Chapter 13
Microwave-Assisted Thermal Sterilization and Pasteurization

Xu Zhou and Juming Tang

1 Introduction

Thermal sterilization and pasteurization are important operations in the food industry in the production of safe foods with extended shelf life. These operations are designed to eliminate foodborne pathogens that can lead to foodborne illnesses, as well as spoilage organisms responsible for food spoilage. Pasteurization involves the application of mild heat (<100 °C) to inactivate specific pathogens and viruses, such as *Listeria monocytogenes* and Hepatitis A virus [1, 2]. To extend the shelf-life of pasteurized foods, refrigeration or freezing is required. On the other hand, commericial sterilization employs more intensive heating (usually ≥110 °C) to "eliminate viable microorganisms of public health concern, such as *Clostridium botulinum*, as well as microorganisms of nonhealth significance, capable of reproducing under normal non-refrigerated conditions (21 CFR 113.3)" [3, 4]. Sterilized foods can be safely stored at ambient temperature for 1–3 years, and in some critical scenarios such as military or space activities, where longer shelf life is essential, the shelf-life can reach up to 5 years [5].

1.1 History of Thermal Processing

The history of thermal processing dates back to the nineteenth century [6]. At that time, the French government openly solicited a method to preserve military foods. In

X. Zhou · J. Tang (✉)
Department of Biological Systems Engineering, Washington State University, Pullman, WA, USA
e-mail: x.zhou@wsu.edu; jtang@wsu.edu

A. Pratap-Singh et al. (eds.), *Microwave Processing of Foods: Challenges, Advances and Prospects*, Food Engineering Series, https://doi.org/10.1007/978-3-031-51613-9_13

1810, Nicolas Appert, a French confectioner, published the first book on canning [6]. In his book, Appert described a process that consisted of (1) enclosing food in closed whisky bottles, (2) subjecting the bottles to boiling water for varying durations depending on the foods, and then (3) cooling the bottles to ambient temperature. This processing method allowed food to be preserved for extended periods and supported the French military during wartime. In the 1860s, Louis Pasteur, a French chemist and biologist, established the microbiological basis of food spoilage underlying Appert's process. Over time, industrial thermal process operations in the modern food industry are now designed based on sound experimental and mathematical calculation methods established through the pioneering work of many scientists and engineers. Systematic research on microbial spoilage by experimental incubation tests began with the collaboration between Prescott (one of America's first canners) and Underwood (a bacteriologist at Massachusetts Institute of Technology) in the 1890s [7]. From the 1920s to the 1950s, mathematical models for characterizing thermal resistance of bacteria using isothermal thermal inactivation tests and methods for calculating lethality in thermal processing based on heat transfer, such as the General Method, and Ball's Formula Method, were established by Bigelow [8, 9], Ball [10], Stumbo [11], and others [6, 12].

1.2 Principle of Thermal Processing

Figure 13.1 provides a general overview of thermal processing principles. From a safety perspective, thermal processing is required to reduce the number of pathogenic microorganisms of public health concern to a statistically small level. The

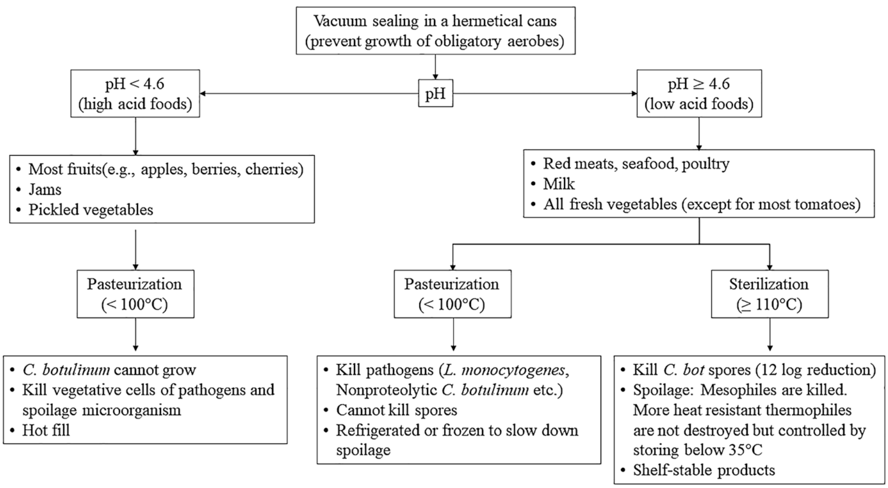

Fig. 13.1 General principle of thermal pasteurization and sterilization

specific requirements for thermal processing vary depending on various factors, such as pH and storage temperature [3, 13, 14].

Prior to commercial thermal processing operations, foods are vacuum sealed or flushed with nitrogen in O_2-free hermetical containers to prevent growth of obligatory aerobes. For low-acid foods (pH $>$ 4.6, water activity $>$ 0.85), *Clostridium botulinum* type A and B spores are of greatest public health concern. *Clostridium botulinum* are rod-shaped bacteria. They are anaerobic, meaning they live and grow in low-oxygen conditions, like in canned foods. The bacteria form protective and very heat-resistant spores when conditions for survival are poor, and the spores can germinate, grow and then produce lethal neurotoxin. The botulinum toxin is among the most toxic substances known and can cause a life-threatening disease, botulism in humans. There are seven difference forms of botulinum toxin, types A-G. Types A, B, E, and rarely F cause human botulism. Types C, D, and E cause illness in animals, such as birds and fish. All type E trains are non-proteolytic and less heat-resistant than type A and B (proteolytic). Thus, spores of *Clostridium botulinum* type A and B are the primary target in the canning processing of foods [15]. Commercial sterilization processes are thus required to reduce the population of *Clostridium botulinum* spores by at least 12 logarithmic cycles, commonly referred to as the 12-D concept or Bot cook [3, 4]. The *D*-values (decimal reduction time), representing the time required to achieve a 90% reduction in the microbial population, range from 0.21 to 0.25 minutes at 121.1 °C (250 °F) for *C. botulinum* spores [16]. Thus, a 12-D process using a *D*-value of 0.25 minutes would require a 3-minute exposure to 121.1 °C.

For high-acid foods (pH $<$ 4.5), such as fruits and sour pickles, it is well established that *C. botulinum* cannot grow or produce toxins in acidic conditions [17]. In these foods, the target microorganisms are typically vegetative pathogens and spoilage microorganisms, which have relatively lower thermal resistance compared to *C. botulinum* [18]. Consequently, high-acid foods can be safely processed at pasteurization temperatures ($<$100 °C) to ensure safety and shelf stability, such as hot filling.

Thermal pasteurization processes for chilled foods aim to reduce bacterial and viral foodborne pathogens to an acceptable level. A common practice is to achieve a 6-$\log_{10}$ reduction of *Listeria monocytogenes* or non-proteolytic *Clostridium botulinum* [1]. In high-moisture foods, *Listeria monocytogenes* (typical *D* value at 70 °C is 0.3 min) is the most heat-resistant vegetative pathogen capable of surviving freezing and growing under refrigerated conditions [13] to achieve a 6-log reduction of *L. monocytogenes*, a minimum temperature of 70 °C for 2 minutes or its equivalent is required [19]. This process inactivates all other less heat-resistant vegetative pathogens, such as *E. coli* and *Salmonella* (i.e., at least a 6 Log reduction). The 70 °C/2 min process is suitable for storage above freezing but at or below 5 °C for up to 10 days [2, 5]. Spore-forming non-proteolytic *C. botulinum* (minimum growth temperature is around 3 °C [19]) is another concern in chilled meals, especially those stored for more than 10 days and seafood [13]. Pasteurization at 90 °C for 10 minutes is recommended to achieve a 6-log reduction of non-proteolytic *C. botulinum* type B (typical *D* value at 90 °C is 1.5 min [19]) in meals intended for storage of up to

6 weeks above freezing but at or below 5 °C [19]. It is important to note that the above pasteurization processes (70 °C/2 min, or 90 °C/10 min) are unable to eliminate more heat-resistant proteolytic *C. botulinum*. Therefore, additional hurdles such as storage temperature < 10 °C, water activity < 0.93, or pH < 4.6 are necessary to control *C. botulinum* growth and toxin formation during storage [14]. Detailed discussion about the microbial safety concerns related to chilled meals, the criteria used for determining pasteurization process conditions, and the expected shelf life of these products can be found in Peng et al. [1] and Inanoglu et al. [13].

From a stability perspective, it is necessary to eliminate or destroy all bacteria that can cause microbial spoilage in foods at ambient temperatures [20]. Mesophilic and psychrophilic spoilage bacteria, being less heat-resistant, generally cannot survive the 12-D thermal processing. However, thermophilic bacteria are highly heat-resistant, and certain strains can produce resilient spores. For example, *Geobacillus stearothermophilus* (formerly known as *Bacillus stearothermophilus*) has a $D_{121°C}$ of 2.4 min, approximately ten times higher than the $D_{121°C}$ of *C. botulinum* (~0.25 min) [21]. But these thermophilic bacteria typically grow between 50 °C and 65 °C, with a minimum growth temperature of around 35 °C. Therefore, commercially sterilized food stored at temperatures below their minimum growth range, such as room temperature (below 30 °C), can inhibit their growth and prevent microbial spoilage. On the other hand, for pasteurized foods, additional hurdles are necessary to control spoilage during storage and transportation. These may include refrigeration or freezing storage, reduced water activity (e.g., added salts), low pH (e.g., acidic conditions), and the use of preservatives [13, 14].

1.3 Conventional Thermal Processing Method and Drawbacks

Canning is the most commonly used method for the commercial production of shelf-stable foods. A canning process involves several steps: (1) sealing foods in airtight containers, such as metal cans, glass jars, and polymeric trays or pouches, (2) loading the sealed containers into retorts (pressure vessels), and heating them to a specific temperature for a given time; various heating methods, including water immersion, steam, and water spray, can be used, and (3) finally cooling the food containers by introducing cold water. Industrial canning processes are designed to ensure that the cold spot of the foods achieves a desirable cumulative lethality level for *C. botulinum*, as defined by [22]:

$$F = \int_0^t 10^{\frac{\left(T - T_{ref}\right)}{z}} dt \qquad (13.1)$$

where F is the thermal death time (min), T(t) is the temperature (°C) of the cold spot inside foods, T_{ref} is the reference temperature (°C), and t is heating time (min). For commercial sterilization processes, T_{ref} is set as 121.1 °C, z-value of the *C. botulinum* spores is 10 °C, and F-value is written as F_0. The canning process of low acid food is required to achieve $F_o \geq 3$ min, corresponding to 12-D concept as mentioned earlier (Sect. 1.2). For pasteurization processes, T_{ref} might be chosen as the pasteurization temperature, and the z-value is selected based on a specific vegetative pathogen [1].

During conventional thermal processing, heat is transferred from the heating medium to the outer walls of the food containers and then transferred towards the inner parts (the coldest spot). The heat transfer rate varies greatly depending on the geometry and dimension of the container and type of food (solid or liquid). Solid foods, such as fish and meats, generally have low thermal conductivity (about 0.1 ~ 0.5 W/m°C) [23], resulting in slow conduction heat transfer. This often requires extended processing times to ensure sufficient heat penetration. For example, Banga et al. (1993) reported that tuna in cans (65 mm diameter × 15 mm height) should be held for 50 min at 121.1 °C to achieve the 12-D process in a still retort [24].

The cook value, C, is used to quantify the influence of a thermal process on food quality. It is defined by [25]:

$$C = \int_0^t 10^{\frac{T(t)-100}{z}} dt \tag{13.2}$$

where C is cooking value (min), z is the temperature change (°C) necessary to change the quality reaction rate by one order of magnitude; it varies from 10 to 40 °C, depending on foods and quality factors such as texture, flavor, color, and nutrient content [25].

In a case study discussed in Tang (2015), to achieve $F_0 = 6$ min for a 10-oz (300 g) food tray using processing temperature of 121 °C, the cook value at the cold spot (food center) was 93 min while the cook value at the hot spot (food surface) was 212 min [4]. The long exposure time causes severe thermal degradation of food quality, particularly near the food surface. The loss of food quality, including vitamins, color, protein, lipids, and texture, due to conventional thermal processing has been summarized by Barbosa-Cánovas et al. [26], Lucci et al. [27], and Peng et al. [1].

Optimizing conventional thermal processes for pre-packaged foods is challenging. The theoretical and experimental studies conducted by leading researchers such as Lund [25], Ohlsson [28], and Teixeira et al. [29, 30] concluded that for fixed sizes of food containers, improving heat transfer in containers is the only viable approach to shorten heating time and improve nutrient retention. For liquid foods or foods with liquid-particle mixtures, advanced retorting techniques such as Shaka, end-over-end, and axial agitation are employed [31–33]. These techniques improve convection heat transfer in liquid foods, reduce processing time, and improve food quality. However, for solid foods or semi-solid foods, creating internal agitation is not feasible.

To overcome these limitations, several novel thermal processing techniques have been developed in recent years, such as ohmic heating, microwave heating, and radio frequency heating. These methods change the way thermal energy is delivered to pre-packaged foods; that is, heat is generated throughout the food volume. Ohmic heating generates heat when an electric current passes through food materials with electric resistance; it is a rapid heating method and is particularly advantageous for processing food products containing particles or dices [34, 35]. Microwave and radio frequency heating involves the conversion of electromagnetic energy into thermal energy within foods. The interaction between dielectric food materials and electromagnetic fields generates instantaneous heat, providing rapid and volumetric heating [4, 36]. The following sections will focus on microwave-assisted thermal processing technologies for in-package foods.

2 Microwave Assisted Thermal Processing Technologies

2.1 Research Studies Using Domestic Microwave Ovens

Most published studies in research laboratories explored the application of microwave in pasteurization using 2450 MHz domestic microwave ovens. However, the studies show considerable variation in microbial inactivation, temperature distribution, heat penetration, and quality losses among different pathogens, food samples, and microwave ovens used. For example, Lu et al. (2011) investigated the influence of microwave heating at two power levels (700 and 750 W) on the inactivation of *Salmonella enterica* and the quality of grape tomatoes [37]. They found that microwave heating at 700 W for 40 seconds led to a 1.45-log reduction of *Salmonella enterica* on tomatoes without adversely affecting the texture quality. In another study, De La Vega-Miranda et al. (2012) reported that microwave heating in a 950 W microwave oven for 10–25 seconds raised the surface temperatures of jalapeño pepper and coriander to approximately 70 °C, leading to a 4–5-log reduction of *Salmonella* Typhimurium [38]. This study indicated that the microwave treatments significantly affected the color of jalapeño pepper and coriander. Ulusoy et al. (2019) reported a 1.7-log reduction and a 3.6-log reduction of *L. monocytogenes* in salmon fillets when heated in a microwave oven (360 W) to internal food temperatures of 50 °C and 70 °C, respectively [39]. These various microwave heating and microbial inactivation data highlight potential food safety concerns when utilizing domestic microwave ovens for pathogen control.

2.2 Industrial and Commercial Microwave Systems

In response to the limitations of domestic microwave ovens, successful industrial and commercial microwave systems were developed in Europe, mostly by equipment and food companies. European equipment manufacturers and food companies, such as OMAC, Bernstorff, and Tops Foods, developed several 2450 MHz industrial microwave heating systems. These systems demonstrated effectiveness in pasteurizing chilled products such as plated meals and soft cheeses [40], as well as sterilizing shelf-stable foods such as pasta meals [41, 42]. The developments of these commercial microwave systems have been reviewed in detail in Tang [4] and Tang et al. [2].

These commercial microwave-assisted thermal processing systems use 2450 MHz multi-mode heating cavities. Despite their commercial success, several issues associated with these 2450 MHz multi-mode systems limited their widespread applications. These issues include (1) multi-mode microwave cavities leading to random and unpredictable heating patterns in foods, (2) shallow microwave penetration depth in foods, and (3) inability to obtain FDA approvals due to concerns about non-uniform and non-reproducible heating patterns, and lack of knowledge about the location of the "cold spot" in the food packages. These issues hindered the introduction of these systems in the United States, where food safety regulations, especially for low-acid foods in hermetically sealed containers, are more rigorous [4].

2.3 Microwave-Assisted Thermal Sterilization and Pasteurization Systems Based on 915 MHz Single-Mode Cavities

To address the limitations of the 2450 MHz multi-mode microwave systems and obtain regulatory acceptance from US FDA (United States Food & Drug Administration), researchers at Washington State University (WSU) invented 915 MHz single-mode cavities for sterilization and pasteurization of packaged foods [50]. This has led to the development of the Microwave Assisted Thermal Sterilization (MATS) system and Microwave Assisted Pasteurization System (MAPS). The research and development efforts at WSU focused on six key areas of activities: (1) designing single-mode microwave cavities to provide predictable and stable heating patterns in foods, (2) developing an effective method for determining heating patterns and identifying cold spots inside food packages, (3) evaluating reliable temperature sensors for heat penetration tests in continuous microwave heating processes, (4) conducting microbial validation, (5) seeking regulatory acceptance, and (6) studying the effects of microwave processing on food quality [2, 4].

2.3.1 Cavity Design

In microwave heating systems, a microwave cavity is an important component for holding and heating foods. Based on their ability to resonate at different frequencies, the microwave cavity can be classified into two types: (1) single-mode and (2) multi-

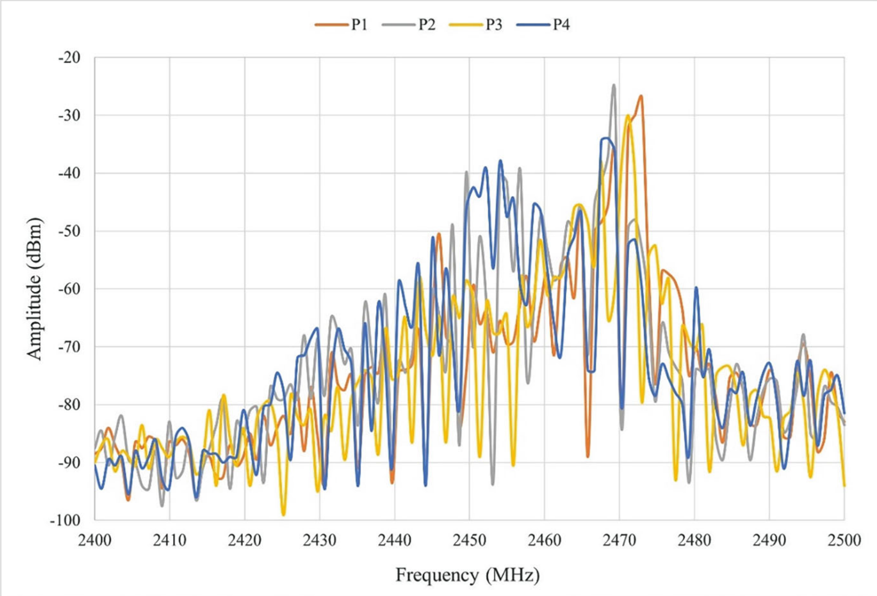

Fig. 13.2 Spectrum of a 2450 MHz magnetron when water load is placed at four different locations in the cavity (P1, P2, P3, P4). (Data adapted from [46])

mode cavities. A single-mode microwave cavity is designed to resonate at a single frequency. This is achieved by carefully selecting the cavity physical dimensions (typically about half the wavelength of the operating frequency) to support only one pattern of the electromagnetic field, known as single mode [43]. On the other hand, a multi-mode microwave cavity has larger dimensions compared to single mode cavities. The dimensions, typically several wavelengths of microwave frequency used, allow the cavity to support multiple modes over the microwave frequency range covered by microwave generators (Fig. 13.2) [44, 45].

The concept of *mode* is related to *standing waves*, which result from the superposition of two counterpropagating waves. Microwaves are produced in a microwave generator and propagate to a cavity through waveguides. Upon reaching the metallic walls of the cavity, the microwaves are reflected. The reflected wave combines with the incident wave to form a standing wave. The standing wave results in either constructive interference, where wave peaks or troughs coincide to amplify the resultant wave (creating antinodes), or destructive interference, where a wave peak coincides with a trough leading to the nullification of the wave (creating nodes). Three-dimensional standing wave patterns (modes) are formed in a microwave cavity due to the reflections at the six metallic walls. Each mode correlates to a unique standing wave pattern. The mode is determined by the dimension of the cavity and the microwave frequency spectrum. The resonant frequency of these modes can be calculated using the following equation [45]:

Table 13.1 Modes in a microwave cavity[a]

Mode index number			
m	*n*	*p*	Mode resonance frequency *f* (MHz)
0	5	1	2417.7
1	0	4	2426.1
0	1	4	2443.7
1	5	1	2445.2
4	4	1	2451.4
2	5	0	2453.7
6	2	1	2459.6
1	1	4	2470.9
3	4	2	2480.3

[a]Cavity dimensions: a (length) = 410 mm, b (width) = 320 mm, c (height) = 250 mm

$$f_r = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{c}\right)^2} \tag{13.3}$$

where f_r is the resonant frequency (Hz), ε is the permittivity (F/m), μ is the permeability (H/m), a, b, c are the cavity dimensions(mm), and the indices m, n, and p are referred to as the number of half-wavelengths of sinusoidal variation of E-field in the x-, y-, z-directions, respectively.

Magnetrons are widely used as the primary power source in microwave heating systems. Magnetrons do not generate microwaves at a single, fixed frequency, but rather over a specific frequency range [43, 46]. For example, in Fig. 13.2, the frequency spectrum of a 2450 MHz magnetron used in a domestic microwave oven (Model: NN-SD681S, Panasonic Co., Tokyo, Japan) shows microwave bandwidth from 2400 to 2500 MHz, and operating frequencies vary depending on the location of the heated subject. To calculate the typically excited modes in a 2450 MHz microwave cavity, we selected a frequency range from 2400 to 2500 MHz. Computational tools, such as MATLAB, were used to calculate all possible modes for a given set of cavity dimensions.

Table 13.1 provides an example of calculated frequencies and modes for a cavity with dimensions of a = 410 mm, b = 320 mm, c = 250 mm. In this case, nine different microwave standing wave patterns (modes) can exist between 2400 and 2500 MHz. This cavity is referred to as a multi-mode cavity [45].

The time-averaged microwave field in the multi-mode cavity is formed by the superposition of various coexisting standing wave patterns [45, 46]. Each standing wave pattern corresponds to a specific frequency, and even a slight frequency shift (e.g., 2 MHz) can result in a completely different pattern, as shown in Fig. 13.3.

Magnetrons are vulnerable to a phenomenon known as “frequency pulling” [43]. That means the peak frequency and bandwidth of the magnetron can vary due to factors such as power settings, the type of food being heated, and the location of the food in the cavity (Fig. 13.2) [46–48]. Also, the operating frequency and

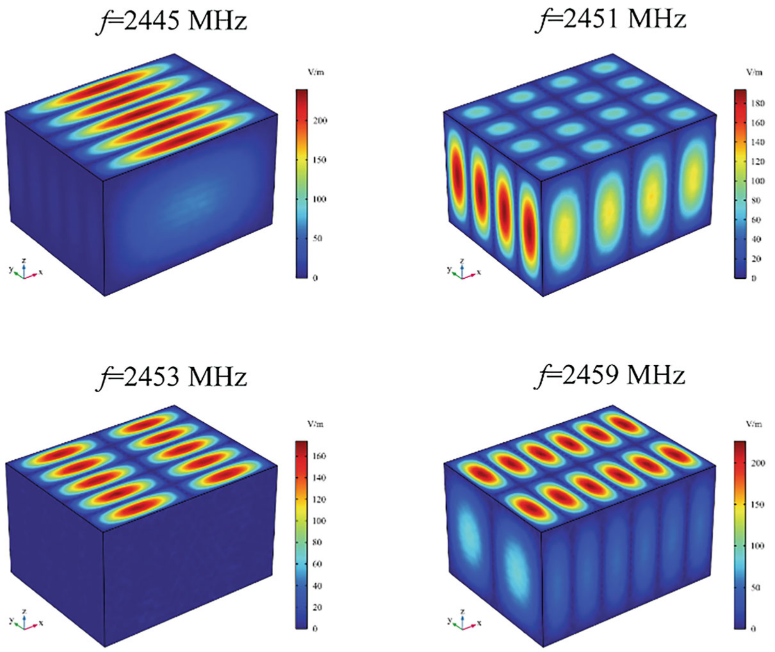

Fig. 13.3 Simulated electric field patterns at four resonant frequencies in an empty multi-mode cavity using COMSOL software

bandwidth of the magnetron can change with power supply (e.g., ripples), temperature, and aging [43]. As a result, it is difficult to predict and control standing wave patterns and, thus, heating patterns of foods in a multi-mode microwave cavity. There is no hope to use multi-mode cavities powered by magnetrons to provide stable and predictable microwave heating patterns for foods.

To address the limitations associated with 2450 MHz multi-mode microwave cavities, the WSU team led by Dr. Juming Tang focused on the development of 915 MHz single-mode cavities. Figure 13.4 illustrates the design of the 915 MHz single-mode cavity used in MAPS and MATS. In this design, microwaves generated by a 915 MHz magnetron are equally divided into each of two waveguides, one on the top and one on the bottom [49]. These synchronized waves propagate to horn applicators and a rectangular heating cavity to generate a standing wave pattern (Fig. 13.4b). The dimensions of both the cavity and the horn applicators, along the *x* and *y* axes in Fig. 13.4, are less than half a microwave wavelength at 915 MHz. This ensures that only a single mode can fit within the cavity. To improve the microwave field and temperature distributions in the food samples, computer simulations based on a finite-difference time-domain (FDTD) method are utilized to optimize the geometry and dimensions of the cavities [50, 51]. A major advantage of the single-mode cavity design is that it can provide stable and predictable standing wave and heating pattern for foods within the operating frequency range of the magnetron (e.g., 900–920 MHz) [48, 52].

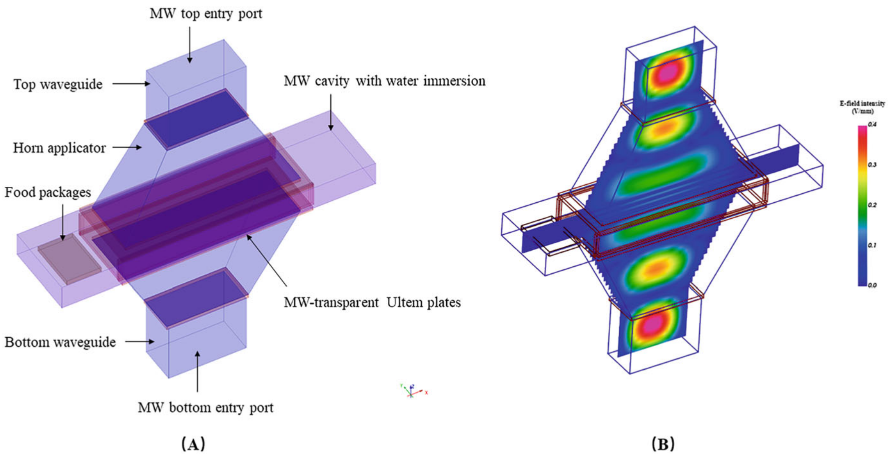

Fig. 13.4 (**a**) Schematical diagram of a 915 MHz single-mode microwave (MW) heating cavity and (**b**) the simulated standing wave pattern by using QWED software

Another advantage of using 915 MHz microwaves is the larger penetration depth of microwave energy in food when compared to 2450 MHz microwaves. The penetration depth (*dp*, m) is defined as the depth where the microwave power intensity decays to 36.8% of the initial strength [4]. Table 13.2 provides a comparison of microwave power penetration depths in different food samples at 915 MHz and 2450 MHz. The penetration depths of microwaves at 915 MHz are several times larger than those at 2450 MHz. For example, in salmon fillets and cooked macaroni noodles, the penetration depths at 915 MHz are 7.0–17.6 mm, while the penetration depths at 2450 MHz are 4.9–8.9 mm (depending on temperature). The deeper penetration of microwaves at 915 MHz allows for more efficient and uniform heating throughout the food sample, particularly for industrial operations.

2.3.2 Description of MAPS and MATS Systems

The MAPS and MAST systems developed at WSU consist of four sections: (1) pre-heating, (2) microwave heating, (3) holding, and (4) cooling sections. Each section has an individual water circulation loop, and the water temperatures are controlled by heat exchangers. Food packages in carriers are loaded into the preheating section, where they are heated to a specified equilibrium temperature. They are then moved into the microwave heating section, equipped with multiple 915 MHz single-mode cavities. The food carriers continuously pass through these heating cavities, ensuring that the coldest spots in the food packages reach the required temperature. After microwave heating, the packages are held in the holding section for a predetermined time and finally moved into the cooling section. MAPS utilizes circulating water at 70 °C – 90 °C, while MATS uses overpressure to heat the water above 100 °C. Detailed design information about these two systems can be found in Tang [4] and Tang et al. [2].

Table 13.2 Microwave penetration depth (mm) in foods and water at different frequencies

T (°C)	Salmon fillets (1.7% fat, 75% moisture)[a]		Cooked macaroni noodles (56% moisture)[b]		Tap water[c]		RO water[c]	
	915 MHz	2450 MHz	915 MHz	2450 MHz	915 MHz	2450 MHz	915 MHz	2450 MHz
20	17.6	8.9	67.3	17.0	107.0	18.0	131.0	19.0
80	9.8	6.8	63.2	28.1	148.0	61.0	369.0	63.0
120	7.0	4.9	51.1	28.1	122.0	86.0	457.0	117.0

[a]From Gezahegn et al. [54]
[b]From Tang [4]
[c]From Wang et al. [53]

Both the MAPS and MATS systems utilize water immersion, which serves three main purposes: (1) reducing or eliminating microwave edge heating in food packages, (2) providing surface convection heating for improved uniformity, and (3) acting as an impedance-matching medium to improve microwave power coupling [4, 55]. The current MATS and MAPS systems at WSU use reverse osmosis (RO) water. Gezahegn et al. (2021) shows that at 915 MHz, microwave power penetration depth in RO water is large, in particular at temperature above 90 °C [54]. Little microwave energy is absorbed by RO water at elevated temperatures used in pasteurization and sterilization processes. Compared to tap water, the use of RO water in MAPS/MATS systems can reduce microwave power loss in the circulation water by about 50–70%, resulting in improved microwave energy efficiency, faster heating rates, and higher food production rate [54].

In the WSU MATS system, a microwave-transparent conveyor belt with pockets made of a low loss tangent polymer material (Polytetrafluoroethylene, PTFE) is used to transport food trays or pouches through the MATS processing. The food packages are placed in the pockets as they move through different sections in MATS [26]. To enhance the transport capability of carriers for food packages of various sizes and shapes, an improved metal transport carrier (Tang Cage™) has been designed for MAPS (Fig. 13.5) [55, 56]. This carrier, made of stainless-steel sheets and cylindrical Polyetherimide (Ultem™), enhances robustness, stability, and performance for industrial microwave systems. The presence of metal plates and Ultem alters the electric field distribution within the microwave cavity and affects the heating patterns in foods. Computer simulation has been used to assist the carrier design with different metal alloy patterns for various or multiple food packages to improve microwave heating uniformity and heating rate [52]. Metal transport carriers offer a reliable and efficient means of transporting food packages during thermal processing in industrial microwave sterilization and pasteurization systems.

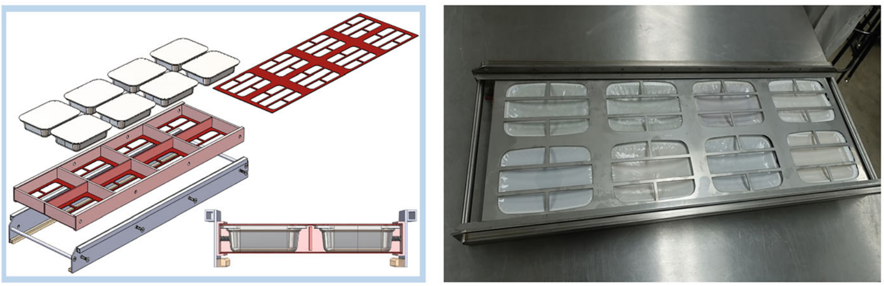

Fig. 13.5 Metal food carrier (Tang Cage™) for industrial microwave systems [55]

2.3.3 Temperature Distribution and Heat Penetration for Microwave Process Development

The regulatory agencies (such as U.S. FDA) require that a thermal process is developed based on the temperature history at the cold spot to calculate the necessary processing time or F-value (Eq. 13.1). However, two challenges associated with microwave heating need to be addressed:

(1) identifying the cold spot in food packages, as the temperature distribution in food packages is influenced by the microwave field distribution, dielectric properties, and thermal properties of food components, and the cold spot may not always be in the geometric center.
(2) accurately measuring temperature history at the cold spot. Fiber optic sensors are commonly used for temperature measurement in microwave heating as they do not interfere with microwaves. However, the fiber optic temperature sensors, which are needed to connected to an external light source, are not suitable for continuous processes where food packages are transported in a closed system.

For the first challenge, we have developed a chemical marker method to effectively determine the heating patterns in food [57, 58]. This method does not directly provide information on temperature distribution; instead, it determines the accumulative temperature-time effects based on color changes in model foods due to chemical marker formation over a complete thermal process [57]. Several model food systems, such as whey protein gels, mashed potatoes, Gellan gel and egg white with M-2 chemical marker precursor, have been developed to cover the range of dielectric and thermal properties of real foods for microwave pasteurization and sterilization [59–62]. A computer vision system is used to quickly visualize heating patterns and identify the cold spot in the foods [58].

We have also developed a metallic mobile temperature sensor method to accurately measure the temperature history of the cold spot during microwave processing. The wireless sensors are embedded in packaged foods to collect and store temperature data in continuous microwave heating systems. Systematic computer simulation studies were conducted to investigate the factors influencing the measurement accuracy of the sensor, such as microwave power, sensor orientation direction, and probe geometry [63, 64]. The simulation results were validated using the chemical marker method. These studies conclude that (1) slim metallic sensors have no influence on the general heating patterns, including the location of the cold spot, and (2) when the sensor probe is oriented perpendicular to the dominant electric field, it can provide reliable temperature history measurements. The chemical marker method and the metallic mobile temperature sensor methods allow the determination of the heating patterns and accurate measurement of the temperature history at the cold spot, facilitating the development of microwave-assisted thermal processing techniques that meet regulatory requirements.

2.3.4 Microbial Validation

Microbial validation is a necessary step in ensuring the effectiveness of a thermal process for achieving microbiological safety in food products. Surrogate organisms are used in the validation studies because it is not safe or practical to introduce pathogenic organisms into commercial food production facilities. For example, we used *Clostridium sporogenes* (PA 3679) spores to validate microwave sterilization processing schedules [65]. Thermal resistance tests were conducted on PA 3679 spore crops in phosphate buffer and several food products, such as salmon fillets and macaroni cheese [4, 65]. The results confirmed that the PA 3679 spore crops had similar z-values and higher D-values at 121.1 °C compared to *Clostridium botulinum*, which indicates that the surrogate spores are suitable for microbial validation studies in microwave sterilization processes. Several microwave processing levels were tested during microbial validation. The obtained data from these validation tests, which provide assurance that the determined thermal process is sufficient to deliver a microbiologically safe product ($F_0 = 6$ min), are then submitted to regulatory agencies, such as the FDA, as part of the validation process [4].

2.3.5 Regulatory Acceptance

Regulatory acceptance is crucial for commercializing microwave-assisted thermal processing systems for low-acid shelf-stable foods in the United States. The Federal Regulations (21 CFR 108) require commercial processors to register their establishments and file scheduled processes with the FDA for each specific product, product style, container size and type, and processing method. The pilot-scale MATS system at WSU played an important role in obtaining FDA and USDA FSIS (Food Safety and Inspection Service) acceptances [26]. The system went through rigorous temperature distribution and heat penetration testing before being used in validation for several food products. In 2009, the first FDA acceptance was obtained for the microwave sterilization of mashed potatoes in 10.5 oz. trays. In 2010, the second FDA acceptance was received for salmon fillets in sauce in 8 oz. pouches. In 2012, a non-objection letter was received from USDA FSIS for use of MATS technology, where a new set of data for chicken and dumplings in 8 oz. was provided. The procedures and required supporting documentation for agency approval have been discussed in detail in Tang [4].

2.3.6 Food Quality

Research studies conducted with MATS and MAPS systems have provided valuable insights into the influences of microwave processing on various food products, such as macaroni and cheese [66], asparagus [67], green beans [68], chicken pasta [69], and fried rice [70]. The results indicate that microwave processing, with its shorter processing time and volumetric heating, enhances the retention of food quality and nutrients compared to traditional thermal methods [5]. For example, Qu et al. (2021) reported that the MAPS-processed green beans had better retention of chlorophyll a, greenness, and vitamin C compared to those treated using traditional hot water methods with the same F-value [68]. The antioxidant activities of sterilized asparagus processed by microwave heating were significantly higher than those processed by the retort [67]. Microwave processing also significantly reduces the salt content in some of the tested recipes [5].

Microwave processing offers other advantages such as higher energy efficiency, reduced energy consumption, and a cleaner work environment. Microwave energy is powered by electricity that can be generated from renewable sources such as hydro, solar, and wind energy. This creates opportunities to assist the food industry in the low-carbon transition towards the Net-Zero CO_2 emission goal, contributing to a sustainable food future.

3 Future Research

Microwave-assisted thermal processing has shown great potential for enhancing food safety and quality for the food industry. In India, Tata SmartFoodz, a Tata Group subsidiary, uses industrial-scale MATS systems in the production of Tata Q line of 12 shelf-stable dishes, including pasta and noodle dishes, appetizers, and combination meals (https://www.tata.com/newsroom/business/tata-q-ready-to-eat-meals, accessed June 1, 2023). The company has a pilot-scale MATS-B system and a MATS-30 and MATS-42 for commercial production and co-manufacturing (https://www.915labs.com/systems, accessed June 1, 2023).

The currently developed microwave systems are powered by magnetrons, which have limitations such as a limited lifespan (e.g., 3000–4000 hours), large size, and high voltage operation (4–20 kV) [43, 71]. Another major problem associated with microwave heating is non-uniform temperature distribution, leading to hot and cold spots within the food product. This issue is partly attributed to the limited control capabilities of magnetrons. To address these challenges, solid-state microwave generators have emerged as a promising alternative [45, 46]. In solid-state microwave generators, the transformation of electrical energy into microwave energy is achieved through a solid-state power amplifier based on GaN or LDMOS transistors [71, 72]. The electrical-to-microwave conversion efficiencies of the solid-state generators have been increasing at a rate of 3% every 2–3 years and are projected to reach the same level as the magnetrons (~70%) by 2024 [72]. The solid-state generators offer several advantages, including a longer lifespan (up to 15 years), compact size, and low-voltage operation (50 V or less) [71]. Solid-state generators provide precise control over microwave frequency, power, and phase. A recent study has demonstrated the solid-state microwave generators provide stable peak microwave frequency with a very narrow bandwidth that are not influenced by the heated subjects [45, 46]. This is in sharp contrast with magnetrons, which exhibit significant variations in microwave frequency and bandwidth with different food types, food locations, and even among microwave ovens of the same model, causing uncertainty in microwave heating performance [45].

Future studies are needed to utilize the unique features of solid-state microwave generators in designing practical industrial microwave systems for the food industry. There is a need to explore effective control strategies for frequency, phase, and power of solid-state generators to improve heating uniformity, food quality, and overall energy efficiency. Future research should also explore the potential of integrating artificial intelligence (AI) with solid-state microwave technology. By using AI algorithms, precise and adaptive control of microwave processing parameters can be achieved. This advancement may create opportunities for efficient digital food manufacturing platforms, where AI-driven control systems can dynamically adjust microwave settings based on real-time data and specific food characteristics.

References

1. Peng, J., Tang, J., Barrett, D. M., Sablani, S. S., Anderson, N., & Powers, J. R. (2017). Thermal pasteurization of ready-to-eat foods and vegetables: Critical factors for process design and effects on quality. *Critical Reviews in Food Science and Nutrition, 57*(14), 2970–2995.
2. Tang, J., Hong, Y.-K., Inanoglu, S., & Liu, F. (2018). Microwave pasteurization for ready-to-eat meals. *Current Opinion in Food Science, 23*, 133–141.
3. Awuah, G. B., Ramaswamy, H. S., & Economides, A. (2007). Thermal processing and quality: Principles and overview. *Chemical Engineering and Processing: Process Intensification, 46*(6), 584–602.
4. Tang, J. (2015). Unlocking potentials of microwaves for food safety and quality. *Journal of Food Science, 80*(8), E1776–E1793.
5. Ross, C., Sablani, S., & Tang, J. (2023). Preserving ready-to-eat meals using microwave technologies for future space programs. *Food, 12*(6), 1322.
6. Goldblith, S. (1971). A condensed history of the science and technology of thermal processing. *Food Technology, 25*(1), 1–11.
7. Prescott, S., & Underwood, W. (1898). Micro-organisms and sterilizing processes in the canning industries. II the souring of canned sweet corn. *Technology Quarterly, 11*(1), 6–30.
8. Bigelow, W. D. (1921). The logarithmic nature of thermal death time curves. *The Journal of Infectious Diseases, 29*(5), 528–536.
9. Bigelow, W., Bohart, G., Richardson, A., & Ball, C. O. (1920). *Heat penetration in processing canned foods*. Research Laboratory, National Canners Association.
10. Ball, C. (1923). *Determining, by methods of calculation, the time necessary to process canned foods*. Bulletin, National Research Council of the National Academy of Sciences.
11. Stumbo, C. (1948). Bacteriological considerations relating to process evaluation. *Food Technology, 2*(2), 115–132.
12. Downing, D. L. (1996). *A complete course in canning and related processes: Fundamental information on canning* (13th ed.). CTI Publications.
13. Inanoglu, S., Barbosa-Canovas, G. V., Sablani, S. S., Zhu, M. J., Keener, L., & Tang, J. M. (2022). High-pressure pasteurization of low-acid chilled ready-to-eat food. *Comprehensive Reviews in Food Science and Food Safety, 21*(6), 4939–4970.
14. Tucker, G. (2016). Pasteurization: Principles and applications. In B. Caballero, P. M. Finglas, & F. Toldrá (Eds.), *Encyclopedia of food and health* (pp. 264–269). Academic.

15. Lund, B. M., & Peck, M. W. (2013). Clostridium botulinum. In R. G. Labbé & S. García (Eds.), *Guide to foodborne pathogens*. Wiley Blackwell.
16. Esty, J., & Meyer, K. (1922). The heat resistance of the spores of B. Botulinus and allied anaerobes. XI. *The Journal of Infectious Diseases, 31*(6), 650–664.
17. USDA Food Safety and Inspection Service (FSIS). (2013). *Clostridium botulinum & Botulism*. Avilable at https://www.fsis.usda.gov/food-safety/foodborne-illness-and-disease/pathogens/clostridium-botulinum. Accessed 6 June 2023.
18. Tola, Y. B., & Ramaswamy, H. S. (2018). Novel processing methods: Updates on acidified vegetables thermal processing. *Current Opinion in Food Science, 23*, 64–69.
19. European Chilled Food Federation (ECFF). (2006). Recommendations for the production of prepackaged chilled food. Available at https://www.ecff.eu/publications/. Accessed 6 June 2023.
20. Gram, L., Ravn, L., Rasch, M., Bruhn, J. B., Christensen, A. B., & Givskov, M. (2002). Food spoilage—Interactions between food spoilage bacteria. *International Journal of Food Microbiology, 78*(1), 79–97.
21. Wells-Bennik, M. H. J., Janssen, P. W. M., Klaus, V., Yang, C., Zwietering, M. H., & Den Besten, H. M. W. (2019). Heat resistance of spores of 18 strains of Geobacillus stearothermophilus and impact of culturing conditions. *International Journal of Food Microbiology, 291*, 161–172.
22. Stumbo, C. R. (1973). *Thermobacteriology in food processing* (2nd ed.). Academic.
23. Çengel, Y. A., & Ghajar, A. J. (2015). *Heat and mass transfer: Fundamentals & applications*. McGraw Hill Education.
24. Banga, J. R., Alonso, A. A., Gallardo, J. M., & Pérez-Martín, R. I. (1993). Kinetics of thermal degradation of thiamine and surface colour in canned tuna. *Zeitschrift fur Lebensmitteluntersuchung und-forschung, 197*(2), 127–131.
25. Lund, D. (1977). *Design of thermal processes for maximizing nutrient retention* (pp. 71–78). Food Technology.
26. Barbosa-Cánovas, G. V., Medina-Meza, I., Candoğan, K., & Bermúdez-Aguirre, D. (2014). Advanced retorting, microwave assisted thermal sterilization (MATS), and pressure assisted thermal sterilization (PATS) to process meat products. *Meat Science, 98*(3), 420–434.
27. Lucci, P., Pacetti, D., Loizzo, M. R., & Frega, N. G. (2016). Canning: Impact on food products quality attributes. In A. K. Jaiswal (Ed.), *Food processing technologies* (pp. 41–60). CRC Press.
28. Ohlsson, T. (1980). Optimal sterilization temperatures for sensory quality in cylindrical containers. *Journal of Food Science, 45*(6), 1517–1521.
29. Teixeira, A. A., Zinsmeister, G. E., & Zahradnik, J. W. (1975). Computer simulation of variable retort control and container geometry as a possible means of improving thiamine retention in thermally processed foods. *Journal of Food Science, 40*(4), 656–659.
30. Teixeira, A. A. (1969). Computer optimization of nutrient retention in the thermal processing of conduction-heated foods. *Food Technology, 23*, 845–850.
31. Pratap Singh, A., Singh, A., & Ramaswamy, H. S. (2017). Effect of reciprocating agitation thermal processing (RA-TP) on quality of canned tomato (Solanum lycopersicum) puree. *Journal of the Science of Food and Agriculture, 97*(8), 2411–2418.
32. Rattan, N. S., & Ramaswamy, H. S. (2014). Comparison of free/bi-axial, fixed axial, end-over-end and static thermal processing effects on process lethality and quality changes in canned potatoes. *LWT – Food Science and Technology, 58*(1), 150–157.
33. Sablani, S. S., & Ramaswamy, H. S. (1999). End-over-end agitation processing of cans containing liquid particle mixtures: Influence of continuous versus oscillatory rotation. *Food Science and Technology International, 5*(5), 385–389.
34. Salengke, S., & Sastry, S. (2007). Experimental investigation of ohmic heating of solid–liquid mixtures under worst-case heating scenarios. *Journal of Food Engineering, 83*(3), 324–336.
35. Salengke, S., & Sastry, S. (2007). Models for ohmic heating of solid–liquid mixtures under worst-case heating scenarios. *Journal of Food Engineering, 83*(3), 337–355.

36. Zhou, X., & Wang, S. J. (2019). Recent developments in radio frequency drying of food and agricultural products: A review. *Drying Technology, 37*(3), 271–286.
37. Lu, Y., Turley, A., Dong, X., & Wu, C. (2011). Reduction of Salmonella enterica on grape tomatoes using microwave heating. *International Journal of Food Microbiology, 145*(1), 349–352.
38. De La Vega-Miranda, B., Santiesteban-López, N., López-Malo, A., & Sosa-Morales, M. (2012). Inactivation of Salmonella Typhimurium in fresh vegetables using water-assisted microwave heating. *Food Control, 26*(1), 19–22.
39. Ulusoy, Ş., Üçok Alakavuk, D., Mol, S., & Coşansu, S. (2019). Effect of microwave cooking on foodborne pathogens in fish. *Journal of Food Processing and Preservation, 43*(8), e14045.
40. Decareau, R. V., & Mudgett, R. E. (1985). *Microwaves in the food processing industry*. Academic.
41. Schiffmann, R. F. (2001). Microwave processes for the food industry. In A. K. Datta & R. C. Anantheswaran (Eds.), *Handbook of microwave technology for food application* (1st ed., pp. 331–370). CRC Press.
42. Buffler, R. C. (1993). *Microwave cooking and processing*. Springer US/Van Nostrand Reinhold.
43. Metaxas, A. C., & Meredith, R. J. (1993). *Industrial microwave heating*. P. Peregrinus on behalf of the Institution of Electrical Engineers.
44. Chan, T. V. C. T., & Reader, H. C. (2000). *Understanding microwave heating cavities*. Artech House.
45. Zhou, X., Tang, Z., Pedrow, P. D., Sablani, S. S., & Tang, J. (2023). Microwave heating based on solid-state generators: New insights into heating pattern, uniformity, and energy absorption in foods. *Journal of Food Engineering, 357*, 111650.
46. Zhou, X., Pedrow, P. D., Tang, Z., Bohnet, S., Sablani, S. S., & Tang, J. (2023). Heating performance of microwave ovens powered by magnetron and solid-state generators. *Innovative Food Science & Emerging Technologies, 83*, 103240.
47. Luan, D. L., Wang, Y. F., Tang, J. M., & Jain, D. (2017). Frequency distribution in domestic microwave ovens and its influence on heating pattern. *Journal of Food Science, 82*(2), 429–436.
48. Resurreccion, F. P., Luan, D., Tang, J., Liu, F., Tang, Z., Pedrow, P. D., & Cavalieri, R. (2015). Effect of changes in microwave frequency on heating patterns of foods in a microwave assisted thermal sterilization system. *Journal of Food Engineering, 150*, 99–105.
49. Luan, D. L., Tang, J. M., Pedrow, P. D., Liu, F., & Tang, Z. W. (2016). Analysis of electric field distribution within a microwave assisted thermal sterilization (MATS) system by computer simulation. *Journal of Food Engineering, 188*, 87–97.
50. Tang, J., Liu, F., Pathak, S. K., & Eves, I. E. E. (2006). Apparatus and method for heating objects with microwaves. US Patent No. 7,119,313 B2.
51. Pathak, S. K., Liu, F., & Tang, J. (2003). Finite domain time domain (FDTD) characterization of a single mode applicator. *Journal of Microwave Power and Electromagnetic Energy, 38*(1), 37–48.
52. Jain, D., Tang, J. M., Liu, F., Tang, Z. W., & Pedrow, P. D. (2018). Computational evaluation of food carrier designs to improve heating uniformity in microwave assisted thermal pasteurization. *Innovative Food Science & Emerging Technologies, 48*, 274–286.
53. Wang, Y., Wig, T. D., Tang, J., & Hallberg, L. M. (2003). Dielectric properties of foods relevant to RF and microwave pasteurization and sterilization. *Journal of Food Engineering, 57*(3), 257–268.
54. Gezahegn, Y. A., Tang, J. M., Sablani, S. S., Pedrow, P. D., Hong, Y. K., Lin, H. M., & Tang, Z. W. (2021). Dielectric properties of water relevant to microwave assisted thermal pasteurization and sterilization of packaged foods. *Innovative Food Science & Emerging Technologies, 74*, 102837.
55. Tang, J., & Liu, F. (2019). *Microwave sterilization or pasteurization transport carriers and system*. US Patent No. 110258066.

56. Hong, Y.-K., Stanley, R., Tang, J., Bui, L., & Ghandi, A. (2021). Effect of electric field distribution on the heating uniformity of a model ready-to-eat meal in microwave-assisted thermal sterilization using the FDTD method. *Food, 10*(2), 311.
57. Pandit, R., Tang, J., Liu, F., & Pitts, M. (2007). Development of a novel approach to determine heating pattern using computer vision and chemical marker (M-2) yield. *Journal of Food Engineering, 78*(2), 522–528.
58. Pandit, R., Tang, J., Liu, F., & Mikhaylenko, G. (2007). A computer vision method to locate cold spots in foods in microwave sterilization processes. *Pattern Recognition, 40*(12), 3667–3676.
59. Bornhorst, E. R., Tang, J., Sablani, S. S., Barbosa-Cánovas, G. V., & Liu, F. (2017). Green pea and garlic puree model food development for thermal pasteurization process quality evaluation. *Journal of Food Science, 82*(7), 1631–1639.
60. Bornhorst, E. R., Tang, J., Sablani, S. S., & Barbosa-Cánovas, G. V. (2017). Thermal pasteurization process evaluation using mashed potato model food with Maillard reaction products. *LWT-Food Science and Technology, 82*, 454–463.
61. Wang, J., Tang, J., Liu, F., & Bohnet, S. (2018). A new chemical marker-model food system for heating pattern determination of microwave-assisted pasteurization processes. *Food and Bioprocess Technology, 11*, 1274–1285.
62. Wang, Y., Tang, J., Rasco, B., Wang, S. J., Alshami, A. A., & Kong, F. B. (2009). Using whey protein gel as a model food to study dielectric heating properties of salmon (Oncorhynchus gorbuscha) fillets. *LWT-Food Science and Technology, 42*(6), 1174–1178.
63. Luan, D., Tang, J., Pedrow, P. D., Liu, F., & Tang, Z. (2015). Performance of mobile metallic temperature sensors in high power microwave heating systems. *Journal of Food Engineering, 149*, 114–122.
64. Luan, D., Tang, J., Pedrow, P. D., Liu, F., & Tang, Z. (2013). Using mobile metallic temperature sensors in continuous microwave assisted sterilization (MATS) systems. *Journal of Food Engineering, 119*(3), 552–560.
65. Guan, D., Gray, P., Kang, D. H., Tang, J., Shafer, B., Ito, K., Younce, F., & Yang, T. (2003). Microbiological validation of microwave-circulated water combination heating technology by inoculated pack studies. *Journal of Food Science, 68*(4), 1428–1432.
66. Guan, D. S., Plotka, V. C. F., Clark, S., & Tang, J. (2002). Sensory evaluation of microwave treated macaroni and cheese. *Journal of Food Processing and Preservation, 26*(5), 307–322.
67. Sun, T., Tang, J., & Powers, J. R. (2007). Antioxidant activity and quality of asparagus affected by microwave-circulated water combination and conventional sterilization. *Food Chemistry, 100*(2), 813–819.
68. Qu, Z., Tang, Z., Liu, F., Sablani, S. S., Ross, C. F., Sankaran, S., & Tang, J. (2021). Quality of green beans (Phaseolus vulgaris L.) influenced by microwave and hot water pasteurization. *Food Control, 124*, 107936.
69. Patel, J., Sonar, C. R., Al-Ghamdi, S., Tang, Z., Yang, T., Tang, J., & Sablani, S. S. (2021). Influence of ultra-high barrier packaging on the shelf-life of microwave-assisted thermally sterilized chicken pasta. *LWT-Food Science and Technology, 136*, 110287.
70. Montero, M. L., Sablani, S., Tang, J. M., & Ross, C. F. (2020). Characterization of the sensory, chemical, and microbial quality of microwave-assisted, thermally pasteurized fried rice during storage. *Journal of Food Science, 85*(9), 2711–2719.
71. Atuonwu, J. C., & Tassou, S. A. (2018). Quality assurance in microwave food processing and the enabling potentials of solid-state power generators: A review. *Journal of Food Engineering, 234*, 1–15.
72. Atuonwu, J. C., & Tassou, S. A. (2019). Energy issues in microwave food processing: A review of developments and the enabling potentials of solid-state power delivery. *Critical Reviews in Food Science and Nutrition, 59*(9), 1392–1407.