

As per the study by Ozturk *et al.*, 2020 it is suggested that the RF heating could be used as an alternative pasteurization method for spices, and it is feasible to design RF pasteurization processes using *Enterococcus*

faecium as a surrogate to validate the inactivation of Salmonella spp. Weibull model was used to validate the radiofrequency heating in Paprika, White pepper and Cumin powder. About 4-5 log reduction was observed in both Enterococcus faecium and Salmonella spp. Dvalue ranges from 1.21 to 4.47 minutes for Salmonella and for Enterococcus faecium it ranges from 1.82 - 9.53 minutes. The Z-value was predicted between 3.6 - 19.1°C. Wei et al. (2018) reported that RF heating is a promising thermal inactivation treatment for Salmonella without significant quality deterioration, and Enterococcus faecium seems to be a suitable surrogate for Salmonella to validate the efficacy heating of black peppercorn. Radiofrequency heating of black peppercorn with the water activity of 0.60 ended up in the 5.31 log reduction of Salmonella whereas 5.26 log reduction Enterococcus faecium.

Wei et al. (2020b) has experimented with the effectiveness of radiofrequency heating in egg white powder. At the temperature of about 80°C with a time range from 0 - 16 h, Salmonella enterica and Enterococcus faecium showed a log reduction from 0.58 to more than 5. This study emphasized that *E. faecium* is a suitable surrogate for Salmonella. The validated RFassisted thermal process has the potential to be scaled up for use in the egg industry. Same as for the organic wheat flour also radiofrequency heating at the water activity of 0.25 resulted in 5 log reductions of Salmonella and 3 log reductions of Enterococcus faecium. RF appears to be an acceptable method to pasteurize Salmonella in wheat flour, and Enterococcus faecium B-2354 may be an adequate surrogate for future evaluation of RF inactivation on a larger scale (Villas Rojas et al., 2017). There was another study that explored the RF inactivation capability in wheat flour at the temperature of 85°C and the water activity of 0.45 (Liu et al., 2017). It reported that there were more than 5 log reductions in both Salmonella Enteritidis PT

30 and Enterococcus faecium NRRL B-2354. D value at 85°C for Salmonella Enteritidis PT 30 was 2.92 minutes. The Z-value of Salmonella Enteritidis PT 30 and Enterococcus faecium NRRL B-2354 was 12.8°C and 11.7°C respectively. Although both microorganisms yielded similar z-values, Enterococcus faecium was more heat-resistant than Salmonella Enteritidis and it can be selected as a surrogate for the validation of inactivation of Salmonella Enteritidis.

In addition to that, there were some studies that experimented the different combinations of treatments with RF heating. Wei et al. (2021) has studied the possibility of hot air assisted radio frequency processing in whole milk powder and non-fat dry milk for the inactivation of Salmonella. At the temperature of 95°C more than 5 log reduction was observed. This study validated a hot air-assisted RF process for pasteurization of milk powder based on previously collected microbial inactivation kinetics data. Similarly, Xu et al., 2020 was also studied the hot air assisted RF in wheat flour for the inactivation of Enterococcus faecium NRRL B-2354 with the water activity of 0.45 at 80 – 85°C. About 2.5 – 3.7 log reduction was observed. The Bigelow model was used for the prediction and the D value at 80°C was observed as 8.3 minutes and the z-value was 11.7°C. Overall, the study concluded that the relatively slow RF heating rate with a hot-air assisted system is helpful to improve the temperature uniformity of RF treatment to obtain a uniformed treated sample. The optimum RF-assisted thermal processing conditions of 80°C for 7 hour and 90°C for 2 hours were recommended for pasteurization of soft wheat flour without any compromise in the quality and functionality (Boreddy et al., 2019).

Cheng *et al.*, 2020 has explored the combination of controlled atmosphere and RF heating. RF heating of almond kernels under a controlled atmosphere (2% O₂, 20% CO₂, and

78% N₂) with a moisture content of 8% at a temperature of 72-78°C resulted in a 4-log reduction of E. coli ATCC 25922. D value was estimated at 75°C as 5 to 5.5 minutes. This study highlighted that RF heating under controlled atmosphere conditions may hold potential as an effective treatment method to control E. coli ATCC 25922 in raw almond kernels and be extended for pasteurization possibly applications. According to Cheng and Wang 2019, modified atmosphere pre-storage assisted thermal treatments induced by RF energy may hold potential as an effective and environmentally friendly method to control E. coli ATCC 25922 in almond kernels. About 4 log reduction was observed under 8.0% wet basis and at the temperature of 75°C.

Zhang et al. (2020) has used thermostatic radiofrequency for Powdered infant formula milk (PIFM) with a water activity of 0.2-0.4 and a temperature range of 55-70°C. It was observed a 0.16 log reduction in Cronobacter sakazakii ATCC 29544. D value at 70°C was observed as 23.3 minutes. At the same time, the Z value was 14.90°C RF heating can provide an outstandingly higher heating rate compared to traditional treatment, so it has great potential to be used to produce PIFM to achieve higher pasteurization efficiency. According to Lin et al. (2020) RF assisted traditional thermal process is more suitable for pasteurization of PIFM than the traditional thermal process due to lower lipid oxidation and much shorter overall processing time.

RF heating and freezing treatment combination experimented in corn flour for the inactivation of *Salmonella* Enteritidis PT30 and *Enterococcus faecium* NRRL B-2354 (Ozturk, *et al.*, 2019). Water activity and temperature were maintained as 0.45 and 85°C respectively. *Salmonella* Enteritidis PT30 showed a 6.59 log reduction and *Enterococcus faecium* showed a 4.9 log reduction. D-value at 85°C for *Salmonella* Enteritidis PT30 was reported as

2.03 minutes. Enterococcus faecium could be used as a surrogate for validation studies in packaged corn flour. Results also confirmed that RF heating combined with freezing storage treatment could significantly reduce the survival of both microorganisms in corn flour. In the case of wheat flour, RF treatment is efficient in inactivating target microorganisms, especially Enterococcus faecium NRRL B-2354 (Xu et al., 2018). Within the temperature range of 75°C -85°C about 1.0 - 4.9 log reduction was observed. D value at 85°C was reported as 2.79 minutes. Z-value was 13.1°C. Freeze-dried Enterococcus faecium proved to be an effective Salmonella surrogate in LMF. Michael et al. (2014) studied radiofrequency dielectric heating on non-fat dry milk. At about a temperature of 90°C, there was a 3-log reduction in Cronobacter sakazakii and Salmonella. D-value for Cronobacter sakazakii at 90°C was reported as 5.57 minutes. D-value for Salmonella at 90°C was reported as 5.82 minutes. Z-values for Cronobacter sakazakii and Salmonella were 23.77 and 26.92 respectively. Radio-frequency dielectric heating can be used as a faster and more uniform heating method for non-fat dry milk to achieve target temperatures for a postprocess lethality treatment of non-fat dry milk before packaging.

Because no single technology can provide an ultimate solution shortcomings in the inactivation mechanisms, it is decisive to search for different non-thermal technologies alternatives. as Gaseous technologies gain their importance nonthermal methods that have been used to reduce the microbial load in foods. One of the key benefits of using gases is their ability to diffuse through the air spaces and pores. This allows the gaseous technologies to perform well with irregularly shaped food products. The section discusses following nonthermal methods such as gaseous chlorine dioxide technology, pulsed light processing, twin-screw extrusion, and high-pressure carbon dioxide technology for the elimination of pathogenic bacteria in various foods which came across during manipulated literature search.

Gaseous chlorine dioxide technology

Chlorine dioxide (ClO₂) is a strong oxidizing agent that has been used as a sanitizer both in the gaseous as well as in the aqueous form. Wei et al. (2021) has researched by applying gaseous chlorine dioxide technology for black peppercorn and cumin seeds for the inactivation of Salmonella and Enterococcus faecium NRRL B-2354. ClO2 gas in a 15 mg/L concentration and relative humidity of 80% at a room temperature of 25°C, could be able to achieve a more than 5 log reduction of Salmonella for both spices. But in the case of Enterococcus faecium NRRL B-2354, there was a 4.36 log reduction in black peppercorn and a 4.17 log reduction in cumin seeds. It was also estimated that the D value of Salmonella at 25°C for black peppercorn was 60.3 minutes and for cumin seeds as 58.7 minutes. This study elaborated that Enterococcus faecium is a suitable surrogate for Salmonella during the ClO₂ treatment.

Pulsed light technology

Pulsed Light (PL) technology is an alternative to thermal treatment for killing pathogenic and spoilage microorganisms in foods. The key component of a Pulsed Light unit is a flash lamp filled with inert gas, such as Xenon, which emits radiation that ranges from 200 nm to 1,100 nm. The exact mechanisms by which PL causes cell death are not yet fully understood, but it is generally accepted that UV plays a critical role in microbial inactivation. Liu et al., 2021 has studied the efficacy of pulsed light in the inactivation of Salmonella in raw almonds. One-time dipping of almonds in water for 1 min followed by a PL treatment of 500 g of almonds at an intensity of 0.75 W/cm²

for 18 min have reached more than a 5-log reduction. It is reported that PL treatment in combination with prior water dipping could be a potential pasteurization method for raw almonds. Prasad *et al.*, 2019 has done a study on the effectiveness of high intensity pulsed lightemitting diode treatment on pet foods for the inactivation of *Escherichia coli* and *Salmonella enterica*. At about a water activity of 0.75 with a LED treatment 365nm of *Salmonella* achieved a 0.79 log reduction and with the treatment of 395 nm LED there was a 1.76 log reduction. Dose, duration of light exposure, bacterial strain, and aw played a major role in the antibacterial efficacy of the 365 and 395 nm LEDs.

X-ray technology

Irradiation is a nonthermal technique used for the preservation of food products and is approved for the elimination of pathogenic microorganisms. Ionizing radiation is a residue free treatment, causing no thermal damage to food products. For food irradiation, three types of radiation consisting of variable energy levels are used such as gamma rays, electron beam and X-ray generated by the X-ray machine. The use of X rays to low-moisture foods commodities is limited as it is energy-intensive and is extremely expensive. But Zhang et al. (2020) has researched the use of 150 KeV lowenergy X-rays for the inactivation of Salmonella Typhimurium, Escherichia coli O157:H7. Staphylococcus aureus and Listeria monocytogenes in cardamom. Weibull model was used to predict the D-values. At about 350 Gy more than 2 log reduction was observed in all microbial species considered. D-value for E. coli O157:H7 was reported as 71.43 Gy. t_R values were reported as 53.57 Gy for Salmonella Typhimurium, 87.74 Gy for Listeria monocytogenes and 114.64 Gy for Salmonella aureus. The study concluded that the 150 KeV low-energy X-ray could be applied to effectively inactivate pathogens in dry cardamom. Although the 150 KeV low-energy

X-ray irradiation affected the content of PUFAs, no 2-DCBs and 2-TCBs were detected after up to 350 Gy irradiation.

High-pressure CO₂

Carbon dioxide (CO₂) is a non-toxic, inert, and economically viable gas that does not leave any toxic residues on the treated commodities. In low-moisture foods such as grains, CO2 gas has been used to induce hypoxia, lethal to insects and moulds; but may not be enough to achieve pasteurization at shorter durations. Research on microbial inactivation of low-moisture foods using highpressure CO₂ is limited, while fewer studies have been done so far. Chen et al., 2017, evaluated the effectiveness of high-pressure carbon dioxide in inactivating Escherichia coli AW1.7 in dry cells. It was reported a more than 3 log reduction at a temperature of 35°C. It was reported that the liquid and supercritical CO2 were ineffective in reducing the cell counts of dry E. coli isolates, and the effectiveness of gaseous CO2 was related to the diffusivity of CO₂.

4. CONCLUSION

There are few nonthermal treatments that able to reduce the microbial load in LMF and ensure the food safety radiofrequency, high pressure CO2, and extrusion. Some new evolving technologies which were approved by FDA (Food and Drug Administration) such high-pressure as processing, pulsed electric field and ultraviolet light have many concerns to the customers thus more research need to be conducted to investigate the effectiveness of treatments and the combination of the treatments to inactivate the microbes in LMFs. The application of pathogen kill step can ensure the safety of LMF thus reduces outbreaks and food recalls. Water activity, temperature, time, product formulation, and a variety of other

factors all have an impact on the effectiveness of the treatments. To design the inactivation steps in LMFs, predictive models such as the Bigelow, Weibull, and Kopelman models can be used. Because different treatments are required to inactivate different LMF products, food manufacturers should implement the most effective method of killing the pathogen based on the food produced. Future studies on secondary inactivation models, application to process validation, must clearly account to ensure the food safety

Ethical Approval

None.

Declaration of Interests

None.

REFERENCES

- Acuff, J C, Wu, J., Marik, C., Waterman, K., Gallagher, D., Huang, H., Williams, R. C., and Ponder, M. A. (2020). Thermal inactivation of Salmonella, Shiga toxin-producing Escherichia coli, Listeria monocytogenes, and a surrogate (Pediococcus acidilactici) on raisins, apricot halves, and macadamia nuts using vacuum-steam pasteurization. International Journal of Food Microbiology, 333.
- Ahmad, N. H., Öztabak, C., Marks, B. P., and Ryser, E. T. (2019). Effect of talc as a dry-inoculation carrier on thermal resistance of Enterococcus faecium NRRL B-2354 in almond meal. Journal of Food Protection, 82(7), 1110–1115.
- Alshammari, J., Xu, J., Tang, J., Sablani, S., and Zhu, M.-J. (2020a). Thermal resistance of Salmonella in low-moisture high-sugar products. Food Control, 114.

Add Alshammari et al (2020b)

- Ballom, K., Dhowlaghar, N., Tsai, H., Yang, R., and Tang, J. (2021). Radiofrequency pasteurization against Salmonella and Listeria monocytogenes in cocoa powder. LWT, 145(April), 111490.
- Ballom, K. F., Tsai, H.-C., Taylor, M., Tang, J., and Zhu, M.-J. (2020). Stability of Listeria monocytogenes in non-fat dry milk powder during isothermal treatment and storage. Food Microbiology, 87.
- Ban, C., Lee, D. H., Jo, Y., Bae, H., Seong, H., Kim, S. O., Lim, S., and Choi, Y. J. (2018). Use of superheated steam to inactivate Salmonella enterica serovars Typhimurium and Enteritidis contamination on black peppercorns, pecans, and almonds. Journal of Food Engineering, 222, 284–291.
- Ban, G.-H., and Kang, D.-H. (2016). Effectiveness of superheated steam for inactivation of Escherichia coli O157: H7, Salmonella Typhimurium, Salmonella Enteritidis phage type 30, and Listeria monocytogenes on almonds and pistachios. International Journal of Food Microbiology, 220, 19–25.

Funding

None.

Acknowledgements

None.

Author Contribution

Concept: NAS, NAAM, NHA
Design: NAS, NHA
Data collecting: NAS, AK, PL
Statistical analysis: AK, PL
Literature review: NAS
Writing: NAS, NAAM, NHA
Critical review: NHA

- Bang, J., Choi, M., Jeong, H., Lee, S., Kim, Y., Ryu, J.-H., and Kim, H. (2017). Heat tolerances of SSalmonella, Cronobacter sakazakii, and Pediococcus acidilactici inoculated into galactooligosaccharide. Journal of Food Protection, 80(7), 1123–1127.
- Baths, C. W. (2020). Water Bath Purpose Principle. 3, 2099–2102.
- Beuchat, L.R., and Mann, D. A. (2011a). Inactivation of Salmonella on pecan nutmeats by hot air treatment and oil roasting. Journal of Food Protection, 74(9), 1441–1450.
- Beuchat, L R, and Mann, D. A. (2011b). Inactivation of Salmonella on in-shell pecans during conditioning treatments preceding cracking and shelling. Journal of Food Protection, 74(4), 588–602.
- Beuchat, Larry R., Komitopoulou, E., Beckers, H., Betts, R. P., Bourdichon, F., Fanning, S., Joosten, H. M., and Kuile, B. H. T. (2013). Low-water activity foods: Increased concern as vehicles of foodborne pathogens. Journal of Food Protection, 76(1), 150–172.
- Boreddy, S. R., Rose, D. J., and Subbiah, J. (2019). Radiofrequency-Assisted Thermal Processing of Soft Wheat Flour. Journal of Food Science, 84(9), 2528–2536.
- CDC. (2017, June 29). Learn about the symptoms of Listeria.

 Centers for Disease Control and Prevention. Retrieved February 12, 2022, from https://www.cdc.gov/listeria/symptoms.html
- CDC. (2022). Questions and Answers | E. coli | CDC. Centers for Disease Control and Prevention. Retrieved February 12, 2022, from https://www.cdc.gov/ecoli/general/index.html
- Channaiah, L. H., Michael, M., Acuff, J. C., Phebus, R. K., Thippareddi, H., and Milliken, G. (2021). Thermal inactivation of Salmonella during hard and soft cookies baking process. Food Microbiology, 100.
- Chen, C., Liao, C., Wongso, I., Wang, W., Khir, R., Huang, G., Niederholze, F., Wang, L., and Pan, Z. (2021a). Drying and

- disinfection of off-ground harvested almonds using stepdown temperature hot air heating. LWT, 152.
- Chen, L., Irmak, S., Chaves, B. D., and Subbiah, J. (2020). Microbial challenge study and quality evaluation of cumin seeds pasteurized by continuous radio frequency processing. Food Control, 111.
- Chen, L., Jung, J., Chaves, B. D., Jones, D., Negahban, M., Zhao, Y., and Subbiah, J. (2021b). Challenges of dry hazelnut shell surface for radio frequency pasteurization of inshell hazelnuts. Food Control, 125.
- Chen, Y. Y., Temelli, F., and Gänzle, M. G. (2017). Mechanisms of inactivation of dry Escherichia coli by high-pressure carbon dioxide. Applied and Environmental Microbiology, 83(10).
- Cheng, T., and Wang, S. (2018). Influence of storage temperature/time and atmosphere on survival and thermal inactivation of Escherichia coli ATCC 25922 inoculated to almond powder. Food Control, 86, 350–358.
- Cheng, T., and Wang, S. (2019). Modified atmosphere packaging pre-storage treatment for thermal control of E. coli ATCC 25922 in almond kernels assisted by radio frequency energy. Journal of Food Engineering, 246, 253–260.
- Cheng, Teng, Ramaswamy, H., Xu, R., Liu, Q., Lan, R., and Wang, S. (2020). Fifty Ohm radio frequency heating treatment under controlled atmosphere for inactivating Escherichia coli ATCC 25922 inoculated on almond kernels. Lwt, 123 (August 2019), 109124.
- Codex. (2018). CODE OF HYGIENIC PRACTICE FOR LOW-MOISTURE FOODS. Code of Hygiene Practice for Low Moisture Foods, 151(2), 10–17.
- Daryaei, H., Peñaloza, W., Hildebrandt, I., Krishnamurthy, K., Thiruvengadam, P., and Wan, J. (2018). Heat inactivation of Shiga toxin-producing Escherichia coli in a selection of low moisture foods. Food Control, 85, 48–56.
- Daryaei, H., Sui, Q., Liu, H., Rehkopf, A., Peñaloza, W., Rytz, A., Luo, Y., and Wan, J. (2020). Heat resistance of Shiga toxin-producing Escherichia coli and potential surrogates in wheat flour at two moisture levels. Food Control, 108.
- Deen, B., and Diez-Gonzalez, F. (2019). Assessment of Pediococcus acidilactici ATCC 8042 as potential Salmonella surrogate for thermal treatments of toasted oats cereal and peanut butter. Food Microbiology, 83, 187–192.
- Dhaliwal, H. K., Gänzle, M., and Roopesh, M. S. (2021). Influence of drying conditions, food composition, and water activity on the thermal resistance of Salmonella enterica. Food Research International, 147.
- Dhowlaghar, N., Tang, J., and Zhu, M.-J. (2021). Thermal inactivation of Salmonella, Listeria monocytogenes and Enterococcus faecium NRRL B-2354 in desiccated shredded coconut. LWT, 149.
- Fan, X., Baik, J., and Gurtler, J. B. (2021). Thermal reduction of Bacillus spp. In naturally contaminated mesquite flour with two different water activities. Journal of Food Protection, 84(3), 490–496.
- Food and Drug Administration. (n.d.). Mountain Mel's Essential Goods, LLC Recalls The Milk Lady's Herbal Tea Blend, Peaceful Baby Herbal Tea Blend, and Diges-teas Herbal Tea Blend, Because of Possible Health Risk. 20–22.
- Forghani, F., den Bakker, M., Futral, A. N., and Diez-Gonzalez, F. (2018). Long-term survival and thermal death kinetics of enterohemorrhagic Escherichia coli serogroups O26, O103, O111, and O157 in wheat flour. Applied and Environmental Microbiology, 84(13).

- Grasso-Kelley, E. M., Liu, X., Halik, L. A., and Douglas, B. (2021). Evaluation of hot-air drying to inactivate Salmonella and Enterococcus faecium on apple pieces. Journal of Food Protection, 84(2), 240–248.
- He, Y., Guo, D., Yang, J., Tortorello, M. L., and Zhang, W. (2011). Survival and heat resistance of Salmonella enterica and Escherichia coli O157:H7 in peanut butter. Applied and Environmental Microbiology, 77(23), 8434–8438.
- Hu, S., Zhao, Y., Hayouka, Z., Wang, D., and Jiao, S. (2018). Inactivation kinetics for Salmonella Typhimurium in red pepper powders treated by radio frequency heating. Food Control, 85, 437–442.
- Izurieta, W. P., and Komitopoulou, E. (2012). Effect of moisture on Salmonella spp. heat resistance in cocoa and hazelnut shells. Food Research International, 45(2), 1087–1092
- Jeong, S., Marks, B. P., and James, M. K. (2017). Comparing thermal process validation methods for Salmonella inactivation on almond kernels. Journal of Food Protection, 80(1), 169–176.
- Jiao, S., Zhang, H., Hu, S., and Zhao, Y. (2019). Radio frequency inactivation kinetics of Bacillus cereus spores in red pepper powder with different initial water activity. Food Control, 105, 174–179.
- Keller, S E, Grasso, E. M., Halik, L. A., Fleischman, G. J., Chirtel, S. J., and Grove, S. F. (2012). Effect of growth on the thermal resistance and survival of Salmonella Tennessee and Oranienburg in peanut butter, measured by a new thin-layer thermal death time device. Journal of Food Protection, 75(6), 1125–1130.
- Keller, Susanne E., Stam, C. N., Gradl, D. R., Chen, Z., Larkin, E. L., Pickens, S. R., and Chirtel, S. J. (2015). Survival of Salmonella on chamomile, peppermint, and green tea during storage and subsequent survival or growth following tea brewing. Journal of Food Protection, 78(4), 661–667.
- Kharel, K., Yemmireddy, V. K., Graham, C. J., Prinyawiwatkul, W., and Adhikari, A. (2018). Hot water treatment as a kill-step to inactivate Escherichia coli O157:H7, Salmonella enterica, Listeria monocytogenes and Enterococcus faecium on in-shell pecans. LWT, 97, 555–560.
- Kottapalli, B., Nguyen, S. P. V., Dawson, K., Casulli, K., Knockenhauer, C., and Schaffner, D. W. (2020). Evaluating the risk of salmonellosis from dry roasted sunflower seeds. Journal of Food Protection, 83(1), 17–27.
- Lang, E., Chemlal, L., Molin, P., Guyot, S., Alvarez-Martin, P., Perrier-Cornet, J.-M., Dantigny, P., and Gervais, P. (2017). Modeling the heat inactivation of foodborne pathogens in milk powder: High relevance of the substrate water activity. Food Research International, 99, 577–585.
- Lang, E., Guyot, S., Peltier, C., Alvarez-Martin, P., Perrier-Cornet, J.-M., and Gervais, P. (2018). Cellular injuries in Cronobacter sakazakii CIP 103183T and Salmonella enterica exposed to drying and subsequent heat treatment in milk powder. Frontiers in Microbiology, 9(MAR).
- Lau, S. K., and Subbiah, J. (2020). TDT Sandwich: An open source dry heat system for characterizing the thermal resistance of microorganisms. HardwareX, 8.
- Li, C., Huang, L., and Chen, J. (2014). Comparative study of thermal inactivation kinetics of Salmonella spp. in peanut butter and peanut butter spread. Food Control, 45, 143–
- Limcharoenchat, P., Buchholz, S. E., James, M. K., Hall, N. O., Ryser, E. T., and Marks, B. P. (2018). Inoculation protocols influence the thermal resistance of Salmonella Enteritidis

- PT 30 in fabricated almond, wheat, and date products. Journal of Food Protection, 81(4), 606–613.
- Lin, Y., Subbiah, J., Chen, L., Verma, T., and Liu, Y. (2020). Validation of radio frequency assisted traditional thermal processing for pasteurization of powdered infant formula milk. Food Control, 109 (2020), 106897.
- Liu, S., Ozturk, S., Xu, J., Kong, F., Gray, P., Zhu, M.-J., Sablani, S. S., and Tang, J. (2018a). Microbial validation of radio frequency pasteurization of wheat flour by inoculated pack studies. Journal of Food Engineering, 217, 68–74.
- Liu, S., Rojas, R. V., Gray, P., Zhu, M.-J., and Tang, J. (2018b). Enterococcus faecium as a Salmonella surrogate in the thermal processing of wheat flour: Influence of water activity at high temperatures. Food Microbiology, 74, 92– 99
- Liu, X., Fan, X., Wang, W., Yao, S., and Chen, H. (2021). Wetting raw almonds to enhance pulse light inactivation of Salmonella and preserve quality. Food Control, 125.
- Lopes, S. M., Carmo, D., and Eduardo, C. (2020). Effect of curing and heat treatments on the Salmonella survival and physicochemical properties of chicken egg yolk. 137(May).
- Malekmohammadi, S., Shah, M. K., Townsend Ramsett, M. K., and Bergholz, T. M. (2020). Survival and thermal resistance among four Salmonella serovars inoculated onto flaxseeds. Food Microbiology, 91.
- Michael, M., Phebus, R. K., Thippareddi, H., Subbiah, J., Birla, S. L., and Schmidt, K. A. (2014). Validation of radio-frequency dielectric heating system for destruction of Cronobacter sakazakii and Salmonella species in nonfat dry milk. Journal of Dairy Science, 97(12), 7316–7324.
- Mohammad, Z. H., Murano, E. A., Moreira, R. G., and Castillo, A. (2020). Effect of post inoculation drying procedures on the reduction of Salmonella on almonds by thermal treatments. Food Research International, 130.
- Mondal, A., Buchanan, R. L., and Lo, Y. M. (2014). Computational fluid dynamics approaches in quality and hygienic production of semisolid low-moisture foods: A review of critical factors. Journal of Food Science, 79(10), R1861–R1870.
- Moussavi, M., Frelka, J. C., Hildebrandt, I. M., Marks, B. P., and Harris, L. J. (2020). Thermal resistance of foodborne pathogens and Enterococcus faecium NRRL B-2354 on inoculated pistachios. Journal of Food Protection, 83(7), 1125–1136
- Nascimento, M. S., Brum, D. M., Pena, P. O., Berto, M. I., and Efraim, P. (2012). Inactivation of Salmonella during cocoa roasting and chocolate conching. International Journal of Food Microbiology, 159(3), 225–229.
- Newkirk, J. J., Wu, J., Acuff, J. C., Caver, C. B., Mallikarjunan, K., Wiersema, B. D., Williams, R. C., and Ponder, M. A. (2018). Inactivation of Salmonella enterica and surrogate Enterococcus faecium on whole black peppercorns and cumin seeds using vacuum steam pasteurization. Frontiers in Sustainable Food Systems, 2.
- Ozturk, S, Kong, F., and Singh, R. K. (2020). Evaluation of Enterococcus faecium NRRL B-2354 as a potential surrogate of Salmonella in packaged paprika, white pepper and cumin powder during radio frequency heating. Food Control, 108.
- Ozturk, Samet, Liu, S., Xu, J., Tang, J., Chen, J., Singh, R. K., and Kong, F. (2019). Inactivation of Salmonella Enteritidis and Enterococcus faecium NRRL B-2354 in corn flour by radio frequency heating with subsequent freezing. Lwt, 111(February), 782–789.

- Pan, Y., Sun, D. W., and Han, Z. (2017). Applications of electromagnetic fields for nonthermal inactivation of microorganisms in foods: An overview. Trends in Food Science and Technology, 64, 13–22.
- Park, H. W., Xu, J., Balasubramaniam, V. M., and Snyder, A. B. (2021). The effect of water activity and temperature on the inactivation of Enterococcus faecium in peanut butter during superheated steam sanitation treatment. Food Control, 125(January), 107942.
- Pasteur, L., and States, U. (n.d.). pasteurization. 21–22.
- Paula, A., Pereira, M., Stelari, H. A., Carlin, F., and Sant, A. S. (2019). LWT Food Science and Technology Inactivation kinetics of Bacillus cereus and Geobacillus stearothermophilus spores through roasting of cocoa beans and nibs. LWT Food Science and Technology, 111(May), 394–400.
- Pelaez, M. A. B., Anapi, G. R., Bautista, D. V., Dallo, M. D. P., Libunao, J. C. M., and Gabriel, A. A. (2020). Thermal inactivation of Salmonella enterica in Philippine flowingtype peanut butter. LWT, 129.
- Pereira, A. A. M., Prestes, F. S., Silva, A. C. M., and Nascimento, M. S. (2020). Evaluation of the thermal resistance of Salmonella Typhimurium ATCC 14028 after long-term blanched peanut kernel storage. LWT, 117.
- Pérez-Reyes, M.E., Jie, X., Zhu, M.-J., Tang, J., and Barbosa-Cánovas, G. V. (2021a). Influence of low water activity on the thermal resistance of Salmonella Enteritidis PT30 and Enterococcus faecium as its surrogate in egg powders. Food Science and Technology International, 27(2), 184– 193
- Pérez-Reyes, Marco E., Tang, J., Barbosa-Cánovas, G. V., and Zhu, M. J. (2021). Influence of water activity and dryheating time on egg white powders quality. Lwt, 140(January 2020).
- the above publication (Pérez-Reyes et al., 2021) is not cited in the text, check and re-edit
- Quinn, A. R., Liao, R. F., Steele, F. M., Jefferies, L. K., and Taylor, B. J. (2021). Isothermal inactivation of Salmonella, Listeria monocytogenes, and Enterococcus faecium NRRL B-2354 in peanut butter, powder infant formula, and wheat flour. Food Control, 121, 107582.
- Rachon, G., Peñaloza, W., and Gibbs, P. A. (2016). Inactivation of Salmonella, Listeria monocytogenes and Enterococcus faecium NRRL B-2354 in a selection of low moisture foods. International Journal of Food Microbiology, 231, 16–25.
- Sekhon, A S, Singh, A., Unger, P., Babb, M., Yang, Y., and Michael, M. (2021). Survival and thermal resistance of Salmonella in dry and hydrated nonfat dry milk and whole milk powder during extended storage. International Journal of Food Microbiology, 337.
- Shah, M., Eklund, B., Conde Lima, L. G., Bergholz, T., and Hall, C. (2018). Microbial and Chemical Shelf-Life of Vacuum Steam-Pasteurized Whole Flaxseed and Milled Flaxseed. Journal of Food Science, 83(2), 300–308.
- Shah, M K, Asa, G., Sherwood, J., Graber, K., and Bergholz, T. M. (2017). Efficacy of vacuum steam pasteurization for inactivation of Salmonella PT 30, Escherichia coli O157:H7 and Enterococcus faecium on low moisture foods. International Journal of Food Microbiology, 244, 111–118.
- Silva, F. V. M., and Gibbs, P. A. (2012a). Thermal pasteurization requirements for the inactivation of Salmonella in foods. Food Research International, 45(2), 695–699.
- Add Silva and Gibbs (2012b)

- Smith, D. F., Hildebrandt, I. M., Casulli, K. E., Dolan, K. D., and Marks, B. P. (2016). Modeling the effect of temperature and water activity on the thermal resistance of Salmonella Enteritidis PT 30 in wheat flour. Journal of Food Protection, 79(12), 2058–2065.
- Smith, D. F., and Marks, B. P. (2015). Effect of rapid product desiccation or hydration on thermal resistance of Salmonella enterica serovar Enteritidis PT 30 in wheat flour. Journal of Food Protection, 78(2), 281–286.
- Snelling, J., Malekmohammadi, S., Bergholz, T. M., Ohm, J., and Simsek, S. (2020). Effect of vacuum steam treatment of hard red spring wheat on flour quality and reduction of Escherichia coli O121 and Salmonella Enteritidis PT 30. Journal of Food Protection, 83(5), 836–843.
- Song, W.-J., and Kang, D.-H. (2021). Influence of packaging methods on the dry heat inactivation of Salmonella Typhimurium, Salmonella Senftenberg, and Salmonella Enteritidis PT 30 on almonds. LWT, 143.
- Steinbrunner, P. J., Limcharoenchat, P., Suehr, Q. J., Ryser, E. T., Marks, B. P., and Jeong, S. (2019). Effect of food structure, water activity, and long-term storage on x-ray irradiation for inactivating Salmonella Enteritidis PT30 in low-moisture foods. Journal of Food Protection, 82(8), 1405–1411.
- Suehr, Q. J., Anderson, N. M., and Keller, S. E. (2019). Desiccation and thermal resistance of Escherichia coli O121 in wheat flour. Journal of Food Protection, 82(8), 1308–1313.
- Syamaladevi, R. M., Tadapaneni, R. K., Xu, J., Villa-Rojas, R., Tang, J., Carter, B., Sablani, S., and Marks, B. (2016). Water activity change at elevated temperatures and thermal resistance of Salmonella in all purpose wheat flour and peanut butter. Food Research International, 81, 163–170.
- Taylor, M. H., Tsai, H.-C., Rasco, B., Tang, J., and Zhu, M.-J. (2018). Stability of Listeria monocytogenes in wheat flour during extended storage and isothermal treatment. Food Control, 91, 434–439.
- Tsai, H.-C., Ballom, K. F., Xia, S., Tang, J., Marks, B. P., and Zhu, M.-J. (2019a). Evaluation of Enterococcus faecium NRRL B-2354 as a surrogate for Salmonella during cocoa powder thermal processing. Food Microbiology, 82, 135–141.
- Tsai, H.-C., Taylor, M. H., Song, X., Sheng, L., Tang, J., and Zhu, M.-J. (2019b). Thermal resistance of Listeria monocytogenes in natural unsweetened cocoa powder under different water activity. Food Control, 102, 22–28.
- Van Doren, J. M., Neil, K. P., Parish, M., Gieraltowski, L., Gould, L. H., andand Gombas, K. L. (2013). Foodborne illness outbreaks from microbial contaminants in spices, 1973-2010. Food Microbiology, 36(2), 456–464.
- Verma, T., Chaves, B. D., Howell, T., and Subbiah, J. (2021a). Thermal inactivation kinetics of Salmonella and Enterococcus faecium NRRL B-2354 on dried basil leaves. Food Microbiology, 96.
- Verma, T., Chaves, B. D., Irmak, S., and Subbiah, J. (2021b). Pasteurization of dried basil leaves using radio frequency heating: A microbial challenge study and quality analysis. Food Control, 124.
- Villa-Rojas, R., Tang, J., Wang, S., Gao, M., Kang, D.-H., Mah, J.-H., Gray, P., Sosa-Morales, M. E., and Pez-Malo, A. L. (2013). Thermal inactivation of Salmonella Enteritidis PT 30 in almond kernels as influenced by water activity. Journal of Food Protection, 76(1), 26–32.
- Villa-Rojas, R., Zhu, M.-J., Marks, B. P., and Tang, J. (2017a).Radiofrequency inactivation of Salmonella Enteritidis PT

- 30 and Enterococcus faecium in wheat flour at different water activities. Biosystems Engineering, 156, 7–16.
- Villa-Rojas, R., Zhu, M.-J., Paul, N. C., Gray, P., Xu, J., Shah, D. H., and Tang, J. (2017b). Biofilm forming Salmonella strains exhibit enhanced thermal resistance in wheat flour. Food Control, 73, 689–695.
- Wason, S., Verma, T., and Subbiah, J. (2021a). Validation of process technologies for enhancing the safety of low-moisture foods: A review. Comprehensive Reviews in Food Science and Food Safety.
- Add Wason et al. (2021b)
- Wei, X., Agarwal, S., and Subbiah, J. (2021a). Heating of milk powders at low water activity to 95°C for 15 minutes using hot air-assisted radio frequency processing achieved pasteurization. Journal of Dairy Science, 104(9), 9607–9616.
- Wei, X., Kiat Lau, S., Stratton, J., Irmak, S., Bianchini, A., and Subbiah, J. (2018). Radio-Frequency Processing for Inactivation of Salmonella enterica and Enterococcus faecium NRRL B-2354 in Black Peppercorn. Journal of Food Protection, 81(10), 1685–1695.
- Wei, X., Lau, S. K., Chaves, B. D., Danao, M.-G. C., Agarwal, S., and Subbiah, J. (2020a). Effect of water activity on the thermal inactivation kinetics of Salmonella in milk powders. Journal of Dairy Science, 103(8), 6904–6917.
- Wei, X., Lau, S. K., Reddy, B. S., and Subbiah, J. (2020b). A microbial challenge study for validating continuous radio-frequency assisted thermal processing pasteurization of egg white powder. Food Microbiology, 85.
- Wei, X., Verma, T., Danao, M.-G. C., Ponder, M. A., and Subbiah, J. (2021). Gaseous chlorine dioxide technology for improving microbial safety of spices. Innovative Food Science and Emerging Technologies, 73. https://doi.org/10.1016/j.ifset.2021.102783
- Wei, X, Agarwal, S., and Subbiah, J. (2021). Evaluation of Enterococcus faecium NRRL B-2354 as a surrogate for Salmonella enterica in milk powders at different storage times and temperatures. Journal of Dairy Science, 104(1), 198–210.
- Wei, X, Chen, L., Chaves, B. D., Ponder, M. A., and Subbiah, J. (2021). Modeling the effect of temperature and relative humidity on the ethylene oxide fumigation of Salmonella and Enterococcus faecium in whole black peppercorn. LWT, 140. https://doi.org/10.1016/j.lwt.2020.110742
- Wei, Xinyao, Lau, S. K., Stratton, J., Irmak, S., and Subbiah, J. (2019). Radiofrequency pasteurization process for inactivation of Salmonella spp. and Enterococcus faecium NRRL B-2354 on ground black pepper. Food Microbiology, 82(October 2018), 388–397.
- Wei, Xinyao, Vasquez, S., Thippareddi, H., and Subbiah, J. (2021b). Evaluation of Enterococcus faecium NRRL B-2354 as a surrogate for Salmonella in ground black pepper at different water activities. International Journal of Food Microbiology, 344(October 2020), 109114.
- Xie, Y., Cheng, T., Wei, L., Zhu, M.-J., Sablani, S. S., and Tang, J. (2021). Thermal inactivation of Salmonella Enteritidis PT30 in ground cinnamon as influenced by water activity and temperature. Food Control, 124.
- Xu, J., Shah, D. H., Song, J., and Tang, J. (2020). Changes in cellular structure of heat-treated Salmonella in lowmoisture environments. Journal of Applied Microbiology, 129(2), 434–442.
- Xu, J., Tang, J., Jin, Y., Song, J., Yang, R., Sablani, S. S., and Zhu, M.-J. (2019). High temperature water activity as a key factor

- influencing survival of Salmonella Enteritidis PT30 in thermal processing. Food Control, 98, 520–528.
- Xu, J., Yang, R., Jin, Y., Barnett, G., and Tang, J. (2020). Modeling the temperature-dependent microbial reduction of Enterococcus faecium NRRL B-2354 in radio-frequency pasteurized wheat flour. Food Control, 107.
- Yan, R., Pinto, G., Taylor-Roseman, R., Cogan, K., D'Alesandre, G., and Kovac, J. (2021). Evaluation of the Thermal Inactivation of a Salmonella serotype Oranienburg strain during cocoa roasting at conditions relevant to the fine chocolate industry. Frontiers in Microbiology, 12.
- Yang, R., Xie, Y., Lombardo, S. P., and Tang, J. (2021). Oil protects bacteria from humid heat in thermal processing. Food Control, 123.
- Yang, R., Xu, J., Lombardo, S. P., Ganjyal, G. M., and Tang, J. (2020). Desiccation in oil protects bacteria in thermal processing. Food Research International, 137.
- Yuqiao, J. I. N., Pickens, S. R., Hildebrandt, I. M., Burbick, S. J., Grasso-Kelley, E. M., Keller, S. E., and Anderson, N. M. (2018). Thermal inactivation of Salmonella agona in Low–Water activity foods: Predictive models for the combined effect of temperature, water activity, and food component. Journal of Food Protection, 81(9), 1411–1417.
- Zhang, B., Zhang, L., Cheng, T., Guan, X., and Wang, S. (2020a). Effects of water activity, temperature and particle size on thermal inactivation of Escherichia coli ATCC 25922 in red pepper powder. Food Control, 107.
- Zhang, H., Seck, H. L., and Zhou, W. (2021). Inactivation of Salmonella Typhimurium, Escherichia coli O157:H7, Staphylococcus aureus, and Listeria monocytogenes in cardamom using 150 KeV low-energy X-ray. Innovative Food Science and Emerging Technologies, 67.
- Zhang, L, Lyng, J. G., Xu, R., Zhang, S., Zhou, X., and Wang, S. (2019). Influence of radio frequency treatment on in-shell walnut quality and Staphylococcus aureus ATCC 25923 survival. Food Control, 102, 197–205.
- Zhang, Lihui, Kou, X., Zhang, S., Cheng, T., and Wang, S. (2018). Effect of water activity and heating rate on Staphylococcus aureus heat resistance in walnut shells. International Journal of Food Microbiology, 266 (December 2017), 282–288.
- Zhang, S, Lan, R., Zhang, L., and Wang, S. (2021). Computational modelling of survival of Aspergillus flavus in peanut kernels during hot air-assisted radio frequency pasteurization. Food Microbiology, 95.
- Zhang, Shuang, Zhang, L., Lan, R., Zhou, X., Kou, X., and Wang, S. (2018). Thermal inactivation of Aspergillus flavus in peanut kernels as influenced by temperature, water activity and heating rate. Food Microbiology, 76(January), 237–244.
- Zhang, Y., Keller, S. E., and Grasso-Kelley, E. M. (2017). Fate of Salmonella throughout production and refrigerated storage of tahini. Journal of Food Protection, 80(6), 940–946.
- Zhang, Y., Xie, Y., Tang, J., Wang, S., Wang, L., Zhu, G., Li, X., and Liu, Y. (2020b). Thermal inactivation of Cronobacter sakazakii ATCC 29544 in powdered infant formula milk using thermostatic radio frequency. Food Control, 114.
- Zheng, A., Zhang, L., and Wang, S. (2017). International Journal of Food Microbiology Veri fi cation of radio frequency pasteurization treatment for controlling Aspergillus parasiticus on corn grains. International Journal of Food Microbiology, 249, 27–34.

- Zhou, Z., Zuber, S., Campagnoli, M., Putallaz, T., Devlieghere, F., and Uyttendaele, M. (2019). Effect of mild steaming treatment on the inactivation of Salmonella, Listeria monocytogenes, Escherichia coli O157:H7 and their surrogates on black peppercorns. Food Control, 106.
- Zhu, M.-J., Song, X., Tsai, H.-C., Shen, X., Taylor, M., and Tang, J. (2021). Desiccation and thermal resistance of Salmonella and Enterococcus faecium NRRL B-2354 in almond meal as impacted by water activity and storage temperature. Food Control, 126.
- Zhu, M., Song, X., Shen, X., and Tang, J. (2020). Listeria monocytogenes in Almond Meal: Desiccation Stability and Isothermal Inactivation. Frontiers in Microbiology, 11.