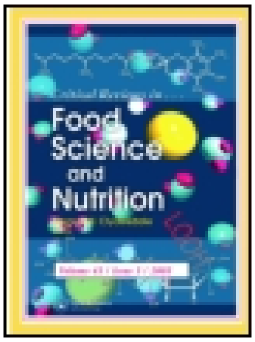

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Microwave processing: effects and impacts on food components

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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 attentions 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 frication losses. Such a heating pattern would cause a certain change in microwave treatment, which is 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.

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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 attracted extensive attentions 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), disinfestation (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.,

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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: 1) Increased process speed; 2) Achieved 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; Lee et al., 2016). Be different from conventional heating methods (solar or hot air drying), heat is generated within the product during MW treatment due to molecular friction resulted from oscillating dipole molecules and migrating ions caused by the applied alternating electric field. Therefore, MW heating is expected to deliver more homogeneous 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, to be an endogenic heating method, both the mass and energy transfers are from interior to surface during MW treatment, while the conventional drying methods show the opposite way between mass and energy transfer, which may raise the mass transfer resistance during processing. It also should be mentioned that RF and MW systems have been recognized to be 50-70% heating efficiency in comparison to 10% efficiency with conventional heating ovens (Mermelstein, 1997). All those results have ensured the advantages of dielectric processing.

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Although there are many advantages of dielectric treatment in the food processing, dielectric energy has not yet been exploited to its fullest potential in the industrial applications. The efficiency of a MW heating relies on two factors: (i) the processing time and (ii) the heating uniformity of the processing/hot spot formation. An important issue on MW processing of samples is thermal runaway, which is primarily due to large MW power absorption or heat generation in places with high temperatures resulted in increasing dielectric loss factors. The non-uniform heating due to thermal runaway during MW heating is one of the key factors to make the product quality deteriorated. However, it can hardly avoid 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; Alfaifi et al., 2014; Jiang 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 is widely existed in the materials, including nuts fruits/vegetables, meats and 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 adding, 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

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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 with heat effect. But a certain change caused by dielectric treatment during applying on foods is unarguable reality. In this concern, the application of MW heating on food materials is highly addressed in previous studies. To be a complex system, a huge amount of elements constitutes 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 interesting 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 feature of dielectric treatment

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All electromagnetic waves are characterized by their wavelength (frequency). Typically, the electromagnetic wavelength ranged from 10 to 10^{-3} m can be considered as the dielectric range (Datta and Anantheswaran, 2001). Those electromagnetic waves can cause the dipolar rotation of agricultural products. In the classical atom mechanics, materials are made by 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 un-coincided (the dipole moment points are only in the same direction as the electric field at the ideal condition). Under this situation the dielectric molecular is vibrated and followed by electromagnetic waves, and then returns to its original state. The time required to do so is the so-called relaxation time, and such the molecular itself is called dipolar molecular (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 molecules 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 decaying back to zero (relaxes), the dipoles return to their

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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 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 molecular. 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 the 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 make the samples heating in 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 its interactions with electric fields. The dielectric properties parameters of usual interest are the relative dielectric constant ε', loss tangent or dissipation factor (tan δ), and the loss factor ε''. The dielectric constant (ε') 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 (ε'') 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 results in heat generation (Mudgett, 2007). The relationship between them is defined as

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad 1$$

Where $j = (-1)^{0.5}$, indicates a 90° phase shift between the real (ε') and imaginary (ε'') 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 (Fig. 1), but also 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.

$$\mathrm{P} = \frac{3.31\times10^{7}}{\mathrm{f}\ \tan\delta\sqrt{\varepsilon_r}} \quad 2$$

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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 ε_r is the specific 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 (Fig. 2). From Fig. 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 Anantheswaran, 2001). Higher surface ε″ of materials results in loss of dielectric energy on 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 pre-packaged 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 the system heating conductivity took the leading role for sample heating.

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As an complex system of MW food processing, it cannot be ignored that the electromagnetic wave incident, sample size and shape as well as sample salvers, and their cross reaction on heating performance. 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; Basak and Rao, 2010, 2011; Bhattacharya et al., 2006, 2012, 2014, 2017; Durairaj and Basak, 2009; Durairaj et al., 2009a, 2009b; Samanta et al., 2008, 2009, 2010; Chandrasekaran et al., 2013). Their results showed that to alleviate the thermal runaway and meanwhile enhance the heating rate, the heating characteristics are found to be the 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 (Table 2). From Table 2 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.

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 Fig. 3 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 ε'' 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 ε'' samples as compared to higher ε'' 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 a 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 non-uniform 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 and amylaceum, 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 α-D-glucopyranosyl units, while amylopectin is a highly branched component of starch that is formed through chains of α-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 crystalline of starch because of molecular vibration, therefore the characteristics of starch, such as polarity, free energy, viscosity, gelatinization, molecular weight and 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 processed by MW radiation (Fig. 4, Lewandowicz et al., 1997). Jiang et al. (2016) employed 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 crystalline changed from type A to type B, and the crystallinity

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increased upon the dielectric drying. Besides, the M_w (molecular weight) of dried starch was ranged from 1.532×10^7 to 2.059×10^7 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 physico-chemical 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 non-waxy starches. This phenomenon showed the equal effect with the starch sulfated (Staroszczyk et al., 2013), which can prove the de-chain reaction happened during MW treatment. Besides, the data obtained in this study also indicated that there was much higher re-aggregation of starch granules in waxy starch after MW heat treatment than occurred in non-waxy starch. Furthermore, MW heating was evidenced to cause a shift in the gelatinization range to higher temperatures, and a drop in solubility and crystallinity (Lewandowicza 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

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an efficient method to make the cellulose hydrogel be hydrolyzed assisted by MW treatments. The results indicated the increasing with the acid concentration the glucose hydrogel to be hydrolyzed increasing from 0.42% to 44.6% at 160°C for 10 min MW heating. This method was effective to obtain glucose from ɑ-cellulose, microcrystalline cellulose, filter paper, ramie fiber and absorbent cotton. Adnadjevic and Jovanovic (2012) studied the comparison of kinetics on the isothermal heterogeneous acid-catalyzed hydrolysis of sucrose under conventional and MW heating. The results indicated that the rates of MW heating were 5-7 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 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 non-thermal MW effect.

The change of carbohydrates' structure is always accomplished with the changes of physic-chemical 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 the crystalline structures and the micro-morphological 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 (Fig. 5).

Microwave techniques applied on protein

As the definition of Encyclopaedia Britannica, protein is 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 3-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 consulted dielectric constant reference guide issued by Institute of Electrical and Electronics Engineers (IEEE). As a result, MW irradiation may have significant impacts 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 accomplish with the structure changes. In Yan's research (2014) the changes of crude protein sub-fraction profiles induced by MW irradiation were evaluated. Compared to raw grains, 5-min 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

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short period (5 min) with a lower energy input can improve the nutritive value and utilization of crude protein in barely grains. Quitain et al. (2006) studied the hydrothermal degradation rate of protein to amino acids by MW treatment, and the results showed a significant increasing 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 configurationally changes during MW treatment (Table 3). Gomaa et al. (2013) considered 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 reaction accelerating, 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 de-gradation 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). Considered 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 by 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

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10 min 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 4). 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 them easy to be oxidized and degraded. But Albi et al. (1997) considered without 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 was main focus on heating and extraction. It was reported by Inchingolo et al. (2013) that MW heating would make the edible oils degradation by accelerated oxidation, hydrolysis and polymerization. At mean time MW led to acidity increased depended on 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

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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 min MW extraction can be equivalent to 8 hrs conventional heating extraction method by accounting the amount of total fat extracted from foodstuffs (Virot et al., 2008). These results are also reported by Young (1995), De Pedro et al. (1997), Garcıa-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 β-carotene content during carrot drying. Jaiswal and Abu-Ghannam (2013) found that after 14 min 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

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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 decrease after vacuum MW drying.

As a heating technology, it is hardly avoided that MW treatment would destroy the pigment existed in agricultural products. However, compared with other heating methods, MW treatment can alleviate such the damage at an extent because MW and RF heating can inhibit the activity of enzyme (polyphenol oxidase and 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 increasing in antioxidant content and a considerable decreasing in browning rate. Gulati et al. (2003) and Zhao et al. (2006) concluded that MW alleviated the pigment degradation can be obtained. 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 (Fig. 6).

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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. 4 g samples, 60 s 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 can achieve 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 min, while 230 W degraded 40% of the vitamin after longer treatment. In contrast, the conventional heating degraded 17% of the vitamin during 12 hrs of processing to achieve the same moisture content. Karatas and Kamsl (2007) used infrared and

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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. arietinum) to 130.7 mg/100 g (M. koengii). 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 α-tocopherol, followed by *y*-, *β*- and δ-tocopherols. Watanabe et al. (1998) studied the effects of MW heating on the loss of vitamin B_{12} in foods, and found that appreciable loss (30-40%) of vitamin B_{12} 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, non-uniform 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 on MW treatment. The mechanism of components changes and interactions between different components during MW treatment are 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 at 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 modelling, much research work still needs to be carried out in the following facets: ① Accurately estimating surface heat and mass transfer coefficients; ② Modelling 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 method, 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 non-uniform 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. Fibre-optical temperature meter is the most common method for temperature measurement under electromagnetic field. 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 part was not quite uniform because of varied components around different part of materials. Homogeneity is a good way to eliminate such the difference. In addition, sample movement, and/or mixings also could 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 ε'' but similar ε' of medium or packaged materials to that of samples could improve MW heating uniformity.

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

Frequency GHz	20 °C		50 °C	
	ε′	ε″	ε′	ε″
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

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Table 2. 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, 2016).

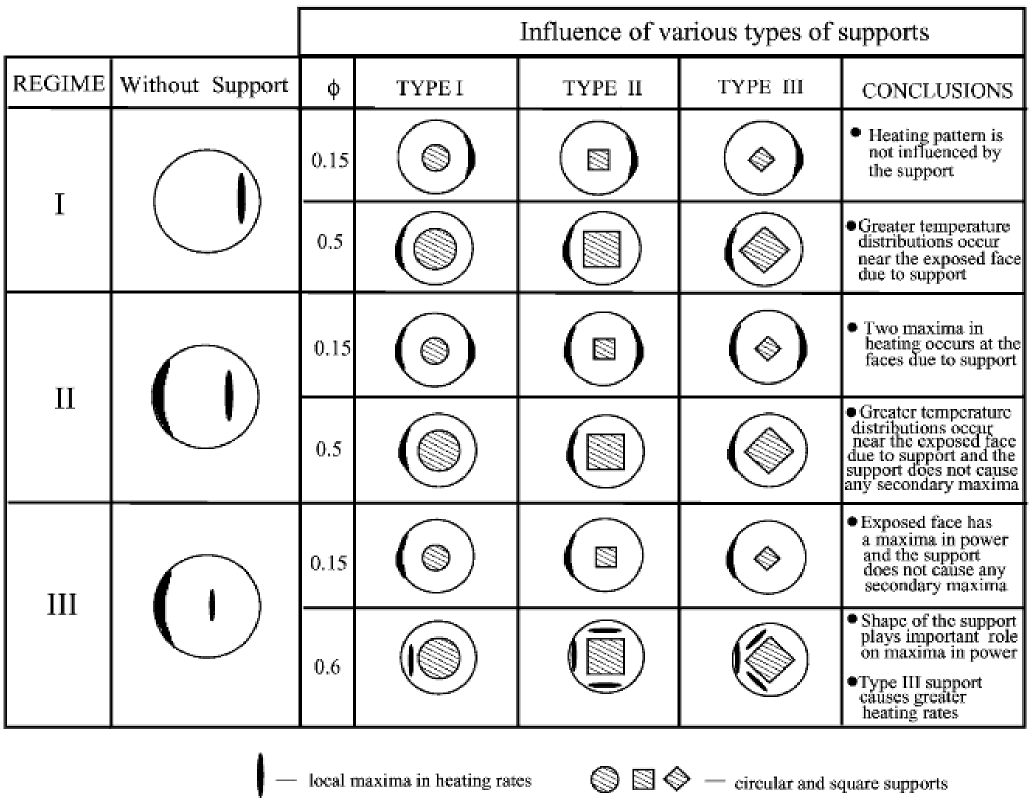

Table 3. Physico-chemical properties (mean ± standard deviation of three replicates) of protein isolated (Khan et al., 2011)

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

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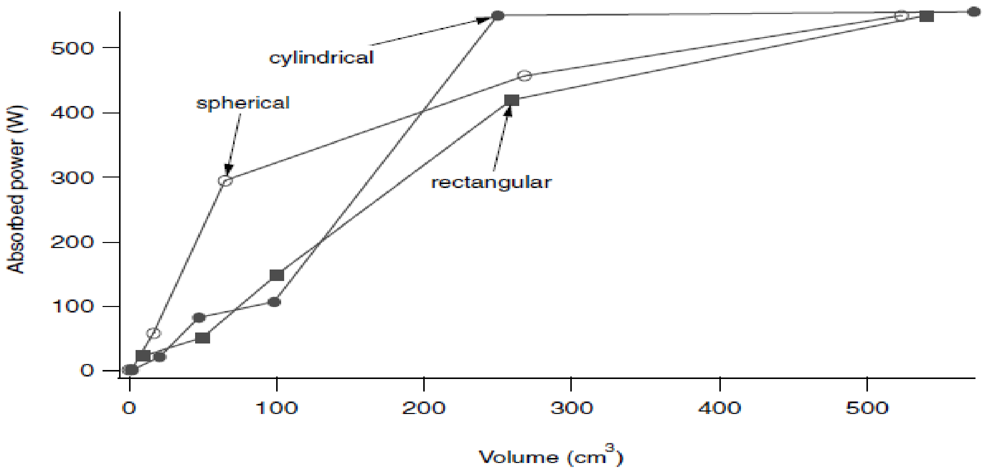
Table 4. Fatty Acid Compositions of Raw Castor Oil and Dehydrated castor oil (Nezihe et al., 2011)

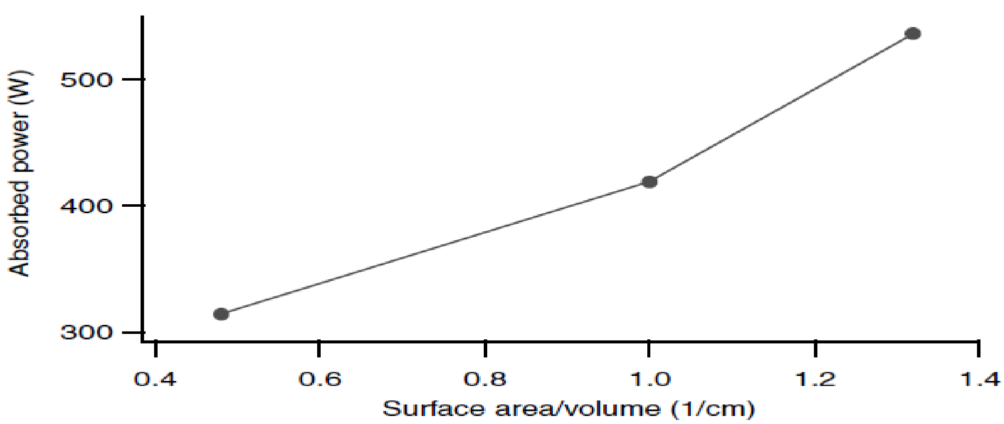
Fatty acid	**Castor oil**	**Dehydrated castor oil (Under N_2)**	**Dehydrated castor oil (Under vacuum)**
16:0	1.4	1.6	1.9
18:0	1.6	1.8	2.0
18:1	3.8	4.3	4.7
18:2 NCLA[a]	5.5	49.2	53.9
18:2 CLA (total)[b]		43.1	37.5
18:3	0.5		
18:1 OH	87.2	Trace	Trace
Total saturated	3.0	3.4	3.9
Total unsaturated	97.0	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.



A



B

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

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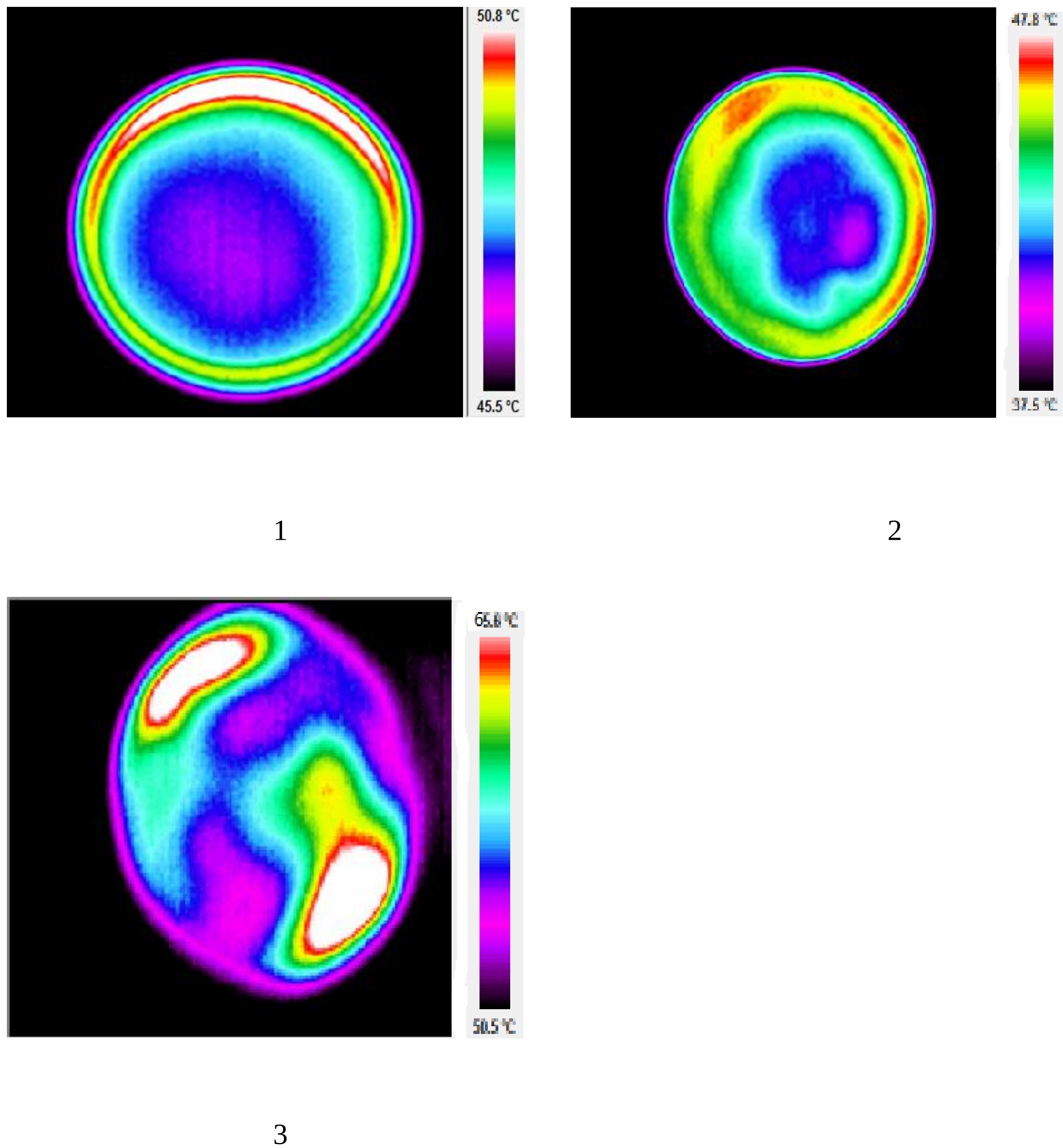

Fig. 2. Temperature distribution of the starch after 10 mins of different drying process: 1. 27 MHz RF dried starch, 2. 915 MHz MW dried starch, 3. 2450 MHz MW dried starch (Jiang et al., 2016). The hot spot can be found clearly in 2450 MHz heating.

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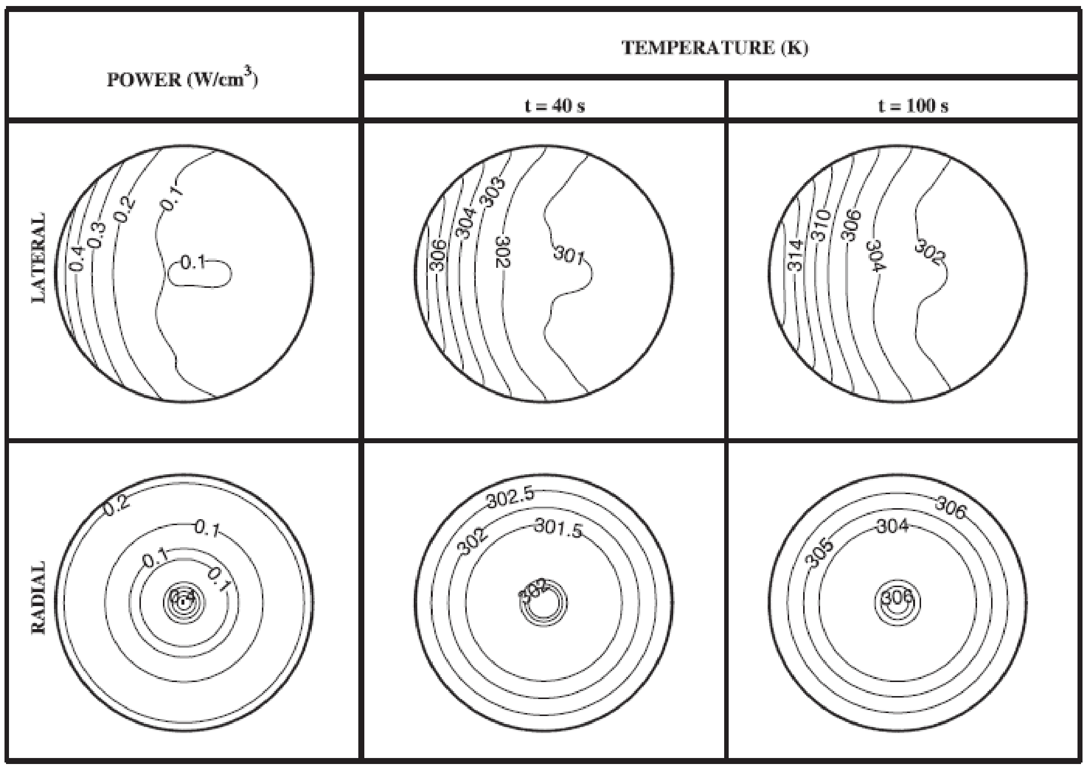

Fig. 3. Power and temperature contours of beef samples with lateral and radial irradiations for radius of the cross section of the sample was 3 cm; frequency was 2450 MHz, the incident microwave intensity was 1 W/cm. The temperature distributions are shown for time 40 and 100 s (Basak, 2007a).

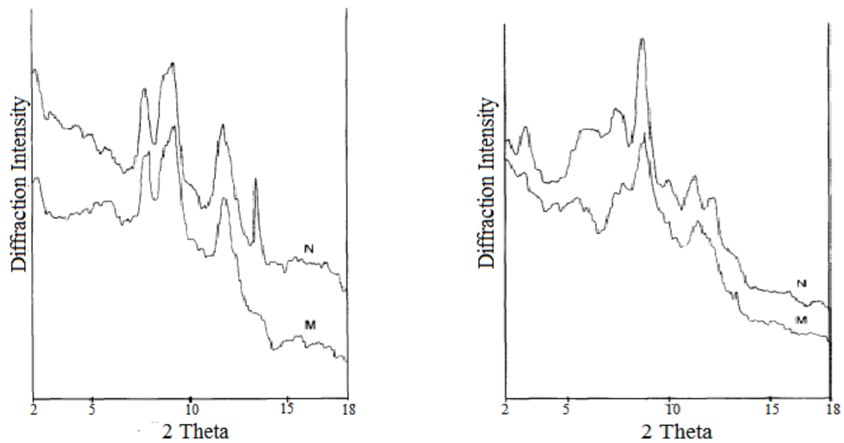

Fig. 4. X-ray diffraction patterns of potato and tapioca starch of moisture content 35% irradiated in a sealed beaker as compared to native starch. N=native starch; compared to native starch. N=native starch; M=microwaved starch (Lewandowicz et al., 1997).

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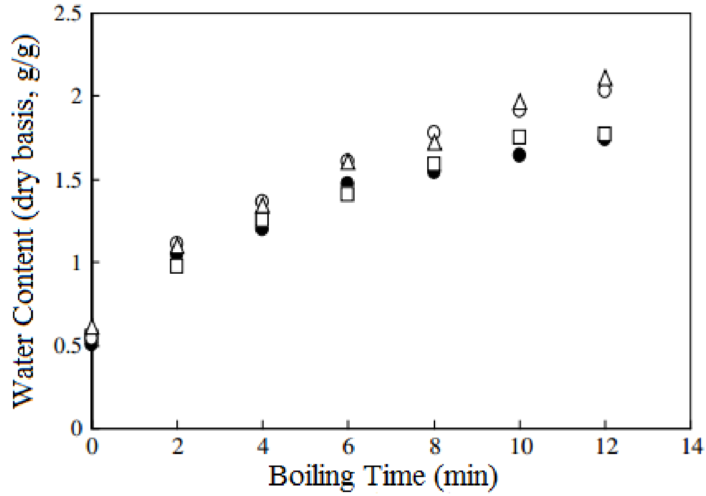

Fig. 5. Changes of the water content of the noodle while microwave boiling: The noodle was made using the dough, which retention time was 40 sec (□), 300 sec (○) and 520 sec (△). The noodle was made using the non-heat treated dough (●) (Xue et al., 2008).

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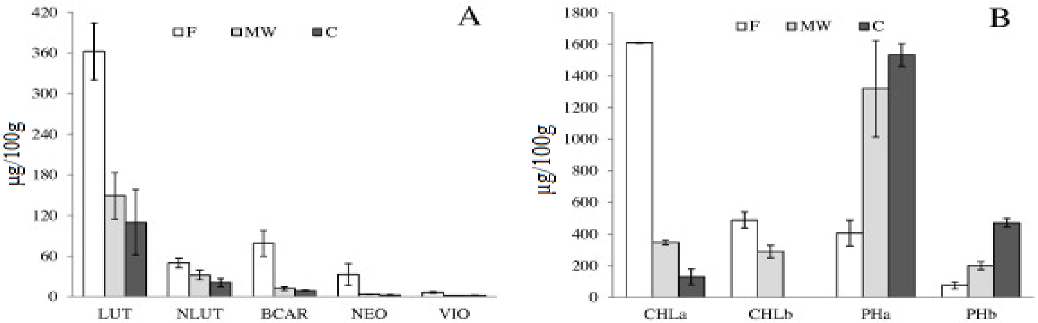

Fig. 6. Quantitative distribution of carotenoids (A) and chlorophylls (B) in fresh (F), microwaved (MW) and conventionally heated (C) kiwifruit puree. LUT: lutein; NLUT: neolutein A + B; BCAR: b-carotene; NEO: neoxanthin; VIO: violaxanthin; CHLa: chlorophyll a; CHLb: chlorophyll b; PHa: pheophytin a; PHb: pheophytinb (Benlloch-Tinoco et al., 2015).

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