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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 neutraceuticals. 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 was 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:

$$\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| e^{-j\delta} \quad (1)$$

where ε is the dielectric properties, ε' the dielectric constant (real part), ε" the dielectric loss factor (imaginary part), and δ dielectric loss angle (tanδ=ε"/ε').

The dielectric constant (ε') is associated to the material's capability to store electric energy (for vacuum ε'=1), while the dielectric loss factor (ε") 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

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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:

$$P = 1/2\,\omega\varepsilon_0\varepsilon_2\left|E_0^2\right| \quad (2)$$

Where ω is angular frequency (Hz), ε_0 is the permittivity of vacuum (F/m), ε_2 is the dielectric permittivity of medium, and E_0 is the electric field intensity (V/m), according to Ayappa and Davis [11].

Microwave heating conduce 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 (HTST) 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 NH_4^+) 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. Muftugil [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	$D_{50,55 \text{ and } 60°C}$ (conventional heating at 50-70°C)	*S. cerevisiae*	58, 25 and 10 s	[21]
	$D_{52.5,55 \text{ and } 67.5°C}$ (microwave heating at 700 W, 2450 MHz)		4.8, 2.1 and 1.1 s	
	$D_{55,60 \text{ and } 70°C}$ (conventional heating at 50-80°C)	*L. plantarum*	52, 22 and 8.4 s	
	$D_{57.5,,60 \text{ and } 62.5°C}$ (microwave heating at 700 W, 2450 MHz)		14, 3.8 and 0.79 s	
Glucose saline	$D_{55,60 \text{ and } 65°C}$ (conventional heating)	*E. coli K-12*	73, 18 and 3.0 s.	[24]
	$D_{55,60 \text{ and } 65°C}$ (microwave heating)		20, 8.3 and 2.0 s	
Foods	$D_{55°C}$ (conventional heating)	*S. aureus*	17.8, 2.4 and 3 min	[25]
	$D_{55°C}$ (microwave heating)	*S. typhimurium* and *E. coli*	11.6, 2.3 and 2.9 s	

Table 1: Changes in viable counts of microorganisms in liquid foods after microwave and conventional heating.

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]
			Vitamin C (mg/100 g$_{dry\ samples}$)	459.77 ± 0.77	
			Iron and Phosphorus (mg/100 g $_{dry\ samples}$)	4.19 ± 0.15 and 516.79 ± 39.24	
		Blanching by microwave (2450 MHz with 950 W for 3 min)	Protein , Ashes (%$_{db}$)	44.34 ± 1.92, 9.11 ± 0.45	
			Vitamin C (mg/100 g$_{dry\ samples}$)	565.56 ± 1.49	
			Iron and Phosphorus (mg/100 g$_{dry\ samples}$)	6.34 ± 1.49 and 905.48 ± 46.95	
	Green beans	Boiling water (100°C for 2 min)	Vitamin C retention (%)	84.7	[33]
		Microwave blanching (Domestic 650 W, 2450 MHz, for 60 s		88.5	
	Frozen spinach	Boiling water (90°C ± 2 for 3.5 min)	Vitamin C retention (%)	33.3	[30]
		Microwave blanching (pilot scale, 3990 W, 2450 MHz, 90 s)		59.1	

Table 2: Nutritive values of different food products after microwave and traditional blanching.

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. Microwave irradiation normally does not induce the Maillard reaction because of the short cooking times and low temperatures [42].

Substantial reduction in the energy consumption was observed with controlled cooking (using microwave oven) of unsoaked rice (14-24%) and presoaked rice (12-33%) compared with normal cooking [43].

Highly significant reduction in cooking time was observed with microwave cooking of legumes such as chickpeas and common beans. Microwave cooking with sealed vessels enabled a drastic reduction in cooking time, from 110 to 11 min for chickpeas and from 55 to 9 min for common beans, compared with conventional cooking [44].

In a study carried out by Arab et al. [45], differences in chemical composition of chickpea flour before and after cooking are significant using different cooking treatments, namely cooking on a hot plate for 90 min, microwave cooking with power level 10 for 5 min, and frying in corn oil at 170°C for 1 min. The obtained data shows that the fat and ash contents in chickpea cooked by microwave were decreased by 8.90 and 6.97%, respectively, compared with the traditional cooking practice (8.01 and 5.76%). Such decrease might be due to their diffusion into cooking water [46]. However, 51.89 and 40% increase in crude fiber content was observed with microwave and traditional cooking treatments, respectively. Table 3 summarizes the percentage of major 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 Schlich [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
Cooking	Green peas	Boiling water (100°C for 12 min)	β-Carotene retention (%)	101.3	[34]
		Microwave blanching (domestic 700 W, 2450 MHz, 6.5 min)		102.3	
	Rice	Microwave blanching (domestic 700 W, 2450 MHz, 6.5 min)	Protein, Fat and Ash (%)	6.83 ± 0.22, 2.12 ± 0.18 and 1.37 ± 0.03	[35]
		Microwave cooking (Heated for 25 min and simmered for 5 min)	Protein, Fat and Ash (%)	8.49 ± 1.26, 2.45 ± 0.09 and 1.42 ± 0.01	
		Steaming (cooked for 30 min)	Protein, Fat and Ash (%)	8.05 ± 0.28, 2.42 ± 0.04 and 2.11 ± 0.29	
	Chickpea	Boiling (100°C for 90 min)	Riboflavin, Thiamin, Niacin and Pyridoxine (%)	48.46, 33.82, 4.33 and 57.19	[36]
		Microwave cooking (2450 MHz, for 15 min.)	Riboflavin, Thiamin, Niacin and Pyridoxine (%)	58.46, 42.35, 13.94 and 80.42	
		Autoclave cooking (121°C at 15 lb for 35 min)	Riboflavin, Thiamin, Niacin and Pyridoxine (%)	52.12, 35.51, 5.14 and 65.69	
	Chickpea	Traditional cooking (soaking, cooking on a hot-plate for 90 min)	Fat, Ash and Fiber (%)	5.17 ± 0.75, 3.11 ± 0.28 and 2.59 ± 0.12	[37]
		Microwave cooking (2450 MHz with power 10 for 5 min)	Fat, Ash and Fiber (%)	5.12 ± 0.78, 3.07 ± 0.22 and 2.81 ± 0.14	
		Traditional cooking	Major minerals (K, Ca. Na and Mg)	298.27, 109.20, 100.40 and 145.31	
			Minor heavy metals (Cu, Fe and Zn) (mg/100 g)	0.64, 5.96 and 2.97	
		Microwave cooking	Major minerals (K, Ca, Na and Mg)	377.85, 114.58, 103.21 and 151.31	
			Minor heavy metals (Cu, Fe and Zn) (mg/100 g)	0.82, 6.38 and 3.45	
	Pepper fresh	Cooking (Boiling) (100°C on a hot pot for 6 min)	Minerals (g/100 g)	0.35	[38]
		Microwave cooking (450 to 850 W for 3 min)		0.43	
	Pepper frozen	Cooking (Boiling) (on a hot pot for 12 min)	Minerals (g/100 g)	0.22	
		Microwave cooking (450 to 850 W for 3 min)		0.38	

Table 3: Nutritive values of different food products after microwave and traditional cooking.

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]. Goedeken 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 pregelatinized starches could bind a greater amount of water inside food [55]. Also, the most of starches, except amylomaize, 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's 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 (MSD). 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]. Malafronte 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 (cm^3), Weight loss (g/100 g)	88.4 ± 5.5, 9.8 ± 2.0	[39]
			Luminosity (L), Weight (g)	82.8 ± 0.4, 40.6 ± 0.95	
			Moisture (g/100 g), Water activity and Density (g/cm^3)	36.2 ± 0.3 and 0.93 ± 0.005, 0.46 ± 0.02	
		Double-cycle microwave-baked (2450 MHz, with 1000 W) and 10 power levels)	Volume (cm^3), Weight loss (g/100 g)	98.3 ± 6.2, 19.3 ± 1.0	
			Luminosity (L), Weight (g)	84.5 ± 0.4, 36.3 ± 0.42	
			Moisture (g/100 g), Water activity and Density (g/cm^3)	21.3 ± 0.67, 0.87 ± 0.004 and 0.37 ± 0.02	
	Madeira cake	Convective-baked at (200 ± 1°C)	Springiness (%), Firmness (N)	42.7, 3.21	[40]
			Moisture content (kg/kg_{db})	0.315	
		Microwave-baked (domestic microwave at 2450 MHz with power 100 to 900 W)	Springiness (%), Firmness (N)	46.7, 2.52	
			Moisture content (kg/kg_{db})	0.329	
	Bread	Conventional-baked (preheating to the set temperatures (175, 200 and 225°C for 12, 13 and 14 min)	Weight loss%, Specific	4.06, 1.60	[41]
			Volume (ml/g)		
			Firmness (N), color change (*ΔE*)	0.67, 47.7	
		Microwave baked 50% power for 2 min and 100% power for 1 min)	Weight loss%, Specific	10.80, 2.04	
			Volume (ml/g)		
			Firmness (N), color change (*ΔE*)	2.88, 3.0	

Table 4: Physical properties of different food products after microwave and traditional baking.

Foodstuff	Treatment	Parameter	Quantities	Reference
Seedless grapes	Microwave oven followed by hot air cabinet dryer (microwave of 900 W for 1 min and followed by hot air at 70°C for 30, 60 and 120 min	Average Specific energy consumption (MJ/ $kg_{water\ evaporated}$)	320.6	[72]
	Hot air cabinet dryer followed by microwave oven (70°C for 30, 60 and 120 min and followed by microwave of 900 W for 1 min.)		371.0	
	Hot air cabinet dryer only (70°C for 60 min)		564.5	
Pumpkin slices	Air oven drying (50 and 75°C for 45-90 min)	Energy consumption (kW h)	0.61-0.78	[113]
	Microwave drying (Domestic microwave with 160 and 350 W for 125-195 min)		0.24-0.26	
	Combined microwave- air-drying for 31-51 min (160 W-50°C, 160 W-75°C, 350 W-50°C and 350 W-75°C)		0.33-0.40	

Table 5: Energy consumption values for various drying methods.

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 $MJ/kg_{water\ evaporated}$ was observed with microwave-drying among three different methods used. On the other hand, the value of energy consumption during grapes drying by hot air cabinet stood at 564.5 $MJ/kg_{water\ evaporated}$, 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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