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## Microwave processing: Effects and impacts on food components

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### ABSTRACT

As an efficient heating method, microwave processing has attracted attention both in academic research and industry. However, the mechanism of dielectric heating is quite distinct from that of the traditional conduction heating, and is widely applied as polar molecules and charged ions interaction with the alternative electromagnetic fields, resulting in fast and volumetric heating through their friction losses. Such a heating pattern would cause a certain change in microwave treatment, which is an unarguable reality. In this review, we made a retrospect of the essential knowledge about dielectric properties and summarized the concept of microwave heating, and the impact of microwave application on the main components of foods and agricultural products, which are classified as carbohydrates, lipids, proteins, chromatic/ flavor substances, and vitamins. Finally, we offered a way to resolve the drawbacks of relevant microwave treatment and outlined the directions for future research.

### KEYWORDS

Foods; carbohydrates; lipids; proteins; chromatic/ flavor substances; vitamins; microwave

### Introduction

Dielectric processing is a technology impelling polar molecules heated by shifting from their average equilibrium positions in electric field to create heating energy from internal molecular friction and charged ions interacted with the alternative electromagnetic fields. It is commonly described as an effective and high production quality heating method, depending on its characteristics of volumetric heating generation and mechanism. Dielectric treatment includes microwave (MW, 2450 and 915 MHz) and radio frequency (RF, 13.56, 27.12, and 40.68 MHz) heating for industrial applications (Alfaifi et al., 2013). MW processing has been attracting extensive attention both in agriculture and industry, including food processing, paper manufacturing, medicine, chemical engineering, and metallurgy (Mujumdar, 2007). For food processing purpose, MW technologies can be used as pasteurization (Awuah et al., 2005; Hong et al., 2016), disinfection (Jian et al., 2015; Hou et al., 2016), baking (Awuah et al., 2014; Yolacaner et al., 2017), blanching (Marra et al., 2009; Xin et al., 2015), cooking/heating (Kirmaci and Singh, 2012; Zhong et al., 2015), drying (Zhu et al., 2012; Jiang et al., 2016), defrosting (Akkari et al., 2006; Llave et al., 2015), and extraction (Ge et al., 2009; Guan et al., 2011). These MW treatments have been adapted to the food categories, including fruits/vegetables (Jiang et al., 2012; Ruan et al., 2013; Benlloch-Tinoco et al., 2015; Singh et al., 2015; Xin et al., 2015), meats (Yoshida et al., 1992; Duan et al., 2008a, 2008b), grains (Lewandowicza et al., 2000; Xue et al., 2008), eggs (Zhang et al., 2013), milk (Awuah et al., 2005; Rodríguez-Alcalá et al., 2014), nuts (Zhu et al., 2012; Valdés et al., 2015),

and lipids (Regulska-Ilow and Ilow, 2002; Hernández-Carrión et al., 2011).

There are many advantages of MW treatment, namely: (1) increases process speed; (2) achieves relatively uniform heating throughout the material. Although not always true, often the bulk heating effect does produce uniform heating, avoiding the large temperature gradients that occur in conventional heating systems; (3) high energy efficiency; (4) precise and rapid process control; (5) reduced floor space requirements; (6) obtained selective heating; (7) improved product quality; and (8) desirable chemical and physical effects may be produced (Mujumdar, 2007; Zhang et al., 2010). Different from conventional heating methods (solar or hot air drying), heat is generated within the product during MW treatment due to molecular friction resulting from oscillating dipole molecules and migrating ions caused by the applied alternating electric field. Therefore, MW heating is expected to deliver more homogenous heat at a faster rate than slow conventional heating, which relies on the processes' conduction and convection to transport heat from the heating sources to the product (Piyasena et al., 2003). Besides, in an endogenous heating method, both mass and energy transfer take place from interior to surface during MW treatment, while in the conventional drying method the opposite is the way between mass and energy transfer, which may raise the mass transfer resistance during processing. It should also be mentioned that RF and MW systems have been recognized to be 50–70% heating efficient in comparison to 10% efficiency with conventional heating ovens (Mermelstein, 1997). All those results have ensured the advantages of dielectric processing.

Although there are many advantages of dielectric treatment in food processing, dielectric energy has not yet been exploited to its fullest potential in the industrial applications. The efficiency of an MW heating relies on two factors: (i) the processing time and (ii) the heating uniformity of the processing/hot spot formation. An important issue in MW processing of samples is thermal runaway, which is primarily due to large MW power absorption or heat generation in places with high temperatures resulting in increasing dielectric loss factors. The non-uniform heating due to thermal runaway during MW heating is one of the key factors behind product quality deterioration. However, it can hardly avoid the fact that dielectric heating is the existence of hot spots in several zones depending on product statuses (size, shape, position, and dielectric properties) and equipments (size of cavity, electromagnetic field, power, and electrode configuration; Wang et al., 2007; Tiwari et al., 2011; Jiang et al., 2012, 2014; Alfaifi et al., 2014; Huang et al., 2015). These factors could result in non-uniform electric field distribution, in turn causing non-uniform temperature distribution. Non-uniform heating widely exists in the materials, including nuts fruits/vegetables, meats, eggs, etc. (Zhang et al., 2010; Alfaifi et al., 2014; Jiang et al., 2014; Wang et al., 2014; Lau, 2015; Llave et al., 2015). Major problems in dielectric treatment, such as poor end quality, pathogens/insects survivals, microbial safety concerns, and overheating, are all related to non-uniform heating during dielectric treatment (Jiao et al., 2012; Kim et al., 2012; Kirmaci and Singh, 2012). Several researchers have studied the methods to solve the non-uniform heating during dielectric treatment by new equipment design and development, exogenous high dielectric properties, micro-particles addition, and homogenization of materials (Duan et al., 2008a, 2008b; Jiang et al., 2014; Chen et al., 2015; Huang et al., 2016). However, due to the structure and properties shifting of components existed inside the food, the trial and error procedures are time consuming, costly, and often provide limited information, which cannot easily identify the mechanism behind non-uniform MW treatment.

MW power absorption, in general, depends on the physico-chemical structure and properties of a material, such as chemical composition, water content, and temperature. These factors alter the dielectric properties of the material, which in turn, alter the energy absorption characteristics via wavelength and penetration depth within the sample. It is also controversial in large part because the “specific” effects of dielectric-assisted reaction are difficult to be determined and dielectric techniques applied on agricultural products always accomplish their goals with heat effect. But a certain change caused by dielectric treatment during application on foods is an unarguable reality. In this respect, the application of MW heating on food materials is highly addressed in previous studies. To be a complex system, a huge amount of elements constitute the foods. Except for the physical altering, such as expansion, charring, or dehydration, the impacts on components of food and the linkage between physical characteristics and chemical changes of components during MW treatment also attracted the interest of researchers. The review collected the essential knowledge about dielectric properties and summarized the concept of MW heating, focused on the impact of MW techniques on the main components of foods (including carbohydrates, lipids, proteins,

chromatic/flavor substances, and vitamins), and discussed the linkage between chemical properties and food quality. Finally, we offered a way to resolve the problems of MW treatment at present and outlined the directions for future research.

## Basic theories and features of dielectric treatment

All electromagnetic waves are characterized by their wavelength (frequency). Typically, the electromagnetic wavelength ranging from 10 to  $10^{-3}$  m can be considered as the dielectric range (Datta and Anantheswaran, 2001). These electromagnetic waves can cause the dipolar rotation of agricultural products. In the classical atom mechanics, materials are made of atoms, while each atom consists of a cloud with negative charge (electrons) bound to and surrounding a positive point charge as center. Once the charge cloud of electric field is distorted, the electric field and the dipole moment show the deflection, which makes them uncoincided (the dipole moment points are only in the same direction as the electric field in an ideal condition). Under this situation, the dielectric molecule vibrates and is followed by electromagnetic waves, and then returns to its original state. The time required to do so is called the relaxation time, and such a molecule is called the dipolar molecule (Guru and Hiziroglu, 2004).

There are two mechanisms of creating heat energy under electromagnetic field. One is dipolar polarization, which plays the most important role in heating agricultural products in electromagnetic field under MW field. Many molecules, such as water, can be dipolar polarized in electromagnetic field. Other molecules may become “induced” dipoles because of the stresses from the electric field. Dipolar polarization is a polarization that is either inherent to polar molecules (orientation polarization), or can be induced in any molecule in which the asymmetric distortion of the nuclei is possible (distortion polarization). When an external electric field is applied on dipolar molecules, the distance between charges within each permanent dipole, which is related to chemical bonding, remains constant in orientation polarization; in a word, the direction of polarization itself rotates, but the electric field attempts to pull them into alignment. However, as the field decays back to zero (relaxes), the dipoles return to their random orientation only to be pulled toward alignment again as the electric field builds up to its opposite polarity. This causes an energy conversion from the electrical field. Energy caused by friction is stored as potential energy and then converted into random kinetic or thermal energy in the material (Mujumdar, 2007). Another mechanism is ionic conduction, which is the polarization caused by relative displacements between positive and negative ion molecules. For instance, in sodium chloride solution, there are sodium, chloride, hydronium, and hydroxyl ions, all of which are moved in the direction opposite to their own polarity by the electric field. As a result, they collide with unionized water molecules, when the polarity changes the ions’ acceleration in the opposite fashion. This phenomenon occurs many millions of times depending on the frequency, and may cause large numbers of collisions and transfers of friction energy to occur (Robert, 2007). In agricultural products, dipolar polarization is the most essential mechanism to heat the samples in the MW range, while ionic conductivity plays a major

role during low-frequency treatment (27.17 MHz, for instance; Wang et al., 2003).

Dielectric properties are the relevant material properties explaining their interactions with electric fields. The dielectric properties' parameters of usual interest are the relative dielectric constant  $\epsilon'$ , loss tangent or dissipation factor ( $\tan \delta$ ), and the loss factor  $\epsilon''$ . The dielectric constant ( $\epsilon'$ ) describes the ability of a material to store energy when it is subjected to an electric field, influencing the electric field distribution and the phase of waves traveling through the material. The loss factor ( $\epsilon''$ ) influences both energy absorption and attenuation, and also describes the ability to dissipate energy in response to an applied electric field or various polarization mechanisms, which commonly result in heat generation (Mudgett, 2007). The relationship between them is defined as

$$\epsilon = \epsilon' - j\epsilon'' \quad (1)$$

where  $j = (-1)^{0.5}$ , indicates a  $90^\circ$  phase shift between the real ( $\epsilon'$ ) and imaginary ( $\epsilon''$ ) parts of the complex dielectric constant.

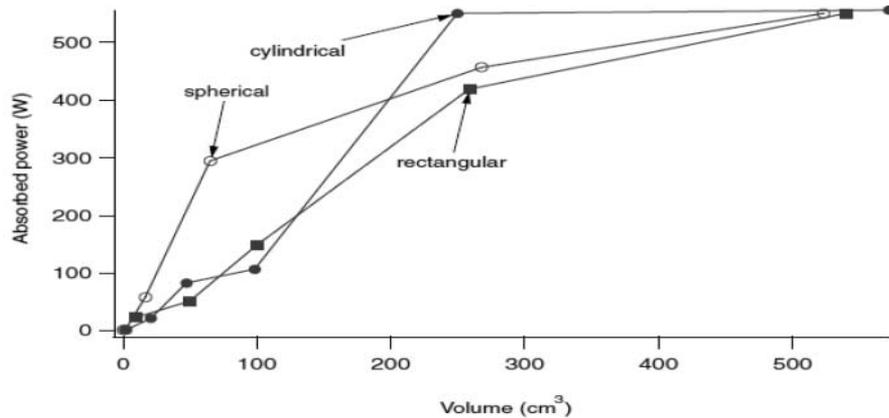
The dielectric properties of foods are the basic and critical factors to influence the dielectric processing. The dielectric properties of most materials vary with several different factors. For agricultural products, the critical factor is moisture content. Besides, those properties determine the absorption of MW

energy and consequent heating behavior of food materials in dielectric heating and processing applications. The MW heating process is not only influenced by physical properties, including shape, volume, surface area, and component of raw materials (Figure 1), but also by the dielectric properties as a function of temperature, moisture content, dielectric frequency, and density.

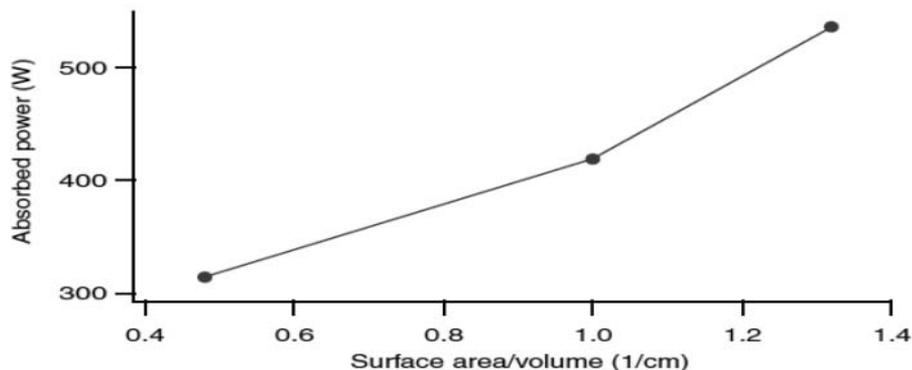
Except altering the electromagnetic field and the dielectric properties of agricultural products, various dielectric frequency applications also can be a way to improve the dielectric treatment (uniformity and penetrability). With the various dielectric frequencies, the dielectric properties of foods would be varied (Table 1). An important phenomenon contributing to the frequency dependence of the dielectric properties is the polarization, arising from the orientation with the imposed electric field, of molecules, which have permanent dipole moments (Nelson and Datta, 2001). As described in Equation (2), smaller frequency accomplished with better penetration, as well as heating uniformity:

$$P = \frac{3.31 \times 10^7}{f \tan \delta \sqrt{\epsilon_r}} \quad (2)$$

where  $P$  is the dielectric energy penetration depth (m),  $f$  is the frequency (Hz),  $\tan \delta$  stands for the dielectric power factor of the dielectric material (loss tangent), and  $\epsilon_r$  is the specific



A



B

Figure 1. Effect of the power absorption at different (A) shape and volume and (B): surface (Zhang and Datta, 2003).

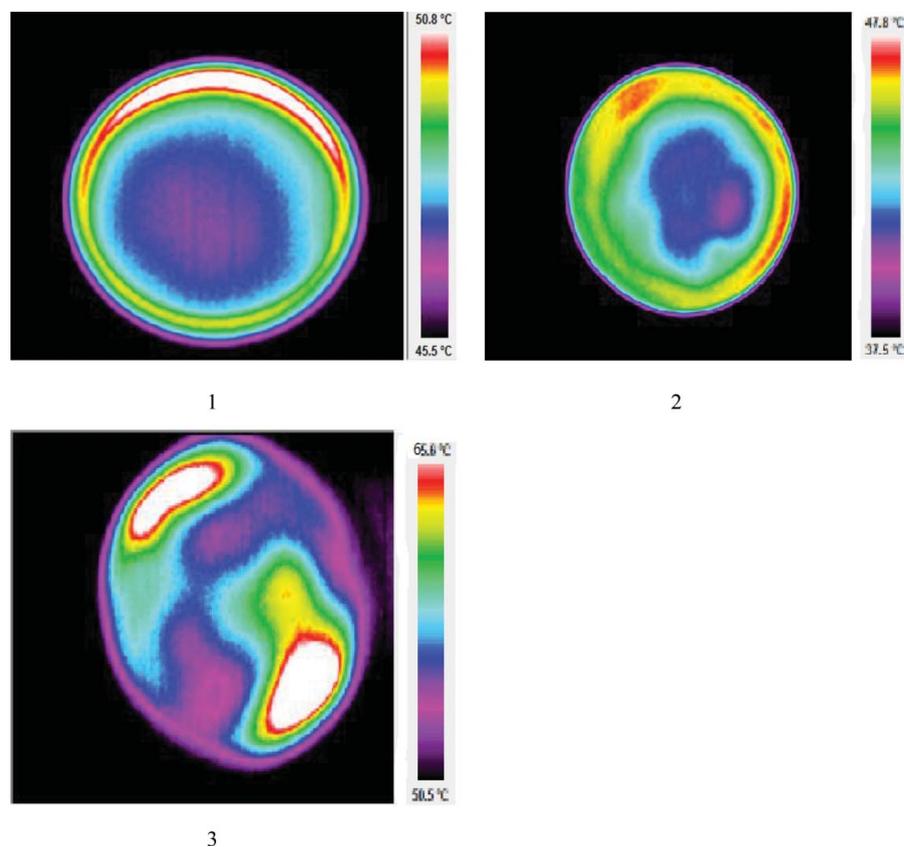
**Table 1.** Microwave dielectric properties of water at indicated temperatures (Kaatz, 1989).

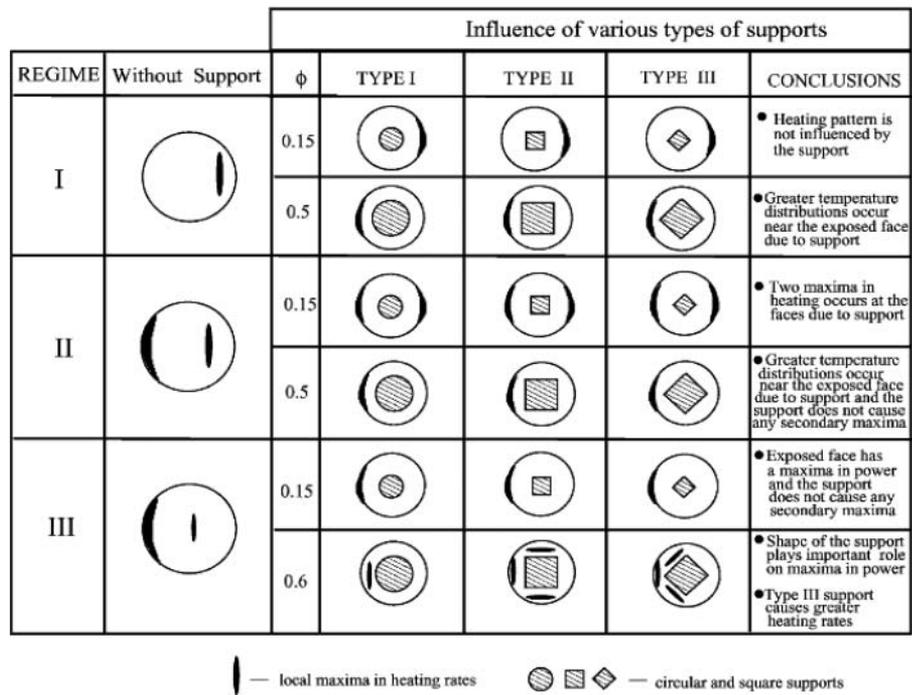
Frequency GHz	20°C		50°C	
	$\epsilon'$	$\epsilon''$	$\epsilon'$	$\epsilon''$
0.6	80.3	2.75	69.9	1.25
1.7	79.2	7.9	69.7	3.6
3.0	77.4	13.0	68.4	5.8
4.6	74.0	18.8	68.5	9.4
7.7	67.4	28.2	67.2	14.5
9.1	63.0	31.5	65.5	16.5
12.5	53.6	35.5	61.5	21.4
17.4	42.0	37.1	56.3	27.2
26.8	26.5	33.9	44.2	32.0
36.4	17.6	28.8	34.3	32.6

inductive capacity of the dielectric material. One of the advantages of MW heating is the volumetric heating, which relied on the penetrability of electromagnetic wave. It ensured MW (2450/915 MHz) can be used for some in-shell food treatment (almond, for instance). Using low-frequency dielectric techniques (such as RF, or 915 MHz MW) can improve not only the operability, but also the penetration and uniformity (Figure 2). From Figure 2, it can be concluded that high temperature (red or brilliant area) was observed in all the dielectric heated samples, but 2450 MHz drying presented the highest temperature compared with others (the highest temperature of RF heating was 50.8°C while the 2450 MHz was 65.8°C).

Frequency is the factor to decide the penetration depth. However, the penetration depth may not properly characterize the decay of power in a material of finite dimensions (Datta and Ananthswaran, 2001). Higher surface  $\epsilon''$  of materials results in loss of dielectric energy of a certain value, which caused temperature difference between inside and outside due to the poor penetration depth. Wang and his colleagues (2008) conducted a study for prepackaged mashed potatoes heated in RF systems with circulating water to remove the heat accumulation at the edges. Water with various electrical conductivities was tested for heating rate, and the highest electrical conductivity (220 S/m) can reduce the hot and cold spot temperature differences from 30.9 to 24.2°C, and 22.4 to 13.6°C on different mashed potato samples. When the electrical conductivity of surrounding water increases, water should absorb most energy and food must be absorbing less energy; in such a system, heating conductivity took the leading role during sample heating.

As a complex system of MW food processing, the electromagnetic wave incident, sample size and shape as well as sample salvers, and their cross reaction on heating performance cannot be ignored. Prof. Basak and his colleagues summarized the MW heating performance with related factors (Basak 2006, 2007a, 2007b, 2011, 2014; Basak et al., 2006, 2008; Basak and Meenakshi, 2006a, 2006b; Bhattacharya and Basak, 2006, 2017; Samanta and Basak, 2008, 2009, 2010; Durairaj et al., 2009; Durairaj and Basak, 2009a, 2009b; Basak and Rao, 2010, 2011; Bhattacharya et al., 2013, 2014; Chandrasekaran et al., 2013). Their results showed that to alleviate the thermal runaway and

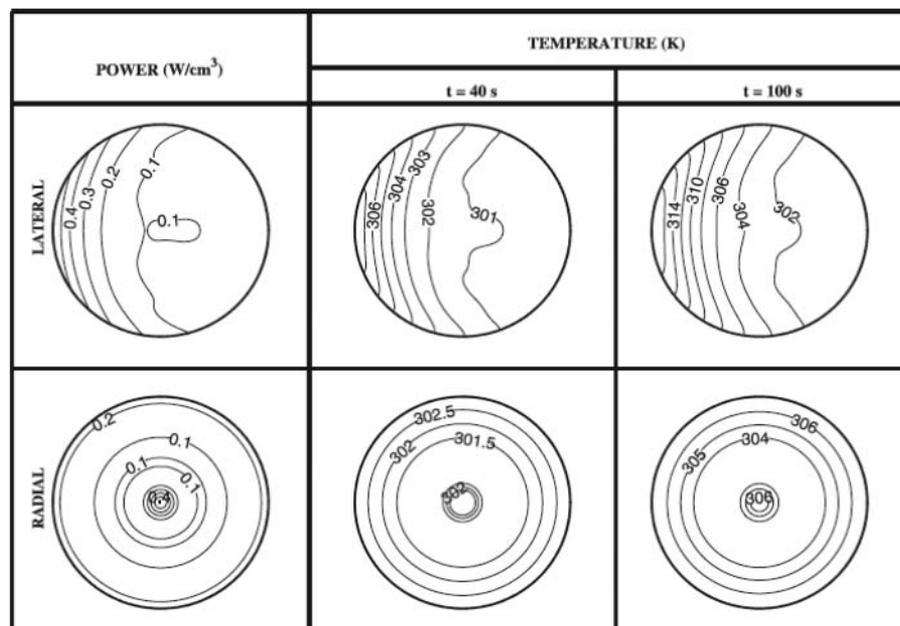
**Figure 2.** Temperature distribution of the starch after 10 minutes of different drying process: 1. 27 MHz RF dried starch, 2. 915 MHz MW dried starch, 3. 2450 MHz MW dried starch (Jiang et al., 2016). The hot spot can be found clearly in 2450 MHz heating.



**Figure 3.** The spatial hot spots occur either at the center or the outer face of the sample or at the face attached with alumina plate and pulsing plays a critical role to minimize hot spot formation or thermal runaway (Basak, 2006).

meanwhile enhance the heating rate, the heating characteristics should be strong functions of the aspect ratio of samples. Heating rate of larger support radius is enhanced at high aspect ratios of samples, which is in contrast with the heating characteristics for smaller ones. At high aspect ratio of samples, annular square supports, where the square is inclined at 45° with the horizontal surface exposed to plane electromagnetic waves, cause maxima in temperature at the three broad regimes. Therefore, this heating type may be the optimal choice of

supports for processing of sample with larger length scales (Figure 3). From Figure 3, it can be found that the different diameter of supports without sample is identified based on maxima in spatial heating rates, such as regime I (smallest radius) corresponds to the maxima at the unexposed face, regime II (medial radius) corresponds to two maxima occurring at exposed face and near the unexposed face, and regime III (largest radius) corresponds to the maxima at the exposed face.



**Figure 4.** Power and temperature contours of beef samples with lateral and radial irradiations for radius of the cross section of the sample was 3 cm; frequency was 2450 MHz, the incident microwave intensity was 1 W/cm. The temperature distributions are shown for time 40 and 100 s (Basak, 2007).

The role of distributed MW incidence is found to play critical roles on enhanced heating rate with optimal thermal runaway. The enhancement of heat absorption is larger for one side incidence as compared to both sides incidence with identical total intensity of MW incidence. It is also observed that radial irradiation corresponds to better heating effect (larger heating rates and/or lesser degree of thermal runaway) than lateral irradiation. However, during MW heating, the central zone for radial irradiation and the direction exposed with MW irradiation for lateral irradiation correspond to hot spot formation. It can be observed from Figure 4 that the maxima in temperature occur at the left exposed face for lateral irradiation whereas the central and outer regimes have maxima in temperature due to radial irradiation. The lateral irradiation corresponds to larger thermal gradient whereas the radial irradiation corresponds to uniform heating. The metallic annuli with circular and square shapes as well as specific aspect ratios are found to be an effective way to achieve overall larger processing rates with minimal thermal runaway for low and high dielectric loss samples.

For discrete samples, electric fields and temperature have been solved for each discrete sample layer and the intermediate air layer. The thickness of air layer plays a significant role to dramatically alter the interference of waves and power absorption within each sample layer. It is observed that the discrete sample layers exhibit larger heating rate than that within continuous sample, especially for smaller sample thicknesses. Suitable ratios of discrete sample thickness and the thickness of air layer also show large heating rate for larger sample thicknesses.

It is found that power absorption is enhanced significantly for higher  $\epsilon''$  sample due to specific thickness of ceramic composite (Alumina and SiC) support or sandwich class corresponding to one side MW incidence. However, the power enhancement is lesser and the temperature difference or thermal runaway is larger for lower  $\epsilon''$  samples as compared to higher  $\epsilon''$  samples. Application of pulsing or rotating is found to be the most optimal for samples with one side MW incidence.

Adding a layer of oil between support and samples is favorable for heating rate enhancement and less thermal runaway.

However, less thermal runaway can be significantly observed for smaller oil layer thicknesses. Although, smaller thermal runaway is observed for larger oil thicknesses, the heating rate within samples is found to be smaller for larger oil thicknesses.

The equipment of MW heating can be divided as power sources (MW tubes and magnetrons), MW oven cavities, feeds, seals, power supplies, control unit, and accessory unit (Turntable, light, etc.). However, some problems still exist in which 2450 MHz is almost the only choice for MW equipment no matter for home or industry uses, and the efficiencies achieved in magnetrons used for MW heating are always below the theoretical limit by 5–10%. Many factors that could influence heating uniformity are difficult to generalize among various foods and ovens (Datta and Anantheswaran, 2001). Although some devices, such as turntables, moving conveyor belts, stirrers, and rotating antennas are used to alleviate the nonuniform temperature distribution during MW heating, the basic theories still need to be promoted to eliminate the adverse effect of MW heating.

### Microwave techniques applied on carbohydrate

The most common carbohydrates existing in the plant tissues are starch and saccharides, which include fructopyranose, saccharose, amylose, etc. Carbohydrate, especially starch, is produced by most plants as energy storage. It is also the most common carbohydrate in human diets, such as potatoes, wheat, maize, rice, and cassava.

Starches are natural, renewable, and biodegradable macromolecules that are widely used in food, pharmaceutical, and chemical industries. The natural starch consists of amylose and amylopectin. Amylose is a linear molecule of (1,4) linked  $\alpha$ -D-glucopyranosyl units, while amylopectin is a highly branched component of starch that is formed through chains of  $\alpha$ -D-glucopyranosyl residues linked together mainly by (1,4) linkages but with 5–6% of (1,6) bonds at the branch points (Luengwilai and Beckles, 2009). The crystalline structure of starch commonly shows two types by analyzing the X-ray diffraction diagram. MW treatment can change the structure and crystallinity of starch (because of molecular vibration), and therefore the

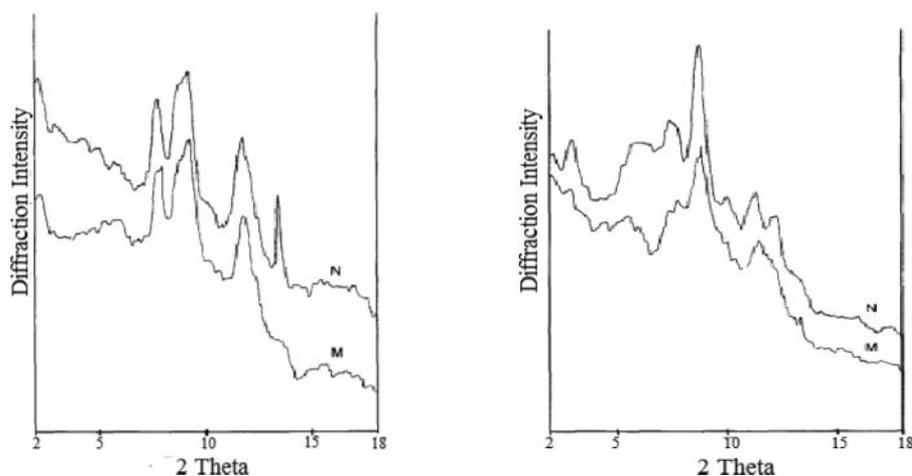
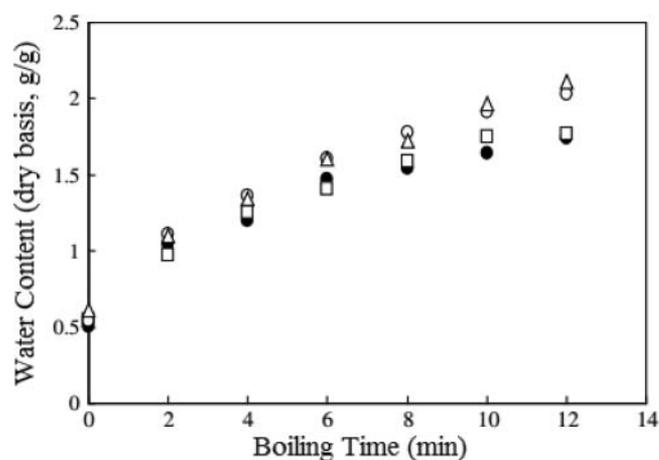


Figure 5. X-ray diffraction patterns of potato and tapioca starch of moisture content 35% irradiated in a sealed beaker as compared to native starch. N = native starch; M = microwaved starch (Lewandowicz et al., 1997).

characteristics of starch, such as polarity, free energy, viscosity, gelatinization, molecular weight, particle size, etc. (Szepes et al., 2005). It can be observed that the crystal structure of potato starch changed from type B to type A after being processed by MW radiation (Figure 5; Lewandowicz et al., 1997). Jiang et al. (2016) employed the water–starch system as the model to investigate the structure change after dielectric drying (three frequencies: 27, 915, and 2450 MHz), the results demonstrated that the starch crystallinity changed from type A to type B, and the crystallinity increased upon the dielectric drying. Besides, the  $M_w$  (molecular weight) of dried starch ranged from  $1.532 \times 10^7$  to  $2.059 \times 10^7$  and the ratio of higher degree of polymerization ( $>150$ ) varied from 20.57 to 6.87% (27 MHz), 0% (915 MHz), and 0% (2450 MHz). Palav and Seetharaman (2007) studied the impact of MW heating on the physicochemical properties of a starch–water model system, and they found that the starch gels by MW heating were significantly different from conduction-heated gels in all parameters measured, while the lack of granule swelling and the resulting soft gel were two key observations. Anderson and Guraya (2006) compared the properties of waxy and non-waxy rice starches after MW treatment, and the results revealed that the significant changes in viscosity properties after MW treatment were observed for both waxy and nonwaxy starches. This phenomenon showed equal effect with the sulfated starch (Staroszczyk et al., 2013), which can prove that the de-chain reaction happened during MW treatment. Besides, the data obtained in this study also indicated that there was much higher reaggregation of starch granules in waxy starch after MW heat treatment than had occurred in nonwaxy starch. Furthermore, MW heating was evidenced to cause a shift in the gelatinization range to higher temperatures, and a drop in solubility and crystallinity (Lewandowicz et al., 2000).

Synthesis is an important function of MW treatment applied on carbohydrate. Many studies reported that the MW treatment can accelerate the synthesis/hydrolysis rate of starch significantly, and meanwhile some reaction can be catalyzed by MW treatment. Pal et al. (2010) reported the synthesis of polyacrylamide-grafted dextrin by MW-assisted heating as the novel polymeric flocculant. It was evident that a novel polymeric flocculant had been developed by grafting polyacrylamide onto dextrin backbone using MW heating. Sun et al. (2015) developed an efficient method to make the cellulose hydrogel be hydrolyzed assisted by MW treatments. The results indicated that with the increase in the acid concentration, the hydrolysis ratio of glucose hydrogel was found to increase from 0.42% to 44.6% at 160 °C for 10 min MW heating. This method was effective to obtain glucose from  $\alpha$ -cellulose, microcrystalline cellulose, filter paper, ramie fiber, and absorbent cotton. Adnadjecic and Jovanovic (2012) studied the comparison of kinetics on the isothermal heterogenous acid-catalyzed hydrolysis of sucrose under conventional and MW heating. The results indicated that the rates of MW heating were five to seven times faster against the conventional heating. Ali et al. (2016) developed a spectrophotometric method based on the MW-assisted synthesis of Maillard product. To develop a new UV/Visible spectroscopic method for the determination of glucose in pharmaceutical formulations, the glucose solutions were oxidized by ammonium molybdate in the presence of



**Figure 6.** Changes of the water content of the noodle while microwave boiling: The noodle was made using the dough, which retention time was 40 sec (□), 300 sec (○), and 520 sec (△). The noodle was made using the non-heat treated dough (●) (Xue et al., 2008).

MW energy and reacted with aniline to produce a colored solution (Mabood et al., 2016). Yu et al. (2011) compared the MW treatment and conventional heating applied on the isomerization of glucose to fructose by immobilized glucose isomerase. The results indicated that MW heating significantly enhanced the activity of isomerase and the effects of acceleration might be a nonthermal MW effect.

The change of carbohydrates' structure is always accomplished with the changes of physicochemical properties. Lewandowicz et al. (1997, 2000) suggested that after MW treatment the gelatinization range shifted to higher temperatures, and the crystal structure changed from type B to type A. The conclusion in Staroszczyk et al. (2013) indicated that after MW modifying, the molecular weight values of these wet starches were considerably reduced. Moreover, the viscosity of starch solution also showed a downward trend. Szepes et al. (2005) considered that the crystalline structures and the micromorphological of the starches were affected by MW irradiation. Furthermore, MW irradiation significantly reduced the surface free energy (how much) and the polarity of the compacts. Xue et al. (2008) used the MW heating to control the degree of starch gelatinization in Japanese noodles (8.6 wt% of the crude protein originally), and found that the rate of water uptake at 100 °C of the partially MW gelatinized noodle was faster than that of the ungelatinized (non-MW treated) noodle (Figure 6).

### Microwave techniques applied on protein

As a definition of Encyclopedia Britannica, protein is a highly complex substance that is present in all living organisms. Proteins play critical roles in nearly all biological processes, including catalyzing metabolic reactions and DNA replication, responding to stimuli, and transporting molecules from one location to another. Most proteins fold into unique three-dimensional structures. Biochemists often refer to four distinct aspects of a protein's structure (Burgess and Deutscher, 2009). It can be easily found that proteins and peptides have higher dielectric constant by consulting the dielectric constant reference guide issued by Institute of Electrical and Electronics

**Table 2.** Physico-chemical properties (mean  $\pm$  standard deviation of three replicates) of protein isolated (Khan et al., 2011).

Sample	Buck density g/cm <sup>3</sup>	Water absorption mL/g	Oil absorption mL/g	Surface hydrophobicity
Un-PI	0.4 $\pm$ 0.0 b	3.8 $\pm$ 0.2 a	2.4 $\pm$ 0.2 b	12.3 $\pm$ 0.2 d
MW-PI	0.3 $\pm$ 0.0 b	3.6 $\pm$ 0.2 a	2.5 $\pm$ 0.1 b	13.9 $\pm$ 0.2 c
DH-PI	0.4 $\pm$ 0.0 b	3.5 $\pm$ 0.3 a	3.0 $\pm$ 0.1 a	22.2 $\pm$ 0.1 b
PAR-PI	0.6 $\pm$ 0.0 a	2.6 $\pm$ 0.3 b	3.3 $\pm$ 0.0 a	29.5 $\pm$ 0.1 a

Means sharing the same letter in a column are not significantly different ( $p > 0.05$ ).

Un-PI: unstabilized rice bran protein isolate; MW-PI: microwave rice bran protein isolate; DH-PI: dry heat rice bran protein isolate; and PAR-PI: parboiled rice bran protein isolate.

Engineers (IEEE). As a result, MW irradiation may have significant impact on their activity and structure (Plagemann et al., 2014).

It is widely drawing the attentions that MW treatment has significant effect on protein degradation and accelerating reaction. These effects may be accomplished with the structure changes. In Yan et al.'s research (2014), the changes of crude protein subfraction profiles induced by MW irradiation were evaluated. Compared to raw grains, five-minute MW treatment can reduce the content of rapidly degradable crude protein subfraction (from 45.22 to 6.36% crude protein) and accelerate the degradation rate. The results from their research indicated that MW heating for a short period (five minutes) with a lower energy input can improve the nutritive value and utilization of crude protein in barley grains. Quitain et al. (2006) studied the hydrothermal degradation rate of protein to amino acids by MW treatment, and the results showed a significant increase in the yield of amino acids compared to the conventional heating method. Khan et al. (2011) studied the functional properties of protein extracted from rice bran by MW energy, and found that the water absorption was slightly impaired owing to some possible configurational changes during MW treatment (Table 2). Gomaa et al. (2013) considered that the MW-heated solutions exhibited more extensive protein aggregation than conventionally heated ones. Similar research can be found in mass of literatures (Guan et al., 2011; Ruan et al. 2013; Chen et al., 2014; Lotfy et al., 2015; Mazinani et al., 2015).

For the accelerating reaction, Chen et al. (2014) used MW to accelerate the acid hydrolysis of proteins in protein sequence analysis. Mazinani et al. (2015) studied the influence of MW radiation on trypsin activity, and the results indicated that the trypsin activity was found to be dramatically increased when the reaction mixture was irradiated by MW energy at a constant temperature. Guan et al. (2011) investigated the mechanism of MW-accelerated soy protein isolate-saccharide graft reactions, and the results suggested that the MW radiation power strongly influenced the reaction kinetics. Ruan et al. (2013) and Lotfy et al. (2015) found that MW can accelerate the degradation kinetics at a certain extent during the stability of protein-based flavoring heating with MW energy.

### Microwave techniques applied on lipid

Lipid is a group of compounds that are generally soluble in organic solvents and largely insoluble in water. Actually lipids may be broadly defined as hydrophobic or amphiphilic small

molecules. It is an important foodstuff for many forms of life. Except for energy storage, lipids also serve with both structural and metabolic functions. The amphiphilic nature of some lipids allows them to form structures, such as vesicles, multilamellar/unilamellar liposomes, or membranes in an aqueous environment. Although humans and other mammals use various biosynthetic pathways to both metabolize and synthesize lipids, some essential lipids cannot be synthesized in this way and must be obtained from the diet (Casimir and David, 2002). Considering lipid is a too large category, oil and fat sometimes used to refer to the lipids in food industry.

It is a strong polarity molecule for analyzing the structure of lipids. For this characteristic, lipids always showed high dielectric constant and loss factor at a certain frequency. The microstructure and dielectric properties of different fat-based sauce thawed in MW oven was studied by Hernández-Carrión et al. (2011), and the results indicated that the thawing method used did not significantly ( $p > 0.05$ ) affect fat globule size and shape, regardless of the agitation speed and type of fat. Zhang et al. (2007) investigated the effect of fat on the thermal and dielectric properties of meat batter and its temperature following MW or RF heating, the results suggested that fat had an influence on thermal properties and a lesser influence than salt on dielectric properties. Leal-Castañeda et al. (2015) found the extent of phytosterol degradation depended on both the heating time and the surrounding medium, which can impact the quality and safety of the food product by studying the effect of MW heating on phytosterol oxidation. Zhang et al. (2013) summarized that the chicken fat rendered at MW power level of 2.75 W/g for 10 minutes had the highest retention rate (70.55%) with the lowest peroxide value, acid value, and thiobarbituric acid value ( $p < 0.05$ ). Nezihe et al. (2011) pointed out that the fatty acid composition after MW heating determined by gas chromatography analysis showed the increased content of unsaturated fatty acid (Table 3). The fatty acid inside rice bran showed no significant difference between raw and MW-heated rice bran during 16 weeks storage except for the oleic palmitic acid contents summarized by Ramezanzadeh et al. (2000). However, Regulska-Ilow and Ilow (2002), Jeong et al (2004), Inchingolo et al (2013), and Rodríguez-Alcalá et al. (2014) all agreed that the lipids and lipid-containing foods were sensitive to MW heating, which made it easy to be oxidized and degraded. But Albi et al. (1997) considered without

**Table 3.** Fatty acid compositions of raw castor oil and dehydrated castor oil (Nezihe et al., 2011).

Fatty acid	Castor oil	Dehydrated castor oil (Under N <sub>2</sub> )	Dehydrated castor oil (Under vacuum)
16:0	1.4	1.6	1.9
18:0	1.6	1.8	2.0
18:1	3.8	4.3	4.7
18:2 NCLAA:	5.5	49.2	53.9
18:2 CLA (total)b:		43.1	37.5
18:3	0.5		
18:1 OH	87.2	Trace	Trace
Total saturated	3.0	3.4	3.9
Total unsaturated	97.0	96.6	96.1

a: Non-conjugated linoleic acid;

b: 9-cis,11-trans-linoleic acid, 10-trans,12-cis-linoleic acid, 9-cis, 11-cis-linoleic acid, 10-trans,12-trans-linoleic acid, and 9-trans,11-trans-linoleic acid.

heating effect of MW energy treatment (temperature lower than 40°C) produced no oil alterations after treatment. Oppositely, Hu et al. (2008) compared the dielectric properties of edible oils and fatty acids in agricultural products from 100 Hz to 1 MHz, and found that oil had low dielectric constant and loss factor at the frequency, meanwhile the dielectric properties were affected by their fatty acid composition significantly.

The application of MW techniques on fat mainly focuses on heating and extraction. It was reported by Inchingolo et al. (2013) that MW heating would make the edible oils degrade by accelerated oxidation, hydrolysis, and polymerization. In the meantime, MW led to increased acidity that depended on the treatment conditions. Those reactions were faster than in traditional heating methods, but it could be focused on the effect that MW accelerated the heating and extraction process significantly. Leal-Castañeda et al. (2015) studied the effect of MW heating on phytosterol. The results indicated that the stability of phytosterol depended on both the heating time and the surrounding medium. Fat extraction was also an important application of MW treatment. It can be considered as a new and general alternative for the lipids extraction by using MW energy because of the high efficiency. Lee et al. (2010) compared five heating methods including MW to extract lipid from microalgae, the results indicated that the MW extraction was identified as the most simple, easy, and effective method for lipid extraction from microalgae. Similar conclusions are also summarized in McKenna et al. (2006), Nezihe et al. (2011), and Ramezanzadeh et al. (2000). Besides, the effect of acceleration reactions, for instance, 42 minute MW extraction can be equivalent to eight hours conventional heating extraction method by accounting the amount of total fat extracted from foodstuffs (Virost et al., 2008). These results are also reported by Young (1995), De Pedro et al. (1997), Garcia-Ayuso et al. (1999), and Mahesar et al. (2008).

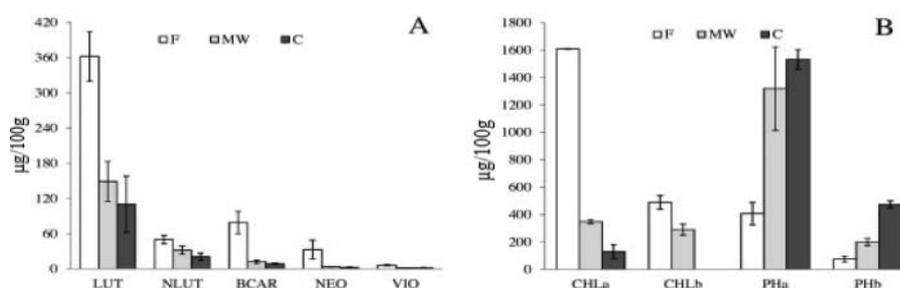
### Microwave techniques applied on chromatic/flavor components

Color and taste are important sensory properties and may be used as a criterion of food quality. However, heating processing can promote reactions that could affect the overall quality of food. Quality loss involves both subjective factors, like taste or color that cannot be readily quantified, and quantifiable factors, such as flavor degradation. Minimization of the drying time is crucial, and MW drying is advantageous in reducing it

significantly. The MW-assisted drying of ginger and basil produces dried herbs with higher amounts of essential oils than oven drying at 50°C (Orphanides et al., 2016). Wang and Xi (2005) reported that slice thickness and MW power can significantly affect the  $\beta$ -carotene content during carrot drying. Jaiswal and Abu-Ghannam (2013) found that after 14 minute MW treatment, the total phenolic content in cabbage reduced by up to 85–90% while the total flavonoid content reduced by up to 60–73%, indicating that the chroma, firmness, and antioxidant capacity all degraded. Similar conclusion can be summarized by Hirun et al. (2014) that the phenolic and curcuminoid content in turmeric showed a certain extent of decrease after vacuum MW drying.

As a heating technology, it is hardly avoided that MW treatment would destroy the pigment that existed in agricultural products. However, compared with other heating methods, MW treatment can alleviate such a damage to an extent because MW and RF heating can inhibit the activity of enzyme (polyphenol oxidase, peroxidase, etc.) effectively, and this phenomenon was called MW branching. De La Cruz-Garcia et al. (1997) compared three heating methods, including covered pot, pressure cooking, and MW oven to heating green bean. The results indicated that MW heating was a simple and fast way to raise the chlorophylls retention after heating. Ramesh et al. (2002) compared hot water and MW branching on vegetables, the effect of peroxidase inactivation indicated that MW blanching was comparable with higher reaction rate in the case of water blanching. The effects of MWs and conventional heating on the kinetics of the monophenolase and diphenolase activities of polyphenoloxidase were studied by Rodríguez-López et al. (1999). Efficiency of MW heating resulted in an increase in antioxidant content and a considerable decrease in browning rate. Gulati et al. (2003) and Zhao et al. (2006) concluded that MW alleviated the pigment degradation. Besides, Benlloch-Tinoco et al. (2015) evaluated the chlorophylls and carotenoids of kiwifruit puree affected by MW and conventional heating during storage. The results indicated that depending on the parameters, the MW treatments led to loss of the chlorophyll (42–100%) and carotenoid (62–91%) content (Figure 7).

Extraction is one of the main MW techniques applied on agricultural products, especially chromatic components. Valdés et al. (2015) studied the phenolic compounds from almond skin byproducts assisted by MW heating. Four gram samples,



**Figure 7.** Quantitative distribution of carotenoids (A) and chlorophylls (B) in fresh (F), microwaved (MW) and conventionally heated (C) kiwifruit puree. LUT: lutein; NLUT: neolutein A + B; BCAR: b-carotene; NEO: neoxanthin; VIO: violaxanthin; CHLa: chlorophyll a; CHLb: chlorophyll b; PHa: pheophytin a; PHb: pheophytinb (Benlloch-Tinoco et al., 2015).

60 second treatment, and 100 W MW power can obtain 60 mL of 70% (v/v) ethanol, while almond skin weight was the most important parameter in the studied responses. Cardoso-Ugarte et al. (2014) extracted betalains from red beet with MW-assisted heating, as well as compared with conventional extraction. It was found that betalain yields obtained by MW-assisted extraction were twice higher than those in conventional extraction. Ge et al. (2009) used rose as the raw materials to extract pigment assisted with MW heating and the highest extraction that can be achieved 81.5%.

### Microwave techniques applied on vitamin

Vitamin can be described as an organic chemical compound (or related set of compounds) of which the organism cannot synthesize in sufficient quantities and must be obtained through the diet. Vitamins have various biochemical functions on human health.

Vitamins are sensitive to water, light, oxygen, and temperature. For this reason, the vitamin content would be lost dramatically during heating. Employing MW techniques as the heating methods, Barba et al. (2015) studied the encapsulated liposoluble vitamin dried by conventional and MW drying. They found that the MW power was the main reason for the vitamin degradation. MW treatment at power 690 W promoted the recovery of 100% of the vitamin and reduced drying times to about 30 minutes, while 230 W degraded 40% of the vitamin after longer treatment. In contrast, the conventional heating degraded 17% of the vitamin during 12 hours of processing to achieve the same moisture content. Karatas and Kamsl (2007) used infrared and MW heating as the drying methods, the values of vitamins A, C, and E in apricot were determined after drying. The results indicated that the values of vitamins A, C, and E in apricots dried by the MW energy were larger than those in samples heated by infrared one. Singh et al. (2015) compared the content of ascorbic acid of 25 vegetables after MW boiling. The mean value of ascorbic acid content was 274.1 mg/100 g. After MW treatment, the range of ascorbic content in different vegetables was from 67.1 mg (*C. arifolium*) to 130.7 mg/100 g (*M. koenigii*). Yoshida et al. (1992) evaluated the effects of MW energy on the relative stability of Vitamin E. After MW heating, the highest rate of loss was  $\alpha$ -tocopherol, followed by  $\gamma$ -,  $\beta$ -, and  $\delta$ -tocopherols. Watanabe et al. (1998) studied the effects of MW heating on the loss of vitamin B<sub>12</sub> in foods, and found that appreciable loss (30–40%) of vitamin B<sub>12</sub> occurred in the foods during MW heating. For the application part, Höller et al. (2003) developed a new rapid procedure for the determination of vitamins A and E in beverages by MW heating.

### Conclusion and trends

MW techniques have been successfully used for many food processes. Although MW energy has wide applications and uses in various food processes, nonuniform temperature and hot spot induced by thermal runaway during MW heating was detrimental for food quality. It needs significant research aimed at improvements in certain areas. Specifically, some effective methods to obtain final food products

with better sensorial and nutritional qualities need to be explored. Those areas include:

#### 1. Reaction between different components of food

It is controversial that heat effect is the only fact to affect the characteristics of components inside foods during MW treatment, especially the nutrition loss. However, by analyzing the related articles it was observed that carbohydrate, lipid, and protein are sensitive to MW treatment. The mechanism of component changes and interactions between different components during MW treatment is still not clear.

#### 2. Enhancement of pilot scale level and accurate modeling research

MW processing of food materials needs to be carried out to a great extent at a pilot-scale level than under laboratory conditions so that the results might be useful for industrial applications. In spite of the complex nature of MW–food interactions, more research needs to be carried out for a better understanding of the process.

Although continuous progress has been made in recent years in improving the accuracy of the modeling, much research work still needs to be carried out in the following facets: ① accurately estimating surface heat and mass transfer coefficients; ② modeling porous media during MW treatment; ③ developing accurate models for temperature distribution to predict the sample quality; ④ considering shrinkage and deformation during MW heating; ⑤ combining MW heat and mass transfer models with other models (biochemical reaction, dielectric properties, microbial deactivation, and mechanics models). Besides, more efforts are also needed to develop computer-aided engineering for a high degree of automation of industrial MW heating processes.

#### 3. Better equipment design and reasonable operation

To alleviate the drawbacks of single MW treatment and combine the superiority of different heating methods, a combination of conventional and MW treating methods shows huge potential on MW-related technologies. The hybrid MW drying methods include MW-assisted air drying, MW-assisted vacuum drying, MW-enhanced spouted bed drying, MW-assisted freeze-drying, and MW-assisted finish drying following osmotic dehydration, and all applied successfully (Zhang et al., 2006).

To get the products with perfect quality, equipment design and operation should be kept in mind as follows: ① electromagnetic field nonuniform distribution, corners, and edges effects should be avoided by optimizing design of MW equipments and changing the shape of materials; ② heating with reduced power for long duration is good for some quality indexes of samples; ③ movement of materials ensures the MW heating uniformity. The equipments, such as rotating oven and fluid bed combined with MW heating, can be an effective way to process high-quality products; and ④ the traditional temperature measurements (thermistor, thermocouples, or infrared temperature meter) are not available under MW fields. Fiber-optical temperature meter is the most common method for temperature measurement under electromagnetic fields. Accurate temperature monitoring is important for high-quality products' processing.

#### 4. Homogenization of food properties and geometries

The distribution of electromagnetic absorbing of different sample parts was not quite uniform because of varied

components around different part of materials. Homogeneity is a good way to eliminate such differences. In addition, sample movement and/or mixings could also be used to ensure MW heating uniformity in industrial applications.

Osmotic treatment can be used as the pretreatment to boost the heating rate of MW process. Except for homogenization, osmotic pretreatment also can change the dielectric properties of samples to boost the heating rate.

Packaged samples with the surrounding medium can be an effective method to achieve uniform heating during MW treatment. Low  $\epsilon''$  but similar  $\epsilon'$  of medium or packaged materials to that of samples could improve MW heating uniformity.

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## References

- Adnadjevic, B. K. and Jovanovic, J. D. (2012). A comparative kinetics study on the isothermal heterogeneous acid-catalyzed hydrolysis of sucrose under conventional and microwave heating. *J. Mol. Catal. A: Chem.* **356**:70–77.
- Albi, T., Lanzon, A., Guinda, A., Leon, M. and Perez-Camino, M. C. (1997). Microwave and conventional heating effects on thermoxidative degradation of edible fats. *J. Agric. Food Chem.* **45**:3795–3798.
- Alfaifi, B., Tang, J., Jiao, Y., Wang, S., Rasco, B., Jiao, S. and Sablani, S. (2014). Radio frequency disinfestation treatments for dried fruit: model development and validation. *J Food En.* **120**:268–276.
- Alfaifi, B., Wang, S., Tang, J., Rasco, B., Sablani, S. and Jiao, Y. (2013). Radio frequency disinfestation treatments for dried fruit: Dielectric properties. *LWT - Food Sci Technol.* **50**:746–754.
- Awuah, G. B., Koral, T., and Guan, D. (2014). Radio-frequency baking and roasting of food products. In: *Radio-Frequency Heating in Food Processing: Principles and Applications*, pp. 231–243. George, A. B. Hoshahalli, S. R. and Tang, J., Eds., CRC Press, Boca Raton, FL.
- Ali, A., Hussain, Z., Arain, M. B., Shah, N., Khan, K. M., Gulab, H. and Zada, A. (2016). Development of microwave assisted spectrophotometric method for the determination of glucose. *Spectrochim. Acta Part A: Mol. Biomol. Spectrosc.* **153**:374–378.
- Anderson, A. K. and Guraya, H. S. (2006). Effects of microwave heat-moisture treatment on properties of waxy and non-waxy rice starches. *Food Chem.* **97**:318–323.
- Awuah, G., Ramaswamy, H., Economides, A. and Mallikarjunan, K. (2005). Inactivation of *Escherichia coli* K-12 and *Listeria innocua* in milk using radio frequency (RF) heating. *Innov Food Sci Emerg Technol.* **6**:396–402.
- Akkari, E., Chevallier, S. and Boillereaux, L. (2006). Observer-based monitoring of thermal runaway in microwaves food defrosting. *J Process Contr.* **6**(9):993–1001.
- Barba, A. A., Dalmoro, A., d'Amore, M. and Lamberti, G. (2015). Liposoluble vitamin encapsulation in shellecore microparticles produced by ultrasonic atomization and microwave stabilization. *LWT - Food Sci Technol.* **64**:149–156.
- Basak, T. (2006). Influence of various shapes of annular metallic support on microwave heating of 2D cylinders. *Chem. Eng. Sci.* **61**:2023–2034.
- Basak, T. (2007a). Role of lateral and radial irradiations on efficient microwave processing of food cylinders. *Chem. Eng. Sci.* **62**:3185–3196.
- Basak, T. (2007b). Role of metallic, ceramic and composite plates on microwave processing of composite dielectric materials. *Mater. Sci. Eng. A.* **457**:261–274.
- Basak, T. (2011). Theoretical analysis on the role of annular metallic shapes for microwave processing of food dielectric cylinders with various irradiations. *Int. J. Heat Mass Transf.* **54**:242–259.
- Basak, T. (2014). Role of various distributions of discrete samples on efficient microwave associated material processing. *Chem. Eng. Sci.* **105**:104–120.
- Basak, T., Aparna, K., Meenakshi, A. and Balakrishnan, A. R. (2006). Effect of ceramic supports on microwave processing of porous food samples. *Int. J. Heat Mass Transf.* **49**:4325–4339.
- Basak, T., Bhattacharya, M. and Panda, S. (2016). A generalized approach on microwave processing for the lateral and radial irradiations of various groups of food materials. *Innov. Food Sci. Emerg. Technol.* **33**:333–347.
- Basak, T. and Meenakshi, A. (2006a). A theoretical analysis on microwave heating of food slabs attached with ceramic plates: Role of distributed microwave incidence. *Food Res. Int.* **39**:932–944.
- Basak, T. and Meenakshi, A. (2006b). Influence of ceramic supports on microwave heating for composite dielectric food slabs. *AIChE J.* **52**:1995–2007.
- Basak, T. and Rao, B. S. (2010). Theoretical analysis on pulsed microwave heating of pork meat supported on ceramic plate. *Meat Sci.* **86**:780–793.
- Basak, T. and Rao, B. S. (2011). Role of ceramic composites and microwave pulsing on efficient microwave processing of pork meat samples. *Food Res. Int.* **44**:2679–2697.
- Basak, T., Samanta, S. K. and Jindamwar, A. (2008). A novel concept on discrete samples for efficient microwave processing of materials. *Chem. Eng. Sci.* **63**:3292–3308.
- Benlloch-Tinoco, M., Kaulmann, A., Corte-Real, J., Rodrigo, D., Martínez-Navarrete, N. and Bohn, T. (2015). Chlorophylls and carotenoids of kiwifruit puree are affected similarly or less by microwave than by conventional heat processing and storage. *Food Chem.* **187**:254–262.
- Bhattacharya, M. and Basak, T. (2006). On the analysis of microwave power and heating characteristics for food processing: Asymptotes and resonances. *Food Res. Int.* **39**:1046–1057.
- Bhattacharya, M. and Basak, T. (2017). A comprehensive analysis on the effect of shape on the microwave heating dynamics of food materials. *Innov. Food Sci. Emerg. Technol.* **39**:247–266.
- Bhattacharya, M., Basak, T. and Sriram, S. (2014). Generalized characterization of microwave power absorption for processing of circular shaped materials. *Chem. Eng. Sci.* **118**:257–279.
- Bhattacharya, M., Venkata, S. K. R. and Basak, T. (2013). Role of microwave heating strategies in enhancing the progress of a first-order endothermic reaction. *AIChE J.* **59**:656–670.
- Bows, J. R., Patrick, M. L., Janes, R. and Dibben, D. C. (1999). Microwave phase control heating. *Int. J. Food Sci. Technol.* **34**:295–304.
- Burgess, R. R. and Deutscher, M. P. (2009). *Guide to Protein Purification*. 2nd ed. Academic Press, New York.
- Cardoso-Ugarte, G. A., Sosa-Morales, M. E., Ballard, T., Liceaga, A. and San Martín-Gonzalez, M. F. (2014). Microwave-assisted extraction of betalains from red beet (*Beta vulgaris*). *LWT - Food Sci. Technol.* **59**:276–282.
- Casimir, C. A. and David, B. M. (2002). *Food Lipids: Chemistry, Nutrition, and Biotechnology*. 2nd ed. CRC Press, Boca Raton, Florida.
- Chandrasekaran, S., Ramanathan, S. and Basak, T. (2013). Microwave food processing. A review. *Food Res. Int.* **52**:243–261.
- Chen, L., Wang, K., Li, W. and Wang, S. (2015). A strategy to simulate radio frequency heating under mixing conditions. *Comput Electron Agr.* **118**: 100–110.
- Chen, L., Wang, N. and Li, L. (2014). Development to microwave-assisted acid hydrolysis of proteins using a commercial microwave reactor and its combination with LC-MS for protein full-sequence analysis. *Talanta.* **129**:290–295.
- Datta, A. K. and Anantheswaran, R. C. (2001). *Handbook of Microwave Technology for Food Application*. CRC Press, U.K.
- De La Cruz-Garcia, C., Gonzalez-Castro, M. J., Oruna-Concha, M. J., Lopez-Hernandez, J., Simal-Lozano, J. A. and Simal-Gandara, J.

- (1997). The effects of various culinary treatments on the pigment content of green beans (*Phaseolus vulgaris*, L.). *Food Res. Int.* **30**:787–791.
- De Pedro, E., Casillas, M. and Miranda, C. M. (1997). Microwave oven application in the extraction of fat from the subcutaneous tissue of Iberian pig ham. *Meat Sci.* **45**:45–51.
- Duan, X., Zhang, M., Li, X. and Mujumdar, A. S. (2008a). Microwave freeze drying of sea cucumber coated with nanoscale silver. *Drying Technol.* **26**(4):413–419.
- Duan, X., Zhang, M., Li, X. and Mujumdar, A. S. (2008b). Ultrasonically enhanced osmotic pretreatment of sea cucumber prior to microwave freeze drying. *Drying Technol.* **26**(4):420–426.
- Durairaj, S. and Basak, T. (2009a). Analysis of pulsed microwave processing of polymer slabs supported with ceramic plates. *Chem. Eng. Sci.* **64**:1488–1502.
- Durairaj, S., Chaudhary, A. and Basak, T. (2009). Efficient microwave heating of discrete food samples layered with ceramic composites. *J. Food Eng.* **95**:62–75.
- Durairaj, S. and Basak, T. (2009b). A new microwave processing strategy for food-ceramic composite layer confined within ceramic plates. *Food Res. Int.* **42**:254–270.
- Feng, Y. F., Zhang, M., Jiang, H. and Sun, J. C. (2012). Microwave-assisted spouted bed drying of lettuce cubes. *Drying Technol.* **30**:1482–1490.
- Garcia-Ayuso, L. E., Velasco, J., Dobarganes, M. C. and Luque de Castro, M. D. (1999). Accelerated extraction of the fat content in cheese using a focused microwave-assisted Soxhlet device. *J. Agric. Food Chem.* **47**:2308–2315.
- Ge, X., Wan, Z., Song, N., Fan, A. and Wu, R. (2009). Efficient methods for the extraction and microencapsulation of red pigments from a hybrid rose. *J. Food Eng.* **94**:122–128.
- Gomaa, A. I., Sedman, J. and Ismail, A. A. (2013). An investigation of the effect of microwave treatment on the structure and unfolding pathways of beta-lacto globulin using FTIR spectroscopy with the application of two-dimensional correlation spectroscopy (2D-COS). *Vib. Spectro.* **65**:101–109.
- Guan, J., Zhang, T., Hui, M., Yin, H., Qiu, A. and Liu, X. (2011). Mechanism of microwave-accelerated soy protein isolate-saccharide graft reactions. *Food Res. Int.* **44**:2647–2654.
- Gulati, A., Rawat, R., Singh, B. and Ravindranth, S. D. (2003). Application of microwave energy in the manufacture of enhanced-quality green tea. *J. Agric. Food Chem.* **51**:4764–4768.
- Guru, B. S. and Hiziroglu, H. R. (2004). *Electromagnetic Field Theory Fundamentals*. 2nd ed. Cambridge University Press, U.K.
- Hernández-Carrión, M., Guardado, L. M., Carot, J. M., Pérez-Munuera, I., Quiles, A. and Hernando, I. (2011). Structural stability of white sauces prepared with different types of fats and thawed in a microwave oven. *J. Food Eng.* **104**:557–564.
- Hirun, S., Utama-ang, N. and Roach, P. D. (2014). Turmeric (*Curcuma longa* L.) drying: An optimization approach using microwave-vacuum drying. *J. Food Sci. Technol.* **51**(9):2127–2133.
- Höller, U., Wolter, D., Hofmann, P. and Spitzer, V. (2003). Microwave-assisted rapid determination of vitamins A and E in beverages. *J. Agric. Food Chem.* **51**:1539–1542.
- Hong, Y., Huang, L., Yoon, W., Liu, F. and Tang, J. (2016). Mathematical modeling and Monte Carlo simulation of thermal inactivation of non-proteolytic *Clostridium botulinum* spores during continuous microwave-assisted pasteurization. *J. Food Eng.* **190**:61–71.
- Hou, L., Johnson, J. A. and Wang, S. (2016). Radio frequency heating for postharvest control of pests in agricultural products: A review. *Postharvest Biol. Technol.* **113**:106–118.
- Hu, L., Toyoda, K. and Ihara, I. (2008). Dielectric properties of edible oils and fatty acids as a function of frequency, temperature, moisture and composition. *J. Food Eng.* **88**:151–158.
- Huang, Z., Zhang, B., Marra, F. and Wang, S. (2016). Computational modelling of the impact of polystyrene containers on radio frequency heating uniformity improvement for dried soybeans. *Innov Food Sci Emerg Technol.* **33**:365–380.
- Huang, Z., Zhu, H. and Wang, S. (2015). Finite element modeling and analysis of radio frequency heating rate in mung beans. *Trans. ASAE.* **58**:149–160.
- Inchingolo, R., Cardenia, V. and Rodriguez-Estrada, M. T. (2013). The effects of microwave heating on edible oils and lipid-containing food. *Lipid Technol.* **25**(3):59–61.
- Jaiswal, A. K. and Abu-Ghannam, N. (2013). Degradation kinetic modeling of color, texture, polyphenols and antioxidant capacity of York cabbage after microwave processing. *Food Res. Int.* **53**:125–133.
- Jeong, J. Y., Lee, E. S., Paik, H. D., Choi, J. H. and Kim, C. J. (2004). Microwave cooking properties of ground pork patties as affected by various fat levels. *J. Food Sci.* **69**(9):708–712.
- Jiang, H., Zhang, M., Fang, Z., Mujumdar, A. S. and Xu, B. (2016). Effect of different dielectric drying methods on the physico-chemical properties of a starch-water model system. *Food Hydrocolloids.* **52**:192–200.
- Jian, F., Jayas, D. S., White, N. D. G., Fields, P. G. and Howe, N. (2015). An evaluation of insect expulsion from wheat samples by microwave treatment for disinfestation. *Biosyst Eng.* **130**:1–12.
- Jiao, S., Johnson, J., Tang, J. and Wang, S. (2012). Industrial-scale radio frequency treatments for insect control in lentils. *J. Stored Product Res.* **48**:143–148.
- Kaatz, U. (1989). Complex permittivity of water as a function of frequency and temperature. *J. Chem. Eng. Data.* **34**(4):371–374.
- Karatas, F. and Kamsil, F. (2007). Variations of vitamins (A, C and E) and MDA in apricots dried in IR and microwave. *J. Food Eng.* **78**:662–668.
- Khan, S. H., Butt, M. S., Sharif, M. K., Sameen, A., Mumtaz, S. and Sultan, M. T. (2011). Functional properties of protein isolates extracted from stabilized rice bran by microwave, dry heat, and parboiling. *J. Agric. Food Chem.* **59**:2416–2420.
- Kim, S. Y., Sagong, H. G., Choi, S. H., Ryu, S., and Kang, D. H. (2012). Radio-frequency heating to inactivate *Salmonella* Typhimurium and *Escherichia coli* O157:H7 on black and red pepper spice. *Int J Food Microbiol.* **153**:171–175.
- Kirmaci, B. and Singh, R. K. (2012). Quality of chicken breast meat cooked in a pilot-scale radio frequency oven. *Innov Food Sci Emerg Technol.* **14**:77–84.
- Lau, S. K. (2015). Simulation and validation of radio frequency heating of shell eggs. PhD dissertation: University of Nebraska-Lincoln, Food Science and Technology Department, Lincoln, Nebraska.
- Leal-Castañeda, E. J., Inchingolo, R., Cardenia, V., Hernandez-Becerra, J. A., Romani, S., Rodriguez-Estrada, M. T. and Galindo, H. S. G. (2015). Effect of microwave heating on phytosterol oxidation. *J. Agric. Food Chem.* **63**:5539–5547.
- Lewandowicz, G., Fornal, J. and Walkowski, A. (1997). Effect of microwave radiation on physico-chemical properties and structure of potato and tapioca starches. *Carbohydr. Polym.* **34**:213–220.
- Lewandowicz, G., Jankowski, T. and Fornal, J. (2000). Effect of microwave radiation on physico-chemical properties and structure of cereal starches. *Carbohydr. Polym.* **42**:193–199.
- Llave, Y., Liu, S., Fukuoka, M., and Sakai, N. (2015). Computer simulation of radiofrequency defrosting of frozen foods. *J. Food Eng.* **152**:32–42.
- Lotfy, S. N., Fadel, H. H. M., El-Ghorab, A. H. and Shaheen, M. S. (2015). Stability of encapsulated beef-like flavourings prepared from enzymatically hydrolysed mushroom proteins with other precursors under conventional and microwave heating. *Food Chem.* **187**:7–13.
- Luengwilai, K. and Beckles, D. M. (2009). Structural investigations and morphology of tomato fruit starch. *J. Agric. Food Chem.* **57**:282–291.
- Mabood, F., Hussain, Z., Haq, H., Arian, M. B., Boqué, R., Khan, K. M., Hussain, K., Jabeen, F., Hussain, J., Ahmed, M., Alharasi, A., Naureen, Z., Hussain, H., Khan, A. and Perveen, S. (2016). Development of new UV-vis spectroscopic microwave-assisted method for determination of glucose in pharmaceutical samples. *Spectrochim. Acta Part A: Mol. Biomol. Spectro.* **153**:212–215.
- Mahesar, S. A., Sherazi, S. T. H., Abroa, K., Kandhro, A., Bhangar, M. I., van de Voort, F. R. and Sedman, J. (2008). Application of microwave heating for the fast extraction of fat content from the poultry feeds. *Talanta.* **75**:1240–1244.
- Marra, F., Zhan, L. and Lyng, J. G. (2009). Radio frequency treatment of foods: Review of recent advances. *J. Food Eng.* **91**(4):497–508.
- Mazinani, S. A., DeLong, B. and Yan, H. (2015). Microwave radiation accelerates trypsin-catalyzed peptide hydrolysis at constant bulk temperature. *Tetrahedr. Lett.* **56**:5804–5807.

- Mermelstein, N. (1997). Interest in radio frequency heating heats up. *Food Technol.* **50**:94–95.
- McKenna, B. M., Lyng, J., Brunton, N. and Shirsat, N. (2006). Advances in radio frequency and ohmic heating of meats. *J. Food Eng.* **77**: 215–229.
- Momenzadeh, L., Zomorodian, A. and Mowla, D. (2011). Experimental and theoretical investigation of shelled corn drying in a microwave-assisted fluidized bed dryer using Artificial Neural Network. *Food Bioprocess Technol.* **89**:15–21.
- Mudgett, R. E. (2007). *Electrical Properties of Foods*. Taylor & Francis, Inc., London.
- Mujumdar, A. S. (2007). *Handbook of Industrial Drying*. Taylor & Francis, Philadelphia.
- Nelson, S. O. and Datta, A. K. (2001). Dielectric properties of food materials and electric field interactions. In: *Handbook of Microwave Technology for Food Applications*. Datta, A. K. and Anantheswaran, R. C., Eds., CRC Press, Florida, USA. 69–107.
- Nezihe, A., Elif, D., Ozlem, Y. and Tuncer, E. A. (2011). Microwave heating application to produce dehydrated castor oil. *Ind. Eng. Chem. Res.* **50**:398–403.
- Orphanides, A., Goulas, V. and Gekas, V. (2016) Drying technologies: vehicle to high-quality herbs. *Food Eng Rev.* **8**(2): 164–180.
- Pal, S., Nasim, T., Patra, A., Ghosh, S. and Panda, A. B. (2010). Microwave assisted synthesis of polyacrylamide grafted dextrin (Dxt-g-PAM): Development and application of a novel polymeric flocculant. *Int. J. Biol. Macromol.* **47**:623–631.
- Palav, T. and Seetharaman, K. (2007). Impact of microwave heating on the physico-chemical properties of a starch–water model system. *Carbohydr. Polym.* **67**:596–604.
- Plagemann, R., Langermann, von J. and Kragl, U. (2014). Microwave-assisted covalent immobilization of enzymes on inorganic surfaces. *Eng. Life Sci.* **14**(5):493–499.
- Piyasena, P., Dussault, C., Koutchma, T., Ramaswamy, H., and Awuah, G. (2003). Radio frequency heating of foods: principles, applications and related properties—a review. *Crit Rev Food Sci Nutr.* **43**:587–606.
- Quitain, A. T., Daimon, H., Fujie, K., Katoh, S. and Moriyoshi, T. (2006). Microwave-assisted hydrothermal degradation of silk protein to amino acids. *Ind. Eng. Chem. Res.* **45**:4471–4474.
- Ramesh, M. N., Wolf, W., Tevini, D. and Bogner, A. (2002). Microwave blanching of vegetables. *J. Food Sci.* **67**(1):390–398.
- Ramezanzadeh, F. M., Rao, R. M., Prinyawiwatkul, W., Marshall, W. E. and Windhauser, M. (2000). Effects of microwave heat, packaging, and storage temperature on fatty acid and proximate compositions in rice bran. *J. Agric. Food Chem.* **48**:464–467.
- Regulska-Ilow, B. and Ilow, R. (2002). Comparison of the effects of microwave cooking and conventional cooking methods on the composition of fatty acids and fat quality indicators in herring. *Mol. Nutr. Food Res.* **6**:383–388.
- Risman, P. O., Ohlsson, T. and Wass, B. (1987). Principles and models of power density distribution in microwave oven loads. *J. Microwave Power Electromagn. Energy.* **22**(4):193–198.
- Robert, F. S. (2007). *Microwave and Dielectric Drying*. Taylor & Francis, London.
- Rodríguez-Alcalá, L. M., Alonso, L. and Fontecha, J. (2014). Stability of fatty acid composition after thermal, high pressure and microwave processing of cow milk as affected by polyunsaturated fatty acid concentration. *J. Dairy Sci.* **97**:7307–7315.
- Rodríguez-Lopez, J. N., Fenoll, L. G., Tudela, J., Devece, C., Sanchez-Hernandez, D., De Los Reyes, E. and Garcia-Canovas, F. (1999). Thermal inactivation of mushroom polyphenoloxidase employing 2450 MHz microwave radiation. *J. Agric. Food Chem.* **47**:3028–3035.
- Ruan, G., Chen, Z., Wei, M., Liu, Y., Li, H. and Du, F. (2013). The study on microwave assisted enzymatic digestion of ginkgo protein. *J. Mol. Catal. B: Enzym.* **94**:23–28.
- Samanta, S. K. and Basak, T. (2008). Theoretical analysis of efficient microwave processing of oil–water emulsions attached with various ceramic plates. *Food Res. Int.* **41**:386–403.
- Samanta, S. K. and Basak, T. (2009). Efficient microwave processing of oil–water emulsion cylinders with lateral and radial irradiations. *Food Res. Int.* **42**:1337–1350.
- Samanta, S. K. and Basak, T. (2010). Efficient processing of oil–water emulsions confined within 2D cylinders with various microwave irradiations: Role of metallic annulus. *Food Res. Int.* **43**:148–166.
- Singh, S., Swain, S., Singh, D. R., Salim, K. M., Nayak, D. and Dam, R. S. (2015). Changes in phytochemicals, anti-nutrients and antioxidant activity in leafy vegetables by microwave boiling with normal and 5% NaCl solution. *Food Chem.* **176**:244–253.
- Staroszczyk, H., Fiedorowicz, M., Opalinska-Piskorz, J. and Tylingo, R. (2013). Rheology of potato starch chemically modified with microwave-assisted reactions. *LWT - Food Sci. Technol.* **53**:249–254.
- Sun, B., Duan, L., Peng, G., Li, X. and Xu, A. (2015). Efficient production of glucose by microwave-assisted acid hydrolysis of cellulose hydrogel. *Bioresour. Technol.* **192**:253–256.
- Szepes, A., Hasznos-Nezdei, M., Kovács, J., Funke, Z., Ulrich, J. and Szabó-Révész, P. (2005). Microwave processing of natural biopolymers—studies on the properties of different starches. *Int. J. Pharm.* **302**:166–171.
- Tiwari, G., Wang, S., Tang, J. and Birla, S. (2011). Analysis of radio frequency (RF) power distribution in dry food materials. *Journal of Food Engineering.* 104.
- Valdés, A., Vidal, L., Beltrán, A., Canals, A. and Garrigós, M. C. (2015). Microwave-assisted extraction of phenolic compounds from almond skin byproducts (prunus amygdalus): A multivariate analysis approach. *J. Agric. Food Chem.* **63**:5395–5402.
- Virost, M., Tomaoa, V., Ginies, C., Visinoni, F. and Chemat, F. (2008). Microwave-integrated extraction of total fats and oils. *J. Chromatogr. A.* **1196–1197**:57–64.
- Wang, J. and Xi, Y. S. (2005). Drying characteristics and drying quality of carrot using a two-stage microwave process. *J. Food Eng.* **68**:505–511.
- Wang, J., Olsen, R. G., Tang, J. and Tang, Z. (2008). Influence of mashed potato dielectric properties and circulating water electric conductivity on radio frequency heating at 27 MHz. *J. microwave power EE.* **42** (2):31–46.
- Wang, S., Monzon, M., Johnson, J., Mitcham, E., and Tang, J. (2007). Industrial-scale radio frequency treatments for insect control in walnuts: I: Heating uniformity and energy efficiency. *Postharvest Biol Technol.* **45**:240–246.
- Wang, Y., Wig, T. D., Tang, J. and Hallberg, L. M. (2003) Dielectric properties of foods relevant to RF and microwave pasteurization and sterilization. *J. Food Eng.* **57**:257–268.
- Wang, Y., Zhang, L., Gao, M., Tang, J., and Wang, S. (2014). Pilot-scale radio frequency drying of macadamia nuts: Heating and drying uniformity. *Dry Technol.* **32**:1052–1059.
- Watanabe, F., Abe, K., Fujita, T., Goto, M., Hiemori, M. and Yoshihisa, N. (1998). Effects of microwave heating on the loss of vitamin B<sub>12</sub> in foods. *J. Agric. Food Chem.* **46**:206–210.
- Xin, Y., Zhang, M., Xu, B., Adhikari, B. and Sun, J., (2015). Research trends in selected blanching pretreatments and quick freezing technologies as applied in fruits and vegetables: A review. *Int J Refrig.* **57**:11–25.
- Xue, C. F., Sakai, N. and Fukuoka, M. (2008). Use of microwave heating to control the degree of starch gelatinization in noodles. *J. Food Eng.* **87**:357–362.
- Yan, X., Khan, N. A., Zhang, F., Yang, L. and Yu, P. (2014). Microwave irradiation induced changes in protein molecular structures of barley grains: relationship to changes in protein chemical profile, protein subfractions, and digestion in dairy cows. *J. Agric. Food Chem.* **62**:6546–6555.
- Yolacaner, E. T., Sumnu, G. and Sahin, S., (2017). Microwave-assisted baking. In: *The Microwave Processing of Foods* (Second Edition), pp. 117–141. Regier, M., Knoerzer, K., Schubert, H., Eds., Woodhead Publishing, U.K.
- Yoshida, H., Kondo, I. and Kajimoto, G. (1992). Effects of microwave energy on the relative stability of vitamin E in animal fats. *J. Sci. Food Agric.* **58**:531–534.
- Young, J. C. (1995). Microwave-assisted extraction of the fungal metabolite ergosterol and total fatty acids. *J. Agric. Food Chem.* **43**:2904–2910.
- Yu, D., Wu, H., Zhang, A., Tian, L., Liu, L., Wang, C. and Fang, X. (2011). Microwave irradiation-assisted isomerization of glucose to fructose by immobilized glucose isomerase. *Process Biochem.* **46**:599–603.
- Zhang, H. and Datta, A. K. (2001). *Electromagnetics of Microwave Heating: Magnitude and Uniformity of Energy Absorption in an Oven*. CRC Press, Boca Raton, Florida.

- Zhang, H. and Datta, A. K. (2003). Microwave power absorption in single-and multiple - item foods. *Food Bioproducts Process.* **81**(3): 257–265.
- Zhang, L., Lyng, J. G. and Brunton, N. P. (2007). The effect of fat, water and salt on the thermal and dielectric properties of meat batter and its temperature following microwave or radio frequency heating. *J. Food Eng.* **80**:142–151.
- Zhang, M., Jiang, H. and Lim, R. (2010). Recent developments in microwave-assisted drying of vegetables, fruits, and aquatic products-drying kinetics and quality considerations. *Dry Technol.* **28**:1307–1316.
- Zhang, M. Tang, J. Mujumdar, A. S. and Wang, S. (2006). Trends in microwave related drying of fruits and vegetables. *Trend Food Sci Technol.* **17**:524–534.
- Zhang, L., Yin, B. and Rui, H. (2013). Effects of microwave rendering on the yield and characteristics of chicken fat from broiler abdominal fat tissue. *J. Food Sci. Technol.* **50**(6):1151–1157.
- Zhao, L., Zhang, G., Chen, F., Wang, Z., Wu, J. and Hu, X. (2006). Different effects of microwave and ultrasound on the stability of (all-E)-Astaxanthin. *J. Agric. Food Chem.* **54**:8346–8351.
- Zhong, X., Dolan, K. D. and Almenar, E. (2015). Effect of steamable bag microwaving versus traditional cooking methods on nutritional preservation and physical properties of frozen vegetables: A case study on broccoli (*Brassica oleracea*). *Innov Food Sci Emerg Technol.* **31**: 116–122.
- Zhu, X., Guo, W., Wu, X., Wang, S. (2012). Dielectric properties of chestnut flour relevant to drying with radio-frequency and microwave energy. *J Food Eng.* **113**(1):143–150.