Potentials of Microwave Heating Technology for Select Food Processing Applications - a Brief Overview and Update

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Abstract
In recent years, microwave heating has been increasingly popular all over the world, in particular for modern household food-processing applications, due to increased economic merits in many developing countries such as steady economic growth, high disposable income, etc. This trend also seems to be associated with increased awareness about the benefits of nutritious and healthy foods as well as functionalities of certain phytochemicals in diets, which may act as nutraceuticals. Microwave heating is known for its operational safety and nutrient retention capacity with minimal loss of heat-labile nutrients such as B and C vitamins, dietary antioxidant phenols and carotenoids. This review aimed to provide a brief yet comprehensive update on prospects of microwave heating for food processing applications, with special emphasis on the benefits at household level and its impact on food quality in terms of microbial and nutritional value changes.

Keywords: Microwave heating; Food processing; Cooking; Blanching; Pasteurization; Baking

Introduction
Microwaves are defined as a part of electromagnetic waves which have frequency range between 300 MHz and 300 GHz corresponding to wavelength from 1mm to 1m. Microwave frequencies of 915 MHz and 2.45 GHz can be utilized for industrial, scientific, and medical applications [1,2]. Microwaves have been applied in a broad range of food processing such as drying, tempering, blanching, cooking, pasteurization, sterilization, and baking. Microwave heating has considerable advantages over conventional heating methods, especially with regard to energy efficiency. Since heat is transferred from the surface of food to the interior by convection and conduction in conventional cooking method, it may result in a temperature gradient between outside and inside food [3]. In addition, it requires higher energy consumption and relatively long processing time [4]. In microwave heating, on the other hand, heat is generated (volumetric heating) inside the food in a short time when microwave penetrates through it [5]. Microwaves have greater penetration depth, and this property coupled with volumetric heating can lead to rapid heating rate with short processing time; and also contribute to the minimization of temperature difference between the surface and interior of food material [3,6].

As aforementioned, microwaves generate heat throughout the volume of food material rapidly because of the complete interaction between microwave, polar water molecules and charged ions in food. Microwave causes polar water molecules in food to constantly rotate and couple with electromagnetic field [7]. Molecular friction resulting from dipolar rotation of water molecule can generate heat. Water constitutes a major portion of most food products. Therefore, water is the primary component that interacts with microwaves due to its strong dipole rotation. Furthermore, heat can be generated through ionic migration that positive and negative ions of dissolved salts in food interact with the electric field by moving towards the oppositely charged regions of the electrical field and disrupt the hydrogen bonds with water [8,9].

Microwave heating rate can be varied depending on dielectric properties of food. Dielectric properties can be defined as:

\[\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon|e^{-j\delta}\]  \tag{1}

where \(\varepsilon\) is the dielectric properties, \(\varepsilon'\) the dielectric constant (real part), \(\varepsilon''\) the dielectric loss factor (imaginary part), and \(\delta\) dielectric loss angle (\(\tan\delta=\varepsilon''/\varepsilon'\)).

The dielectric constant (\(\varepsilon'\)) is associated to the material’s capability to store electric energy (for vacuum \(\varepsilon'=1\)), while the dielectric loss factor (\(\varepsilon''\)) is related to dissipation of electric energy due to different mechanisms. The dielectric properties describe the ability of a material to absorb, transmit, and reflect electromagnetic energy. Foods can be considered neither good electrical insulators nor good electrical conductors; thus can be categorized into ‘lossy dielectric materials’. Dielectric properties of foods have the ability to drive the influential interaction between the food components and electric field and can be influenced by many factors such as temperature, moisture content, salt content, frequency of the microwaves and other ingredients [10]. Microwave heating mechanism is very complex that depends on numerous factors i.e., propagation of microwaves governed by Maxwell’s equations for electromagnetic waves, the interactions between microwaves and dielectric properties of food, and the heat dissipation governed by heat and mass transfer. However, the magnetic part of electromagnetic waves does not have an interaction.
with natural media; therefore, it is not linked to microwave heating for most chemical reaction [1]. However, the loss tangent (tanδ) in eq. (1) can be used to describe the capability of a compound to convert microwave radiation into thermal energy. The higher loss tangent at 2.45 GHz indicates large susceptibility to microwave energy [1]. On the other hand, combination of ionic heating with dielectric heating of the contiguous solvent and the power (P) per total volume of a dielectric material in a microwave field can be written as follows:

$$P = \frac{1}{2} \varepsilon_0 \varepsilon_r |E|^2$$

(2)

Where $\omega$ is angular frequency (Hz), $\varepsilon_r$ is the permittivity of vacuum (F/m), $\varepsilon_r$ is the dielectric permittivity of medium, and $E_0$ is the electric field intensity (V/m), according to Ayappa and Davis [11].

Microwave heating conduces to the reduction of come up time in the processing for food products and is insensitive to food heterogeneity [12]. In addition, microwave heating is effective to heat up the prepared (ready to eat, RTE) food [13]. Therefore, the microwave oven operated in the simple manner became an indispensable home appliance to cook RTE food. Western foods are often considered to be more suitable for microwave cooking and can be ascribed due to fact that those include a majority of baked food products and precooked meat patties that require preheating process, i.e. oven-roasting or baking before consumption. In recent years, however, even in the countries like India where the traditional cooking methods are still popularly used, the application of microwave heating for cooking has been significantly increased. This transforming trend strongly suggests that microwave heating have been widely adopted for cooking various food types.

This paper was aimed to evaluate the effectiveness and potentials of microwave heating technology for different food processing methods and to briefly present a synthesis of experimental approaches of microwave heating from recently published literatures.

**Applications of Microwave Heating in Food Processing**

**Microwave pasteurization and sterilization**

Pasteurization is the most widely used technology for killing pathogenic and spoilage microorganisms in milk and fruit juices, however, it may largely destroy the organoleptic, nutritional value and physiochemical characteristics of food [14]. Safe and minimally processed foods with high quality attributes are essential to satisfy consumer needs, and those traits encourage those in the food and academic industries for finding innovative food processing techniques [15]. In earlier studies [16,17], pasteurization using 2450 MHz microwaves has been reported. However, even more uniform heating of foods (pasteurization) was achieved using 915 MHz microwave radiation, and it could be due to greater penetration depths of 915 MHz microwaves than 2450 MHz microwaves [18,19].

A number of studies show that either superior lethality or higher D-values can be observed using microwave treatment (Table 1) compared to conventional heating. This indicates the development of microbial thermal resistance against the conventional heat treatment, whereas the devastating effect of microwave treatment could be due to an explosion of internal pressure generated within the core [20,21].

Microwave sterilization process is a high-temperature-short-time (HTSTT) type; it is used not only to inactivate spoilage microorganisms in foods, but also to minimize the quality deterioration of foods [22]. Microwave sterilization process (128°C and 3 min processing time) produced products superior to those from conventional processes of canning (120°C retort temperature and 45 min processing time) and retorting foil pouches (125°C and 13 min cooking time) [23]. When microwave heating at 915MHz was used to sterilize pouches containing cooked macaroni and cheese, there was no significant change observed in the texture of product or loss of flavor [18].

Possible non-thermal effect on destruction of microorganisms under microwave heating has been reported; the polar and/or charged moieties of proteins (i.e., COO− and NH4+) can be affected by the electrical component of the microwaves [6]. And, the disruption of non-covalent bonds by microwaves is a more likely cause of speedy microbial death [24].

**Microwave blanching**

Blanching is a thermal pretreatment process, which is an essential step in several food processing techniques such as freezing, canning or drying, generally applied to inactivate enzymes that substantially affect to texture, color, flavor, and nutritive values of fruits and vegetables [26,27]. In general, hot water or steam blanching treatment is most commonly used in commercial sites for processing of food products. However, the conventional blanching method is closely associated with the serious loss of weight and nutritional values of food products. To retain nutritional quality of food products, several researchers suggested the use of microwave heating as an alternative to conventional blanching method for food products [27-30]. Since microwave blanching requires little or no water for efficient heat transfer in food, it can reduce the amount of nutrients lost by leaching as compared with hot water immersion [31]. Patricia and others [32] have observed a clear positive impact of microwave blanching on the nutritional quality of broccoli as summarized in Table 2. The amounts of protein, ashes, vitamin C, iron and phosphorus found in broccoli blanched by microwave were much higher than in the sample treated by hot water blanching, and were closer to that of fresh broccoli.

The levels of vitamin C retained after microwave and hot water blanching treatments are presented in Table 2. Mufutugil [33] compared both hot water and microwave blanching methods based on their effect on the retention of vitamin C in green beans. Microwave blanched samples showed better retention in vitamin C as compared with hot water blanched samples. Furthermore, superior retention of vitamin C

| Growth medium | Treatment | Microorganism | D value | References |
|---------------|-----------|---------------|---------|------------|
| Apple juice   | D50 (55°C) | S. cerevisiae | 58, 25 and 10 s | [21] |
|               | D90 (55°C) | L. plantarum  | 4.8, 2.1 and 1.1 s | |
| Glucose saline| D50 (55°C) | E. coli K-12  | 73, 18 and 3.0 s | [24] |
| Foods         | D50 (55°C) | S. aureus     | 17.8, 2.4 and 3 min | [25] |

Table 1: Changes in viable counts of microorganisms in liquid foods after microwave and conventional heating.
in microwave blanched frozen spinach over hot water blanched sample has been reported [30]. Such higher retention rates of vitamin C are more likely due to blanching in minimal water for a reduced time using microwaves. In addition, after blanching of 150g of green peas with 100 ml water using microwave and water heating, total β-carotene retained better in microwave treated sample [34].

Straumite et al. [35] observed only a small difference in color, volatile aroma compounds, and sensory attributes between fresh dill and dried dill that was hot water blanched at 90°C temperature for 30 s following microwave pretreatment at 900 W for 30 s. The positive outcome on overall quality would be because of the synergistic effect of hot water blanching assisted with microwave pretreatment.

### Microwave cooking

Cooking with microwaves has recently become the most adaptable method all over the world. Microwave ovens are now used in about 92% of homes in the US [17]. Microwave ovens are very popular home appliances for the food processing applications. Zhang and Hamauzu [36] reported that the physical and chemical properties of the most vegetables tend to be changed upon cooking by boiling in water or microwave. Moreover, the cooking process exerts some structural changes and reduction in dietary fiber components of various vegetables [37,38]. Compared to ordinary microwave cooking, a more pronounced reduction of dietary fiber components has been observed with pressure cooking of cabbage, carrots, cauliflower, eggplant, onions, peas, potatoes, radish, spinach and turnips [39].

Microwave oven is well suited for cooking the food in small quantities, especially for households [40], though not convenient for mass cooking. Daomukda et al. [41] studied the effect of different cooking methods on physicochemical properties of brown rice. They concluded that the protein, fat and ash contents in rice cooked by microwave are retained at higher levels (8.49%, 2.45% and 1.42%, respectively) than conventional boiling and steaming methods. Parallel findings were observed by Alajaji and El-Adawy [46] also reported that minerals (K, Ca, Na and Mg) and minor elements (Cu, Fe, and Zn) observed in chickpea before and after different cooking treatments. The highest retention of minerals was detected with microwave cooking unlike fried cooking and traditional cooking methods, which recorded the lowest and moderate retentions, respectively. Parallel findings were observed by Alajaji and El-Adawy [46] with additional elements such as P and Mn. Bernhardt and Schlitch [47] also reported that minerals content of fresh and frozen pepper were retained at high levels (0.43 and 0.38 g/100g, respectively) in microwave cooking compared with cooking by boiling (0.35 and 0.22 g/100g, respectively).

Alajaji and El-Adawy [46] also reported that cooking treatments can significantly affect the vitamin contents in chickpea seeds, and such negative impacts are probably due to the combined effects of leaching and chemical destruction. However, a mild reduction in vitamin levels was observed through microwave cooking. The retained concentrations of riboflavin, thiamin, niacin and pyridoxine in microwave cooked chickpea seeds were significantly higher than those obtained with boiling and autoclave cooking. These results are in agreement with the earlier reports [48]. Conventional cooking of broccoli for 30, 60, 90, 120 and 300 s has been found to reduce total phenolic content by 31.6%, 47.5%, 55.9%, 61.7% and 71.9% in florets and 13.3%, 22.2%, 26.7%, 28.9% and 42.2% in stems and, there was no significant difference in the total phenolic content between microwave and conventionally cooked samples [46].

Because microwave oven is able to heat up foods using the energy of oscillating electromagnetic wave, it is possible to do selective and quick cooking. But the penetration depth of microwave is under about a few inches or below the surfaces of foods. So, if the sizes of foods are small and the shape of foods is flat, the uniform heating through overall volume is possible. It will lead less loss of moisture contents and the greatest energy savings, and the nutrition of foods will be preserved very well. But using conventional method, cooking of multiple foods containing particles of any shape and size together can be achieved through moist-heat method, but at the expense of moisture which

| Treatment | Foodstuff | Procedure | Parameter (Nutrients) | Quantities | Reference |
|-----------|-----------|-----------|-----------------------|------------|-----------|
| Blanching | Broccoli | Blanched by a traditional process (92°C for 0.5 to 4 min) | Protein, Ashes (%db) | 42.62 ± 4.88, 4.220 ± 0.99 | [32] |
|          |          | Blanched by microwave (2450 MHz with 950 W for 3 min) | Protein, Ashes (%db) | 44.34 ± 1.92, 9.11 ± 0.45 | [33] |
|          | Green beans | Boiling water (100°C for 2 min) | Vitamin C retention (%) | 84.7 | [30] |
|          | Frozen spinach | Boiling water (90°C ± 2 for 3.5 min) | Vitamin C retention (%) | 69.1 | [30] |

Table 2: Nutritive values of different food products after microwave and traditional blanching.
keeps some of their nutrition. Therefore, new combination techniques, making the best use of the merits of microwave heating, should be studied.

**Microwave baking**

Baking is one of the thermal processes that significantly changes physicochemical properties of dough. Baking process includes three phases: expansion of dough and moisture loss initiates in the first phase; the second phase, in which expansion and the rate of moisture loss becomes maximal. The changes that continue to take place in the third phase of baking include rise in product height and decrease in rate of moisture loss because the structure of the air cells within the dough medium collapses as a result of increased vapor pressure [49,50].

Many studies have been undertaken to address various issues related to the microwave baking. These problems include texture, low volume, lack of color, and crust formation, more dehydration and rapid staling [51,52]. Goedecken et al. [53] suggested that the power of microwave oven should be controlled in order to avoid notable water loss. Seyhun et al. [54] reported that the amount of moisture content of microwave-baked cake containing pregelatinized starch is not significantly different from conventionally backed cakes during baking and storage because the pregelatinated starches could bind a greater amount of water inside food [55]. Also, the most of starches, except amylozae, were effective in reducing firmness during storage. Texture is one of the major quality characteristics of foods. Megahey et al. [50] observed the influences of different baking conditions on quality in terms of texture of cake using microwave oven at 250 W and convection oven at 200°C. Microwave-baked cake was found to possess high springiness, moisture content and the low firmness as texture attributes compared with the cake that baked in convection method. Phenolic compounds, which are related with flavor, color and one of important factors, namely, healthy quality of foods, were studied using domestic microwave oven [56]. The quantitative analysis of phenolic compounds showed that microwave baking at the power of 500 W is a good level for retention of the compounds. Temperature distribution of food sample during baking could be changed depending on the characteristics of pan materials. In the case of glass, the temperatures at the center of the pan were smaller than the edge and surface of sample [57,58]. On the other hand, the reverse phenomenon was observed in a Teflon pan [59]. Unfortunately, microwaves do not have the ability to induce browning, which is more pronounced with the conventional baked products [60]. Durairaj et al. [61] found that ceramic layer is useful to enhance the power absorption and decrease the thermal runaway for discrete food samples layered with ceramic composites.

Over the past two decades, there has been an increasing interest in the use of combination of microwave with other heating systems to reduce processing time and increase the quality of products. When the microwave technique was applied for bread cooking for the first time, there were a few main issues that the inside of bread was firm, while the outside was tough, and the low moisture content was observed [62-65]. To overcome these hurdles, two cycle microwave oven, of which the first cycle is an internal cooking using commercial methods and the second cycle is an overall cooking using microwave, was tested. It showed reduced duration time, energy saving effect and better quality [66,51]. Chemat et al. [67] reported a design of microwave (MW)-ultraviolet (UV) combined reactor (a modified microwave oven), wherein high energy level of UV lamp and mechanism of microwave heat transfer can induce effective photo-thermal reactions, and the use of such ovens was also recommended for food sterilization purposes.
Halogen lamp-microwave combination heating is one of such technologies. Near-infrared radiation generated by halogen lamp has a high frequency and low penetration depth and it occupies the visible region in the electromagnetic spectrum [68]. It revealed the additional advantages such as browning and crisping effects by halogen lamp heating [41]. Also, microwave heating was found to be the dominant mechanism in halogen lamp-microwave combination baking in terms of affecting weight loss and texture development. Different studies have shown improvement in the quality of microwave-baked products when infrared is added to microwave heating [69,70]. Some of the relative benefits of microwave baking over conventional baking methods are listed in Table 4.

### Microwave drying

One of the oldest methods for the preservation of vegetables is drying. Drying fruits and vegetables is of great technological interest to extend the shelf-life [71]. Drying is one of the thermal processes that intended to reduce the moisture content of fruits and vegetables, and it is one of the time-and energy-consuming processes in the food industry. Consequently, new methods are aimed to decrease drying time and energy consumption with preservation of quality [72]. Microwave drying is a relatively newer addition to the family of conventional dehydration methods. In microwave drying, heat is generated directly in the interior the material, making possible higher heat transfer and thus a much faster temperature rise than in conventional heating. In conventional heating, thermal energy is transferred to the surface of material to be heated by conduction, convection, and/or radiation [73-74]. There are significant differences in the mechanisms of microwave and conventional drying processes; the temperature and moisture gradients are in the same direction in case of microwave heating unlike conventional heating, wherein significant moisture loss from the material against temperature gradient is pronounced. In addition, microwaves are able to penetrate dry food solids to reach unevaporated moisture [19,75].

Drying methods using microwave can be divided into four categories; Microwave Drying (MD), Microwave-Assisted Freezing Drying (MFD), Microwave-Assisted Vacuum Drying (MVD), Microwave-Assisted Hot Air Drying (MHD) and Microwave-Enhanced Spouted Bed Drying (MSE). In the MD, the relationship between the constant microwave power and the ratio of moisture content was studied mainly [76-78]. After that, the methods to control the microwave power in real time were executed by applying various sensors [79-81]. Freeze drying can maintain the quality of dried product best to compare with other conventional techniques but it is a long time processing and brings high energy consumption issue. The MFD could be a one of alternatives to be able to avoid these weaknesses. It can produce the same quality as that of conventional freeze drying and can reduce the drying time effectively [82,83]. One problem is the possibility of corona or plasma discharge under high vacuum state and then, it induces the melting of ice formed inside foods during processing time [84]. In order to avoid corona discharge during MFD, the pressure of cavity should be within the range 50-100 Pa [85]. The characteristic of the MVD is that the changes of moisture ratio follow the exponential or empirical function, and have been described by using Lewis equation, Page’s model and Fick’s law. The effective moisture diffusivity was significantly increased when microwave drying was applied under vacuum condition, compared to hot air drying [86]. The MVD can create a more porous dehydrated product, which rehydrated more quickly and more completely than the air dried product [87-90]. The most common drying method is hot air drying (AD) process because it is a very simple method. But in the AD process, there are many disadvantages such as low energy efficiency and lengthy drying time. This is mainly caused by rapid reduction of surface moisture due to the low thermal conductivity and internal resistance to moisture transfer. Finally, such a phenomenon results in reducing the quality of food because of the shrinkage induced by the reduction of moisture content [91-94]. To overcome these drawbacks, microwave with the constant level of power during drying process was combined with hot air system and it brought significant advantages with regard to processing time and food quality [95,96]. Also, the effects of phase-controlled and cycle-controlled input electrical power on drying characteristics were evaluated through combined microwave and hot air system [97,98]. In a recent study, the pineapple samples pre-treated by osmotic dehydration were dried quickly under variable microwave power conditions without significant charring [99]. Malafonté et al. [100] tried to simulate the combined convective-microwave assisted drying process under various conditions using mathematical model. They reaffirmed the key role of dielectric properties in the microwave assisted processes. Conventional fluidized bed dryer is one of the most suitable equipments for efficient drying of fine particle products. However, long drying time during the falling rate period and low

| Treatment | Foodstuff | Procedure | Parameter | Quantities | Reference |
|-----------|-----------|-----------|-----------|------------|-----------|
| Baking    | Pound cake| Conventional oven-baked (commercial electric oven at 180°C for 35 min.) | Volume (cm³), Weight loss (g/100 g) | 88.4 ± 5.5, 9.8 ± 2.0 | [39] |
|           |           | Double-cycle microwave-baked (2450 MHz, with 1000 W and 10 power levels) | Volume (cm³), Weight loss (g/100 g) | 98.3 ± 6.2, 19.3 ± 1.0 | |
|           | Madeira cake | Convective-baked at (200 ± 1°C) | Luminosity (L), Weight (g) | 84.5 ± 0.4, 36.3 ± 0.42 | [40] |
|           |           | Microwave-baked (domestic microwave at 2450 MHz with power 100 to 900 W) | Springiness (%), Firmness (N) | 42.7, 3.21 | |
|           |           | Conventional-baked (preheating to the set temperatures (175, 200 and 225°C for 12, 13 and 14 min) | Springiness (%), Firmness (N) | 46.7, 2.52 | [41] |
|           |           | Microwave baked 50% power for 2 min and 100% power for 1 min) | Springiness (%), Firmness (N) | 0.329, | |

Table 4: Physical properties of different food products after microwave and traditional baking.
energy efficiency are the major disadvantages [101]. Conventional fluidized bed drying with microwave heating assistance has resulted in energy saving and short drying time and increased quality of foods [102-107]. The air blower provides a pneumatic agitation so that the non-uniform heating problems could be overcome [108]. Nowadays, the combined method was expanded by using freeze drying, multi-state heat pump, vacuum drying and so on [109-111].

Soysal et al. [112] reported that color demonstrates the chemical changes in food material during drying; in addition, it plays a crucial role in improving the attractiveness of a food product. Alibas [113] demonstrated the color characteristics of pumpkin slices dried using air drying, microwave drying and combined microwave-air drying methods; higher color values were obtained during combined microwave-air drying and was followed by microwave drying, and air drying. Combined microwave-air drying has shorter drying time compared with other drying methods. Kathirvel et al. [114] found that the color values of coriander leaves dried using a 90 Wg⁻¹ microwave power density level was almost similar to that of the fresh coriander leaves. Furthermore, exceptionally high brightness, redness and yellowness values were obtained after microwave drying at the power levels of 500 and 750 W. The color values L (brightness) and a (redness) achieved through microwave drying at the power levels 750,650 and 500W were close to the color of samples before drying [77].

Table 5 lists the average values of specific energy consumption for seedless grape drying using different methods. Kassem et al. [72] concluded that the lowest energy consumption of about 320.6 MJ/kgₑₙₑⱼ for seedless grapes evaporated, with long drying times unlike microwave drying, wherein the evaporated was observed with microwave-drying among three different drying methods used. On the other hand, the value of energy consumption during grapes drying by hot air cabinet stood at 564.5 MJ/kgₑₙₑⱼ with long drying times unlike microwave drying, wherein the heating period is relatively short. Alibas [113] evaluated the energy consumption for drying of pumpkin slices using microwave, air and combined microwave-air-drying treatments. He concluded that high energy consumption was observed for air oven drying compared to combined microwave-air-drying treatment and, the lowest energy consumption among treatments was observed during microwave drying.

However, there is one key problem with the above-mentioned techniques. Because of non-uniform heating, the uneven distribution of microwave field can occur. In addition, the overheating and quality deterioration can take place [115,116]. To overcome these problems, the microwave drying technique has been combined with various other methods. The Microwave Freeze Drying (MFD) and Microwave Vacuum Drying (MVD) are good examples, wherein drying is assisted by microwaves to produce high quality foods. Especially, conventional fluidized bed dryer combined with microwave heating is good choice for drying products containing fine particles. In the future, various hybrid methods will emerge.

### Conclusion

The successful applications of microwave heating technology for processing of various foods have been discussed in the present review. The microwave heating technology for pasteurization and sterilization contributed to effectively destroy pathogenic microorganisms and significantly reduce processing time without serious damage in overall quality of liquid food as compared to traditional methods. The use of microwave heating for food processing applications such as blanching, cooking, and baking has a great effect on the preservation of nutritional quality of food. Furthermore, microwave heating could significantly require less energy consumption for dehydrating food than conventional method. In these days, the potential of continuous flow microwave heating at commercial scale and the combination heating methods supplemented with conventional thermal treatment for uniform heating of particulate foods has been widely investigated due to inherent advantages of microwave heating. Although microwave heating technology for a variety of food processing applications provide significant advantages with respect to lethal effect on pathogens, processing time, and energy consumption, several other quality aspects of food products processed using conventional methods are still better than microwave in terms of color, texture, and other organoleptic properties of food products. Therefore, the investigation of parameters which can influence the workability of microwave heating such as dielectric, physical, and chemical properties of food products should be carried out.

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### References

1. Hoogenboom R, Wilms TFA, Erdmenger T, Schubert US (2009) Microwave-Assisted Chemistry: a Closer Look at Heating Efficiency. Aust J Chem 62: 236-243.
2. Meredith RJ (1998) Engineers’ Handbook of Industrial Microwave Heating. Institution of Electrical Engineering, London.
3. Wiltkiwicz K, Nastaj JF (2010) Simulation Strategies in Mathematical Modeling of Microwave Heating in Freeze-Drying Process. Drying Technol 28: 1001-1012.
4. Varith J, Dijkanarukkul P, Achariyaviriya A, Achariyaviriya S (2007) Combined microwave-hot air drying of peeled longan. J Food Eng 81: 459-468.
5. Pozar DM (2009) Microwave engineering. John Wiley & Sons.
6. Decareau RV (1985) Microwaves in the Food Processing Industry. New York: Academic Press Inc.
7. Ahmed J, Ramaswamy HS, Raghavan VGS (2007) Dielectric properties of Indian Basmati rice flour slurry. J Food Eng 80: 1125-1133.
8. Oliveira MEC, Franca AS (2002) Microwave heating of foodstuffs. J Food Eng 53: 347-359.
9. Decareau RV, Peterson RA (1986) Microwave processing and engineering. Chichester: Ellis Horwood, 37-87.
10. Buffler CR (1993) Microwave Cooking and Processing: Engineering Fundamentals for the Food Scientists. Van Nostrand Reinhold, New York, USA.
11. Ayappa KG, Davis HT, Davis EA, Gordon J (1991) Analysis of microwave heating of materials with temperature-dependent properties. Aiche J 37: 313-322.
12. Coronel P, Simanovic J, Sandeep KP (2003) Temperature Profiles within Milk after Heating in a Continuous-flow Tubular Microwave System Operating at 915 MHz. J Food Sci 68: 1976-1981.
13. Hossan MR, Byun DY, Dutta P (2010) Analysis of microwave heating for cylindrical shaped objects. Int J Heat Mass Tran 53: 5129-5138.
14. Espachs-Barroso A, Barbosa-Canovas GV, Martin-Belloso O (2003) Microbial and Enzymatic Changes in Fruit Juice Induced by High-Intensity Pulsed Electric Fields. Food Rev Int 19: 253-273.
15. Riahi F, Ramaswamy HS (2004) High pressure inactivation kinetics of amylase in apple juice. J Food Eng 64: 151-160.
16. Decareau RV (1992) Microwave Foods: New Product Development. Connecticut: Food nutrition press Inc.
17. Giese J (1992) Advances in microwave food processing. Food Technol 42: 118-123.
18. Tong CH, Lentz RR, Rossen JL (1994) Dielectric Properties of Pea Puree at 915 MHz and 2450 MHz as a Function of Temperature. J Food Sci 59: 121-122.
19. Mudgell RE (1989) Microwave food processing. Food Technol 43: 117-126.
20. Khali HM, Villota R (1988) Comparative study on injury and recovery of Staphylococcus aureus using microwave and conventional heating. J Food Protect 51: 181-186.
21. Tajchakavit S, Ramaswamy HS, Fustier P (1998) Enhanced destruction of spoilage microorganisms in apple juice during continuous flow microwave heating. Food Res Int 31: 713-722.
22. Estève MJ, Frigola A, Martorell L, Rodrigo C (1998) Kinetics of ascorbic acid degradation in green asparagus during heat processing. J Food Prot 61: 1518-1521.
23. Ottsion T (1987) Sterilization of foods by microwaves. International Seminar on New Trends in Aseptic Processing and Packaging of Food stuffs; 22 Oct. 1987; Munich. SLK Report No. 564, The Swedish Institute for Food and Biotechnology, Goteborg, Sweden.
24. Koutchma T, Le Bail A, Ramaswamy HS (2001) Comparative experimental evaluation of microbial destruction in continuous-flow microwave and conventional heating systems. Can Biosyst Eng 43: 3.1-3.8.
25. Rosenberg U, Sinnel HJ (1990) D-value determinations in the microwave field for micro-organisms isolated from foods. Pletschwirtschaft 70: 396-402.
26. Dorantes-Alvarez L, Jaramillo-Flores E, Gonzalez K, Martinez R, Parada L (2011) Blanching peppers using microwaves. Procedia Food Science 1: 178-183.
27. Ramesh MN, Wolf W, Tepini D, Bognar A (2002) Microwave Blanching of Vegetables. J Food Sci 67: 390-398.
28. Gianni SY (1991) Effect of pretreatments on the texture and ascorbic acid content of frozen plantain pulp (Musa paradisiaca). J Sci Food Agr 45: 667-671.
29. Sánchez-Hernández D, Devece C, Catalá JM, Rodríguez-López JN, Tudela J, et al. (1999) Enzyme inactivation analyses for industrial blanching applications employing 2450 MHz monomode microwave cavities. J Microw Power Electromag Energy 34: 239-252.
30. Ponne CT, Baysal T, Yuksei D (1994) Blanching Leafy Vegetables with Electromagnetic Energy. J Food Sci 59: 1037-1041.
31. Lin S, Brewer MS (2005) Effed of Blanching Method on the Quality Characteristics of Frozen Peas. J Food Quality 28: 350-360.
32. Patricia CM, Bibiana DY, Jose PM (2011) Evaluation of microwave technology in blanching of broccoli (Brassica oleracea L. var Botrytis) as a substitute for conventional blanching. Procedia Food Science 1: 426-432.
33. Mutfuglu N (1986) Effect of Different Types of Blanching on the Color and the Ascorbic Acid and Chlorophyll Contents of Green Beans. J Food Process Pres 10: 69-76.
34. Jen JJ (1981) Effect of microwave and conventional cooking on the nutritive value of cosusus peas (Vigna unguiculata). J Food Sci 46: 272-273.
35. Straumt L, Kruma Z, Galoburda R, Saulie K (2012) Effect of Blanching on the Quality of Microwave Vacuum Dried Dill (Anethum graveolens L.). World Academy of Science, Engineering and Technology 64: 756-762.
36. Zhang D, Hamauzu Y (2004) Phenolics, ascorbic acid, carotenoids and antioxidant activity of broccoli and their changes during conventional and microwave cooking. Food Chem 88: 503-509.
37. Roehrig KL (1986) The physiological effects of dietary fiber-a review. Food Hydrocolloid 2: 1-18.
38. Sukhward MK, Harvinder K, Teijinder G (1992) Effect of cooking on fibre content of vegetables. J Food Sci Technol 29: 185-186.
39. Zia-ur-Rehman Z, Islam M, Shah WH (2003) Effect of microwave and conventional cooking on insoluble dietary fiber components of vegetables. Food Chem 80: 237-240.
40. Juliano BO (1985) Production and utilization of rice. In Juliano BO (ed.) Rice chemistry and technology, (2ndedn.) St. Paul: American Association of Cereal Chemists 1-16.
41. Daomukda N, Moongngarm A, Payakapol L, Nisusawan A (2011) Effect of Cooking Methods on Physicochemical Properties of Brown Rice 6: V1-1-V1-4. Singapore: IACSIT Press.
42. Yeo HCH, Shibamoto T (1991) Chemical comparison of flavours in microwave and conventionally heated foods. Trends Food Sci Technol 2: 329-332.
43. Lakshmi S, Chakkaravarthi A, Subramanian R, Singh V (2007) Energy consumption in microwave cooking of rice and its comparison with other domestic appliances. J Food Eng 75: 715-722.
44. Marconi E, Ruggeri S, Cappelloni M, LeonardI D, Carnovale E (2000) Physicochemical, nutritional, and microstructural characteristics of chickpeas (Cicer arietinum L.) and common beans (Phaseolus vulgaris L.) following microwave cooking. J Agric Food Chem 48: 5986-5994.
45. Arab EAA, Helmy IMF, Baren GF (2010) Nutritional Evaluation and Functional Properties of Chickpea (Cicer arietinum L.) Flour and the Improvement of Spaghetti Produced from its. J Am Sci 6: 1055-1072.
46. Fenaroli E (2006) Impact of different cooking methods on food quality: Retention of lipophilic vitamins in fresh and frozen vegetables. J Food Eng 77: 327-333.
47. Bernhardt S, Schlich E (2006) Impact of different cooking methods on food quality: Retention of lipophilic vitamins in fresh and frozen vegetables. J Food Eng 77: 327-333.
48. Salama AM, Ragab GH (1997) Composition of conventional and microwave cooking of kidney beans and carrot in relation to chemical composition, nutritive value and sensory characteristics. Journal of Home Economics-Menoufi University 7: 213-225.
49. Mondal A, Datta AK (2008) Bread baking - a review. J Food Sci 66: 465-474.
50. Megahy EK, McMinn WM, Magee TRA (2005) Experimental Study of Microwave Baking of Madeira Cake Batter. Food Bioprod Process 83: 277-287.
51. Sumnu G (2001) A review on microwave baking of foods. Int J Food Sci Technol 36: 117-127.
52. Sumnu G, Sahin S, Sevimli M (2005) Microwave, infrared and infrared-microwave combination baking of cakes. J Food Eng 71: 150-155.
53. Goedeke DL, Tong CH, Virtanen AJ (1997) Dielectric Properties of a Preheated Breaf System at 2450 MHz as a Function of Temperature, Moisture, Salt and Specific Volume. J Food Sci 62: 145-149.
54. Seyhun N, Sumnu G, Sahin S (2005) Effects of Different Starch Types on
Retardation of Staling of Microwave-baked Cakes. Food Bioprod Process 83: 1-5.

55. Brain SM, Zallie JP (1990) Role and function of starches in microwaveable food formulation. Food Australia official journal of CAFTA and AIFST 42: 523-524.

56. Barba AA, Calabretti A, d’Amore M, Piccinelli AL, Rastrelli L (2008) Phenolic constituents levels in cv. Agria potato under microwave processing. Food Sci Technol-LEB 41: 1919-1926.

57. Baker BA, Davis EA, Gordon J (1990) The Influence of Sugar and Emulsifier Type During Microwave and Conventional Heating of a Lean Formula Cake Batter. Cereal Chem 67: 451-457.

58. Sumnu G, Ndile MK, Bayindirli L (1999) Temperature and weight loss profiles of model cakes baked in the microwave oven. J Microw Power Electromagn Energy 34: 221-226.

59. Lambert LLP, Gordon J, Davis EA (1992) Water Loss and Structure Development in Model Cake Systems Heated by Microwave and Convection Methods. Cereal Chem 69: 303-309.

60. Chavan RS, Chavan SR (2010) Microwave Baking in Food Industry: A Review. Int J Dairy Sci 5: 113-127.

61. Durairaj S, Chauhdary A, Basak T (2009) Efficient microwave heating of discrete food samples layered with ceramic composites. J Food Eng 95: 62-75.

62. Ovadla C, Walker CE (1996) Microwave pressure baking with vacuum cooling. In Proceedings of the 31st microwave power symposium. VA: International Microwave Power Institute, Manassas, USA, 89-92.

63. Sánchez PME, Ortiz MA, Mora ER, Chanona PJ, Necochea MH (2008) Comparison of crumb microstructure from pound cakes baked in a microwave or conventional oven. Food Sci Technol-LEB 41: 620-627.

64. Shukla TP (1993) Bread and bread-like dough formulations for the microwave. Cereal Food World 38: 95-96.

65. Higo A, Noguchi S (1987) Comparative studies on food treated with microwave and conductive heating. Part 1. Process of bread hardening by microwave-heating. J Jpn Soc Food Sci 34: 781-787.

66. Sanchez-Pardo ME, Ortiz-Moreno A, Garcia-Zaragoza FJ, Necochea-Mondragon H, Chanona-Perez JJ (2012) Comparison of pound cake baked in a two cycle microwave-toaster oven and in conventional oven. Food Sci Technol-LEB 46: 356-362.

67. Chemat S, Aouabed A, Bartels PV, Esveild DC, Chemat F (1999) An Original Microwave-Ultra Violet Combined Reactor Suitable for Organic Synthesis and Degradation. J Microw Power Electromagn Energy 34: 55-60.

68. Keskin SO, Sumnu G, Sahin S (2004) Bread baking in halogen lamp-microwave combination oven. Food Res Int 37: 489-495.

69. Sevinni KM, Sumnu G, Sahin S (2005) Optimization of halogen lamp-microwave combination baking of cakes: a response surface methodology study. Eur Food Res Technol 221: 61-68.

70. Datta AK, Ni H (2002) Infrared and hot-air-assisted microwave heating of foods for control of surface moisture. J Food Eng 51: 355-364.

71. Doymaz I (2006) Drying kinetics of black grapes treated with different solutions. J Food Eng 76: 212-217.

72. Kassem AS, Shokr AZ, El-Mahdy AR, Aboukarima AM, Hamed EY (2011) Comparison of drying characteristics of Thompson seedless grapes using combined microwave oven and hot air drying. Journal of the Saudi Society of Agricultural Sciences 10: 33-40.

73. Sutar PP, Prasad S (2008) Microwave drying technology-recent developments and R&D needs in India. In proceedings of 42nd ISAE Annual Convention, 1-3.

74. Gowen A, Abu-Ghannam N, Frias J, Oliveira J (2006) Optimization of dehydration and rehydration properties of cooked chickpeas (Cicer arietinum L.) undergoing microwave-hot air combination drying. Trends Food Sci Tech 17: 177-183.

75. Murthy GS, Prasad S (2005) A completely coupled model for microwave heating of food in microwave oven. Paper No. 056062, 2005 ISAE Annual Meeting.

76. Wang Z, Sun J, Chen F, Liao X, Hu X (2007) Mathematical modelling on thin layer microwave drying of apple pomace with and without hot air pre-drying. J Food Eng 80: 536-544.
102. Hatamipour MS, Mowla D (2002) Shrinkage of carrots during drying in an inert medium fluidized bed. J Food Eng 55: 247-252.

103. Hatamipour MS, Mowla D (2003) Experimental Investigation of Drying of Carrots in a Fluidized Bed with Energy Carrier. 26: 43-49.

104. Hatamipour MS, Mowla D (2006) Drying Behaviour of Maize and Green Peas Immersed in Fluidized Bed of Inert Energy Carrier Particles. Food and Bioproducts Processing 84: 220-226.

105. Lee DH, Kim SD (1993) Drying characteristics of starch in an inert medium fluidized bed. Chem Eng Technol 16: 263-269.

106. Lee DH, Kim SD (1999) Mathematical Model for Batch Drying in an Inert Medium Fluidized Bed. Chem Eng Technol 22: 443-450.

107. Zhou SJ, Mowla D, Wang FY, Rudolph V (1998) Experimental investigation of food drying processes in dense phase fluidized bed with energy carrier. CHEMeca 98, port Douglas, North Queenslands, Australia.

108. Souraki BA, Mowla D (2008) Experimental and theoretical investigation of drying behavior of garlic in an inert medium fluidized bed assisted by microwave. J Food Eng 88: 438-449.

109. Uddin MS, Hawlander MNA, Hui X (2004) A Comparative Study on Heat Pump, Microwave and Freeze Drying of Fresh Fruits. In: Proceedings of the 14th International Drying Symposium, Sao Paulo, Brazil, 2035-2042.

110. Claussen IC, Ustad TS, Strommen I, Walde PM (2007) Atmospheric Freeze Drying-A Review. Drying Technol 25: 947-957.

111. Zielinska M, Zapotoczny P, Alves-Filho O, Eikevik TM, Blaszczak W (2013) A multi-stage combined heat pump and microwave vacuum drying of green peas. J Food Eng 115: 347-355.

112. Soyosal Y, Ayhan Z, Esturk O, Arikun MF (2009) Intermittent microwave-convective drying of red pepper: Drying kinetics, physical (color and texture) and sensory quality. Biosyst Eng 103: 455-463.

113. Alibas IL (2007) Microwave, air and combined microwave-air-drying parameters of pumpkin slices. Food Sci Technol-LEB 40: 1445-1451.

114. Kathirvel K, Naik KR, Gariepy Y, Orsat V, Raghavan GSV (2006) Microwave drying - a promising alternative for the herb processing industry. Canadian Society for Bioengineering, Paper No. 06-212, Edmonton, Alberta, 662-668.

115. Dolan JP, Scott EP (1994) Microwave freeze-drying of aqueous solutions. Advances in heat and mass transfer in biological systems. ASME - Heat Transfer Division, HTD 288: 91-98.

116. Zhang M, Tang J, Mujumdar AS, Wang S (2006) Trends in microwave-related drying of fruits and vegetables. Trends Food Sci Technol 17: 524-534.

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