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Chapter

# Microwave Heating for Food Preservation

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## Abstract

Since food is generally of low thermal conductivity, heating by conventional methods remains relatively slow. Thanks to its volumetric and rapid heating, microwave (MW) technology is successfully used in many applications of food processing. In this chapter, fundamental principles of MW heating are briefly presented. MW drying and MW microbial decontamination are extensively reviewed as innovative methods for food preservation. However, the complex interactions between microwaves and materials to be heated are not yet sufficiently controlled. Moreover, MW heating heterogeneity and thermal runaway are the main drawbacks of this technology. Several methods have been proposed and investigated in the literature to overcome these problems in order to assure the microbiological safety and quality of food products.

**Keywords:** microwave heating, microwave modeling, drying, pasteurization, sterilization, microbial decontamination, food safety, food quality

## 1. An overview of microwave heating

Microwaves (MWs) are electromagnetic (EM) waves, which are synchronized perpendicularly oscillations of electric and magnetic fields that propagate at the speed of light in a free space. MWs are characterized by the frequency (between 300 MHz and 300 GHz) and the wavelength (ranging from 1 m to 1 mm). According to the countries and regions, five frequencies (433, 896, 915, 2375, and 2450 MHz) are authorized for MW heating operations. The 2450 MHZ is the exclusive frequency for home appliances.

### 1.1 Mechanisms of microwave heating

The interaction of a wave with the material depends on its own characteristics (frequencies, wavelength) and the nature of the material, particularly its absolute permittivity $\varepsilon^*$, a complex number that determines how the material stores the electrical energy of the EF and its dissipation into heat. The readers can consult more specialized references for detailed information [1]. We can define rapidly here the real permittivity, or dielectric constant, of a material which denotes the capacity of the material to store electrical energy and the effective loss factor which expresses the ability of the material to absorb energy of the wave and dissipate it into the heat by dielectric relaxation and ionic conduction. If a material contains free charges (ions) and polar molecules (e.g., water molecule) when this material is subjected to an EF, the ions will move at an accelerated rate according to their charge, which will cause collisions between them and, by the result, a conversion of the kinetic energy into heat (ohmic heating). In the same way, the polar molecules of this material, which was initially randomly oriented, will be oriented according to the polarity of the field. If the EF is an alternative, these molecules will rotate to remain aligned on it. This dipolar rotation will generate frictions between the molecules which will lead to an internal generation of heat (dielectric heating).

### 1.2 Penetration and absorption of a wave in a material

When an EM wave is directed toward a material, a part of the wave is reflected on the surface, while the other part penetrates it to be absorbed. The absorption of the wave during its crossing results in a decrease of the amplitude of the internal EF and so of its power. For small or thin materials, the accurate calculation of the internal electric field is recommended by using the Maxwell equations. Lambert's law (exponential EF decayed) may be used for larger objects.

The penetration depth is defined as the penetration distance in the material for which the 63% of incident power of the incident wave has been absorbed. This depth depends on the dielectric properties of the material as well as the wavelength. The penetration depth at 915 MHz is larger than the penetration depth at 2450 MHz at the same conditions. More power will be absorbed when the loss factor is high [1].

### 1.3 About the heterogeneity of microwave heating

MW heating is inherently heterogeneous for several reasons:

- For most cases, product size is very large compared to the penetration depth; thus, the energy of the EM wave will be completely absorbed before being able to reach the core or the bottom of the product. All the parts of the product not crossed by the EM wave will not undergo heating. Smaller products will heat faster than large ones, because MWs are able to penetrate the entire product. However, small products are also more sensitive to variations in EM fields that exist in the oven, particularly in a multimode cavity.

- Dimensional resonance phenomena: sometimes, the wave is reflected against the lower edge of the product leading to interference phenomena. This results in producing cold spots (transmitted and reflected waves cancel each other) and/or hot spots (transmitted and reflected waves add up).

- If the product is made of several components, the component with the highest dielectric constant tends to concentrate the energy, and its temperature will increase strongly compared to the other components which leads to selective overheating. The dependence of dielectric properties with the temperature often leads to increase the local temperature of the already hot points. As foods are generally low thermal conductivities, this phenomenon leads to local overheating (thermal runaway).

- The shape of the product plays a major role in the heterogeneity of MW heating. The shape of the sample influences the penetration depth of the MWs and the location of the hot spots. In general, the presence of sharp edges and right angles leads to significant local overheating at these locations. Sundberg et al. [2, 3] found that the power density at the edge decreased with the increase of the opening angle; thus, oval or circular forms may in some cases reduce this problem. However, in these forms the MW power is concentrated in the center [4].

## 2. Microwave drying

### 2.1 Introduction

Drying is one of the most used methods for preserving food and preventing microbiological degradation. Food drying is also used for economic interests by lightening the product to minimize the transport costs (e.g., milk powder) or even for consumption aspects by creating new textures and/or products (e.g., prunes). This process aims to reduce the water activity (Aw) of the food product by removing some of its water. The amount of water to be removed to achieve the microbiological stability can be determined thanks to the sorption isotherm curve which shows the relationship between the water content and the water activity of a product. Generally, the water activity threshold from which there is no further development of pathogenic bacteria is 0.85–0.86 and 0.7 and 0.6 for yeasts and molds, respectively.

It is interesting to note that Aw does not only control the development of microorganisms, it also influences the rate of the chemical and biochemical reactions that take place within the food. The nonenzymatic browning (Maillard reaction) has a maximal activity for an Aw of 0.6–0.7, while the oxidation of lipids develops rather at very low and very high values of Aw. Thus, it is proper to adjust the final moisture of the product according to these considerations. The area generally targeted for good stability of the dried product is the range of Aw between 0.3 and 0.4. An important aspect must be emphasized here, namely, that drying has almost no lethal effect on the microorganisms present on the product due to insufficient product temperatures reached during drying. Proper packaging is therefore essential to avoid moisture recovery and keep the quality of the dehydrated product.

Industrial drying techniques are very varied depending on the nature of the product to dry (liquid, pasty, solid, or particulate) and of the desired final qualities. Most often, hot air (HA) convective drying is the main dehydration technique used in food industries. However, this method undergoes several problems such as poor end-product quality and low operation performance. Generally, in conventional drying method, two steps take place: a heat transfer from hot and dry surrounding medium to the product and then a mass (water and/or volatile compounds) transfer from the product to the surrounding atmosphere. In general, external heat and mass transfer can be easily controlled by a good monitoring of the drying air characteristics (velocity, temperature, relative humidity); thus, the internal transfer is the limiting step and the effective driving force for the drying operation. The drying rate decreases with time, and the removal of water becomes difficult. Therefore, conventional HA drying requires the application of severe conditions, particularly at the end of operation, which result in overheating and overdrying of the product surface. These reasons have greatly encouraged engineers to develop and propose new drying techniques such as MW drying. For example, MW drying was successfully applied to dry potatoes chips, pasta, and snacks [5]. Several studies of MW drying were resumed in the literature [6].

### 2.2 Microwave drying versus hot air drying

During MW drying of strong moisture content product, EM energy is supplied directly to the volume of the product, which causes a rapid increase of the product temperature and an instantaneous vaporization of water inside the product [7]. This phenomenon causes an increase in the internal pressure and drives the water to liquid state toward the product surface [8]. This forced outflow of water increases the drying rate and so reduces the operation time (up to five times less than HA air drying for many products). Likewise, the increase in internal pressure prevents food shrinkage and case hardening during drying, which have a positive impact on the texture of the MW dried product. Indeed, it promotes a greater porosity and increases the rehydration ability [9].

The action of conservation provided by the drying to foodstuffs is mainly due to the decrease of Aw which thus makes it possible to limit the development of microorganisms. However, an additional action is observed in the case of MW drying. In fact, the rapid rise in temperature for water-rich products seems to produce a thermal shock effect on thermosensitive microorganisms. Laguerre et al. [10] have shown, in a comparative study of drying of onions either by HA or by MWs, a reduction of the total microbial count ten times greater for MW drying (about one to two log reductions). This is a significant advantage of MW drying compared to hot air drying.

Although the selectivity of EF may cause heating heterogeneity, this selectivity is rather an advantage in the case of MW drying. The level of energy absorption is controlled by the wet parts, resulting in positive selective heating of the inner layers of the product still having a relatively high moisture content without affecting the relatively dry outer layers, thereby facilitating the outflow of water to the surface.

However, even if the MW drying is faster than that of HA method, the MW drying efficiency is limited because of the rapid saturation of the surrounded air due to its low temperature. For this reason, MWs are usually associated with HA flow to improve water transfer at the surface of the product. Another difference between MW and HA drying is the surface temperature. During HA drying, the surface temperature does not exceed the controlled surrounding air temperature, which may be low (30–40°C) during thermosensitive product drying (e.g., aromatic plants), whereas excessive surface temperature may occur during MW drying, especially along the corner or edges, resulting in product carbonization and production of off-flavors especially during the final stages of operation [6].

### 2.3 Controlled power microwave drying: innovative method to prevent runaway heating

In many works, a constant MW applied power is usually used throughout the drying period. This practice promotes the phenomena of thermal runaway (local overheating) at the end of drying. During MW drying performed at constant power, the applied specific power (power/product mass) increases exponentially as can be seen in **Figure 1** for the drying of tomato as an example [11]. Thus, the product receives more and more energy over time while it needs less and less. Moreover, the thermal properties of the product (specific heat and thermal diffusivity) decrease at the same time as the moisture of the product; therefore, it becomes easier to heat the product while the heat accumulated in a zone can less easily diffuse to the whole product. All this, combined with the phenomenon of dimensional resonance, can lead to thermal runaway. This phenomenon can be observed in the case of drying onions [10, 12]. **Figure 2** shows the evolution of hot spots up to charring on onion slices during MW drying. The fact that the black spots are very localized initially confirms the presence of dimensional resonance phenomena in this case.

To improve the quality of MW dried foods, the control of the applied power throughout the drying was studied in the literature. Li et al. [13] proposed the control of applied power according to the set product temperature, whereas Soysal et al. [14] adapted the applied power as a function of processing time. A very good quality product was obtained by Laguerre et al. [10, 15]. The authors controlled the power as a function of the product mass. This method was successfully tested for drying onions and tomatoes as presented in **Table 1**. A final product of fresh-like color, without any black spots, was obtained.

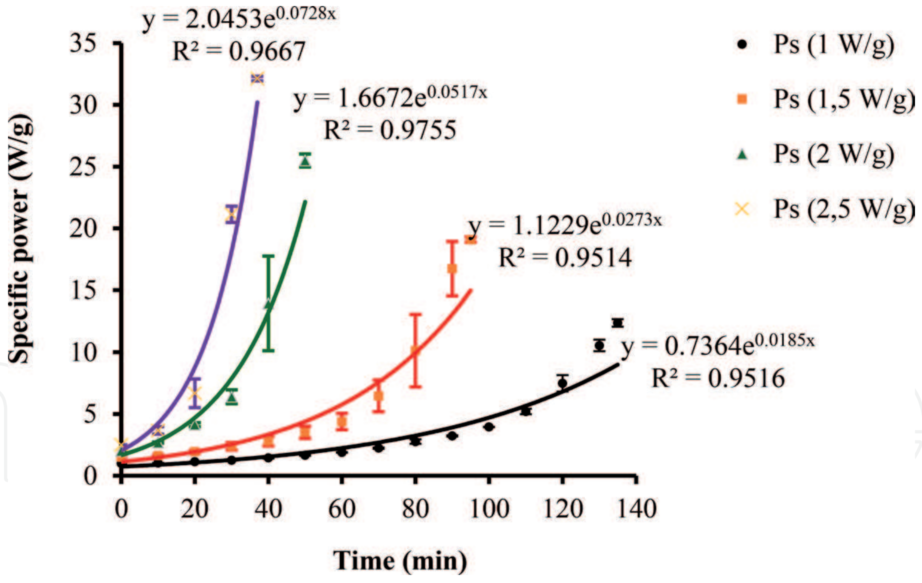


**Figure 1.**
*Evolution of the specific power (W/g) as a function of time (min) for different initial specific power values during drying of tomatoes [11].*

## 2.4 Combined microwave drying technologies

Despite its several advantages over the conventional methods, MW drying has some crucial problems as explained above. However, MW drying combined with other conventional heating methods enhances the drying efficiency as well as the dried product quality compared to MW drying alone. Applications of combined MW drying, principally, include MW-assisted hot air (HA) drying, MW vacuum drying, and MW freeze drying.

### *2.4.1 MW-assisted hot air drying*

The application of MW energy (internal heating) associated with hot air flow (superficial heating) is a good method to overcome certain problems related to the use of these two methods separately. MW heating may be applied at the beginning of the drying process to heat the internal layers of the product rapidly. MW heating can be also applied at the second step of drying process, when the temperature profile is established, to force vapor out of the product which leads to create a porous structure. MW heating can also be applied at the end of drying process, where the mass transfer is reduced to improve the drying rate by removing the bound water [9]. For example, MW drying combined with HA drying at the last stage reduced the drying time by 64% as compared to convective air drying [16]. Saving drying time and improved quality were also reported, using this method, for other fruits such as blueberries [17], macadamia nuts [18], and green peas [19].


**Figure 2.**
*Evolution of hot spot during MW drying of onion slices [10].*

| Product | MW/hot air drying | |
| --- | --- | --- |
| | Without MW power adaptation | With MW power adaptation |
| Onion [10] |  |  |
| Tomato [11] |  |  |

**Table 1.**
*Effect of the adaptation of the power applied on the color of the dried product.*

### *2.4.2 MW vacuum drying*

In order to reduce the boiling point of water and to prevent the oxidation reactions, MW heating can be associated with a vacuum to maintain the quality (color and flavor) of the dried products. This method was successfully used to dry apple slices [20], pumpkin [21], and cranberries [22]. This method is better than MW air drying in terms of energy consumption, drying time, and quality of the dried products [6].

### *2.4.3 MW freeze drying*

Lyophilization, also known as freeze drying, is a low-temperature dehydration process, which involves freezing the product at the first step and then removing the ice by sublimation under low-pressure conditions. It is used for dehydration of very heat-sensitive materials particularly in food and pharmaceutical industries. This method preserves the structure and minimizes the loss of valuable compounds. However, this technology is limited by its high cost. In MW freeze drying, MW heating can be applied concurrently during the sublimation to supply the heat under vacuum conditions. MW heating can also be applied separately after a traditional lyophilization step. MW freeze drying offers many advantages due to its low processing temperature and lack of oxygen in the processing environment [23, 24]. However, as the MW energy does not interact with frozen water, thermal runaway might take place which may result in poor product quality [6].

## 3. Microwave pasteurization and sterilization of foods

Pasteurization and sterilization are widely used to extend the shelf life of most foods. The main goals of pasteurization are to destroy vegetative pathogenic microorganisms and to deactivate some enzymes in foods. Pasteurization temperatures and treatment time vary, primarily, depending on the nature, the pH of the product, and the target microorganism. In most pasteurization processes, the food is heated up to 60–85°C for a time varying from a few seconds to an hour. Pasteurization requires refrigerated storage conditions (3–4°C) for a storage life of 2–6 weeks. Sterilization, which can be seen as further pasteurization, destroys bacterial spores [25]. In solid or semisolid products, the heat transfer takes place mainly by conduction from the surface to the center often considered as the "cold" point. This leads to apply more severe conditions to reach the target temperature at the cold point, which results in an overcooking of the surface and a degradation of the quality of products. Optimizing thermal treatments (i.e., maximizing inactivation of bacteria while minimizing nutrient degradation) is therefore an important issue. However, this is not an easy task and it is always a technical and scientific challenge. Thanks to the direct and volumetric interaction between MWs and food, MW heating has the advantage of overcoming the limitation imposed by slow thermal diffusion of conventional heating.

### 3.1 Microbial decontamination by microwave heating

Many studies demonstrated the effectiveness of using MW heating for pasteurization and sterilization of food [26–28]. Furthermore, different strains of microorganisms have been inactivated by MW heating, for example, *Bacillus cereus*, *Campylobacter jejuni*, *Clostridium perfringens*, *Escherichia coli*, *Enterococcus faecalis*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Salmonella* [29, 30].

### 3.2 Thermal and athermal effects of microwave heating on microorganisms

The study of microbial destruction mechanisms during an MW heating has attracted a lot of interest [31, 32]. In particular, the possible existence of nonthermal (athermal) effects of microwaves is a subject of debate. Several theories have been proposed to explain how electromagnetic fields can inactivate microorganisms at sublethal temperature conditions. This effect would be due to the interaction between microwaves and certain cellular constituents. In contrast, many studies have refuted the lethal nonthermal effect of MWs. To distinguish between thermal and nonthermal effects, most studies are based on the experimental evaluation of conventional and MW inactivation under identical heating conditions.

Fujikawa et al. [33] showed no difference between inactivation treatments for *E. coli* (suspended in PB phosphate buffer) in a conventional water bath and in a MW oven. Welt et al. [34] have developed a device to evaluate the possible nonthermal effects of microwaves. They compared the inactivation of *Clostridium sporogenes* spores in a model medium (a phosphate buffer) under a same time-temperature condition for conventional and MW treatment. The results demonstrate the absence of a nonthermal effect.

On the other hand, several studies demonstrated that the microwaves have a more important bactericidal effect [35, 36]. Sato et al. [37] found that the inactivation of *E. coli* K12 exposed to MW radiation was higher than that obtained in a water bath at the same temperature (45, 47, and 50°C).

Some authors support the thesis of improved bactericidal effect of microwaves. Kozempel et al. [38] developed an experimental device for detecting a possible nonthermal effect of microwaves on microorganisms at low temperature. The process combines instantaneous energy input to the food system by microwaves with rapid removal of thermal energy. The system used is a double-tube heat exchanger installed inside a continuous MW tunnel. The outer tube is microwaveable, while the inner tube is stainless steel and was used to cool the system instantly to keep the temperature at 45°C. The nonthermal effect of MW radiation has not been observed for yeast, *Pediococcus* sp., *Escherichia coli*, *Listeria innocua*, or *Enterobacter aerogenes*, in various liquids. However, the author has reported that MWs can improve or amplify the thermal effect in lethal conditions [38]. In the same context, Ramaswamy et al. [39] found that the inactivation of *S. cerevisiae* inoculated in apple juice treated with steam, hot water, or MW was not significantly different at sublethal temperature (<40°C). However, they found that MW radiations enhanced inactivation for same lethal temperature conditions (55–65°C).

Numerous studies on the interactions between MWs and certain cellular constituents, such as DNA, the cell membrane, enzymes, and proteins, have been carried out. Kakita et al. [40] studied the survival of bacteriophage PL-1, which is specific for *Lactobacillus casei*, under MW irradiation. More viral DNA fragmentation was found for MW heating over conventional heating. Shamis et al. [41] studied the effects of MW radiation on the membrane of the *E. coli* cell under sublethal temperature conditions (<40°C). Compared to conventional treatment, a different cellular morphology was observed (the cells are contracted and dehydrated). Nevertheless, this effect seems to be temporary; 10 min after the end of the exposure, the morphology of the cell seemed to return to the initial state of untreated controls. In this experiment, cell viability test revealed that the MW treatment was not bactericidal, since 88% of the cells were recovered. Similarly, Woo et al. [42] reported that MW radiation of *Escherichia coli* and *Bacillus subtilis* resulted in an increase in the amounts of nucleotides and protein released from cells. This leak was strongly correlated to MW power. The authors observed, by scanning electron microscopy, a significant damage on the surface of MW-treated *E. coli* cells; however, there was no significant change observed for *B. subtilis* cells. Likewise, Shin and Pyun [43] showed that MW treatment (at 50°C) causes irreversible damage to the membrane of *Lactobacillus plantarum*, associated with increase of the permeability. Also, observations by electron microscopy showed a change in cellular morphology on *Candida albicans* treated with MW [44].

To prove the existence of nonthermal effect of microwaves on microorganisms, exactly the same thermal history must be reproduced for MW and conventional treatments. Most of studies previously cited applied temperature measurement techniques inappropriate to MW heating, where the temperature was monitored at a single point of the sample. In addition, it is also important to eliminate the heating heterogeneity inherent in MW processing. Consequently, microorganisms are subjected to uneven heating as a result of the presence of cold and hot spots within the same sample. In summary, so far, the existence of nonthermal effect of MWs on microorganisms has not been proven; even if this effect exists, it has no significant consequence on the MW heating of foods.

### 3.3 Advantages and limitations of microwave microbial decontamination

In fact, it is difficult to compare the efficiency of MW over conventional heating process because of the inherent differences of heating principle between the two technologies [45].

In the case of conventional heating, a slow heat exchange occurs between the heating medium and the product. The heat diffusion inside the product depends on its physical properties (specific heat, thermal conductivity, porosity, etc.). However, it is well known that foods are bad thermal conductors, heat diffusion toward the cold spot is usually slow, and MW heating is generally faster than conventional heating. The heat is generated directly within the food. This direct volumetric heating significantly reduces the processing time resulting in greater retention of nutrients, sensitive vitamins, and aromatic constituents. Microwave-processed foods may also have better texture, taste, and appearance than products processed by conventional methods. For example, a two times faster MW pasteurization treatment of pickled asparagus at 915 MHz was published [46]. This advantage reduced significantly the thermal degradation of asparagus compared to a conventional treatment in a water bath. Similarly, an acceptable MW pasteurization of foie gras was reported with a time saving of 50% and better organoleptic qualities compared to a traditional method [47]. Moreover, MW pasteurization of packaged products is possible for different packaging materials (plastic, paper, and glass) [48, 49]. Furthermore, this technology can be combined with other technologies such as infrared heating for surface cooking, for example [50].

Despite the numerous advantages of MW decontamination technology, heating heterogeneity is a serious problem that leads to incomplete inactivation of microorganisms. Several studies have reported the survival of pathogens such as *Salmonella* spp. [51] and *L. monocytogenes* [52], in foods heated in MW ovens.

Goksoy et al. [53, 54] studied the effect of short-time MW exposures on *Escherichia coli* K12 and *Campylobacter jejuni* inoculated on chicken meat. A temperature variation of 20°C was measured between different parts of the sample. The auteurs reported that the samples subjected to MWs showed signs of partial cooking areas. There was no evidence that short-time exposure (up to 30 s) to MWs had any bactericidal effect on microorganisms. Apostolou et al. [55] confirmed these results. MW heating of chicken portions did not eliminate *E. coli O157: H7*. A significant variation of temperature (from 66.7 to 92°C) was also observed.

On the other hand, the heterogeneous heating causes a severe deterioration of food quality. Local overheating often results in irremediable changes of color where the temperature is highest [56]. These phenomena are mainly observed at the corners and the edges of the product due to wave reflection.

Another difficulty concerning MW decontamination is the problem of cold spot localization. During a typical thermal process, the cold point is well defined and located often at the center of the product. During MW pasteurization, one point temperature monitoring within the product is not sufficient to ensure food safety [57]. For example, Schnepf and Barbeau [58] studied the inactivation of inoculated *Salmonella* in poultry. Their results showed that measuring the internal temperature during MW treatment does not reflect the surface inactivation, where the temperature was lower. To locate the cold spot, the chemical marker method developed by Kim and Taub [59] was successfully used [60–62]. Combined with experimental investigations, numerical simulations are highly recommended to find the cold spot and to achieve an accurate study to develop a reliable MW decontamination process [57, 63, 64].

### 3.4 Minimizing the heterogeneity of microwave heating

Before accepting MW technology as a reliable method for pasteurization and/or sterilization of food, it is important to ensure uniform heating during treatment. Several studies have been conducted to improve the quality and safety of MW-treated products, and various solutions have been proposed.

Fung and Cunningham [65] reported that MW heating in combination with conventional heating results in more uniform heating of food and better inactivation of bacteria. Datta et al. [66] found that MW heating in combination with infrared heating or air jets decreases the nonuniformity of temperature distribution. In the same field, Maktabi et al. [67] investigated the synergistic killing effect of laser, MW, and UV radiation on *E. coli* and on some other spoilage and pathogenic bacteria. It was found that the overall reduction in viable counts was significantly higher than the sum of the reduction values for the individual treatments. The order of the treatment processes had also a significant influence on microbial destruction. A successive process by laser, MW, and then UV was the most effective. Similarly, Lau and Tang [46] studied the heating uniformity and textural quality of pickled asparagus pasteurized by MW in comparison with the conventional hot-water pasteurization method. Two successive heating steps, first in water bath and then in 915 MHz MW oven, were successfully applied. Moreover, covering the top one-third of the product glass bottle with aluminum foil eliminated the overheating at the edges. MW pasteurization also reduced the cook value for pickled asparagus and reduced textural degradation.

On the other hand, the presence of an absorbent medium around the product can reduce the overheating of edges and corners. For example, some authors reported that immersion of the sample in hot water [48] or the use of a steam flow into the oven cavity [68] may be used to ensure a safer and better quality end product. Microwave-circulated water combination (MCWC) heating system demonstrated a relatively uniform heat distribution within packaged food products. Guan et al. [48] reported that microbial destruction by a pilot-scale MCWC heating system matched with designed degrees of sterilization ($F_0$ value) for a conventional treatment.

Koskiniemi et al. [69] improved the heating uniformity of packaged acidified vegetables using a continuous 915 MHz MW system with a two-stage rotation device to rotate the products 180° during treatment. This method increased also the average temperature at the cold point to meet the industrial standard for in-pack pasteurization of acidified vegetables.

Pulsed MW heating technique was also successfully tested. In this method, pulsed application of energy—i.e., turning the magnetron power "on" and "off" intermittently—leads to thermal energy equalization via conduction from hot to cold region during the power-off periods. This results in more uniform temperature distribution within the sample than during continuous application of energy [70, 71]. Sato et al. [37] reported also an enhanced killing rate of *Escherichia coli* K12 by using pulsed waves compared to continuous treatment.

### 3.5 Modeling and optimization of microwave heating

Computational fluid dynamics (CFD) is widely used as an established approach for understanding and then optimizing food processing based on the solution to partial differential equations of mass, momentum, and energy transport. MW heating is a multiphysics phenomenon that requires electromagnetic propagation equations (i.e., Maxwell's equation) to be combined simultaneously with the heat transfer equation to predict the MW power absorption as well as the temperature distribution inside the product [72]. Modeling of MW heating is widely studied in the literature. Interested readers can consult specialized references for more details [73].

In order to design and optimize a reliable MW pasteurization and/or sterilization process, heating model needs to be coupled with kinetic models correlating microbial decontamination. The resulting global model has to mimic the spatial temperature distribution as well as the microbial inactivation at every point within the sample. Few coupled numerical studies of bacterial inactivation by MW heating are reported in the literature. Recently, Masood et al. [64] published an excellent review about emerging technologies modeling to ensure microbial safety of foods.

The classical concept of decimal reduction time and thermal resistance constant (D and z values) was also used to characterize the microbial inactivation by MW heating. Cañumir et al. [74] determined D-values at constant power levels and proposed a z-value in watt to represent the resistance of a target germ during MW heating. Laguerre et al. [75] proposed new specific power destruction parameters, $D_p$- and $z_p$-values, to qualify MW heating. The decimal reduction time ($D_p$ value) is the treatment time required to reduce microbial population by 90% at a constant applied specific power expressed in W/mL or in W/g. The $z_p$ value is the change of specific power necessary to cause a tenfold change in the $D_p$ values of microorganism under specified conditions. This concept has been successfully tested for sterilization of infant food in a lab-scale MW pilot. The optimal condition for MW sterilization of infant food was also determined.

Because of the heterogeneity of MW heating, microbial inactivation kinetics need to be coupled with nonlinear heat transfer model to calculate the temporospatial survival of bacteria [63]. Mallikarjunan et al. [76] developed a mathematical model that includes mass heat transfer to microbial inactivation kinetics. The variation of the dielectric properties with respect to the temperature is taken into account in the simulation process. A good agreement with experimental data was obtained. Hamoud-Agha et al. [57, 63] used COMSOL Multiphysics to investigate the inactivation of *E. coli* K12 suspended in a gel medium, comparing MW processing with conventional thermal treatment in a water bath. The authors coupled the thermal nonlinear microbiological inactivation model of Geeraerd et al. [77] with heat transfer and Maxwell's equations integrated into a finite element model under dynamic heating conditions. The results revealed uneven temperature distribution during MW heating which led to a lower inactivation efficiency than water bath treatment. Simulation results were in good agreement with experimental data. The modeling approach to estimate efficiency of microbial inactivation was reliable despite the thermal heterogeneity inherent in the MW treatment. Application of holding time at lethal temperatures (55 and 57°C) did not help to homogenize the temperature distribution within the sample [57, 63].

However, because of digital resources required and time consumption, the use of physical models as presented before could be delicate for real industrial applications in the food industry. On the other hand, another approach based on experimental designs (EDs) and response surface methodology (RSM) can be relatively easy, fast to implement, and quite useful [78]. Nevertheless, RSM has some limitations [8]: (1) it uses a priori models (quadratic model whatever the studied response); (2) the number of tests to be reset can increase very quickly with the number of factors in the plan; (3) the factors must be completely independent; and (4) uncontrolled factors cannot be taken into account.

Another method proposed by Lesty et al. [79], based on iconographic correlations (CORICO), makes it possible to circumvent these difficulties [8]. After analysis of the experimental plan data, CORICO proposes regression models whose regressors are logical interactions (AND, Exclusive OR, IF, etc.) between factors. In addition, CORICO tolerates linked factors and allows the consideration of uncontrolled factors. Furthermore, it needs few numbers of essays comparatively to classical EDs, (17 essays for a 9-factor CORICO designs against 533 for a 9-factor Doehlert design), which allows to minimize costs. This method has recently been used in the agri-food sector for the optimization of the drying process of different food products (tomato, microalgae, apple) [11, 80, 81] as well as for MW cooking processes (beef burgundy, fish) [82, 83].

## 4. Conclusions

Conventional heat treatments for food preservation are generally characterized by poor end-product quality. Furthermore, these methods are not optimized for solid foods because of slow heat transfer from the surface to the cold point, often at the center of the product. Enhanced organoleptic and nutritional food properties combined with food safety is the aim of modern food processing technologies. Microwave (MW) heating has the advantages to overcome the limitation of slow thermal diffusion imposed by conventional heating. This technology knows a growing industrial demand thanks to its flexible and rapid heating performance. MW heating is successfully used for food drying and decontamination. However, this process is still relatively poorly controlled because of complex interactions between foods and MWs. Furthermore, the heating heterogeneity is the major drawback of this technology. Several methods were, nevertheless, proposed in the literature to improve the heating homogeneity. In general, coupling MW heating with other heating methods largely improved the microbiological safety, the drying efficiency, and the quality of various food products. Physical modeling and simulation are important tools to understand and to optimize MW heating processes. The application of these models is limited in industrial scale; however, experimental design-based approaches could be promising methods. Even so, developing a reliable industrial MW heating process is still a challenge.

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