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Properties of the drying of agricultural products in microwave vacuum: A review article

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Drying is ancient process used to preserve foods. Conventional drying (hot air) offers dehydrated products that can have an extended life of a year. Unfortunately, the quality of a conventionally dried product is drastically reduced from that of the original foodstaff. Before industry accepts a new technology like processing in microwave vacuum drying (MVD), it must be proven to provide these benefits in the area of processing where drying of a product is not the primary concern. The idea to combine fast heating of microwave and low temperature processing of vacuum has been investigated by a number of researchers. It was found that the vacuum-microwave drying that is an alternative way to improve the quality of dried products. The comparison of both preservation processes, hot air and superheated steam drying, was done for taking into account several important characteristics such as Drying rate, Retention of chemical components and new improvements. An updated bibliographic research served to investigate and compare drying processes for food product such as Carrots, Banana, Apple and Garlic. Theoretical results, from several years of research in the subject, were presented and compiled in order to support conclusion.

Key words: drying, microwave vacuum, Carrots, Banana, Apple, Garlic

Introduction

Several types of dryers and drying methods have to be developed and adapted for each specific situation, and to be commercially applicable. There are several types of drying methods that can be divided according to many factors, such as pressure (atmospheric, subatmospheric), type of unit operation (continuous, batch, semicontinuous), temperature (freeze drying, hot air convective) and many others.

As indicated by Jayaraman and Das Gupta (1992) and Somogyi and Luh (1986), there are three basic types of drying processes:

1. Sun drying and solar drying.
2. Atmospheric dehydration including:

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- Stationary or batch processes (kiln, tower and cabinet dryers).
- Continuous processes (tunnel, continuous belt, belt-through, fluidized bed, explosion puffing, foam-mat, spray, drum and microwave-heated dryers).

3. Subatmospheric dehydration (vacuum shelf, vacuum belt, vacuum drum and freeze dryers).

In industry, it is imperative to know what we dry and what we want to attain. This is a prerequisite for the appropriate choice of dryer and drying conditions. Numerous experiments have to be performed, for example establishing the data required for planning, investigation of the efficiency and capacity of existing drying equipment, analysis of the effect of operational conditions on the shape and quality of the product, and considerable study of the drying mechanism for particular product. It is unacceptable to use solar dryer in northern hemisphere where number of sunny days is not sufficient or to dry liquids like fruit juices in the cabinet drier. Conventional drying of foods is a very slow process, reaching in some cases more than one day. There are many suggested improvements based on upgrading of drying operation, but few of them are in reality applied in industry (Ratti and Mujumdar, 1996). According to Ratti and Mujumdar (1996) there are three main advantages of microwave heating:

Microwave heating has profound penetrating value that is of indisputable quality, leading to uniform heating of water all over the material depth. Selective adsorption of energy by water, without dangerous heating of material. Rapid response of water to heating, subsequently the control of process itself is easier. Microwaves are the portion of election of electromagnetic spectrum between far infrared and the conventional radio frequency region. Radiation with frequencies between 300 MHz and 300 GHz (with wavelengths ranging from λ=1 mm to 1 m) are microwaves, and the heat that they cause microwave heating (Sanga *et al*., 2000). Microwave are convenient method to combine with other methods of drying, such as air drying, heat pump (Jia *et al*., 1993) or vacuum application, but factors such as dielectric coefficient, shape of the material and its moisture have to be considered while drying a food by microwave method (Barbosa-Canovas and Vega-Mercado, 1996).

The main purpose of vacuum drying is to enable the removal of moisture at lower temperature than the boiling point under ambient condition (Fig. 1). Water is boiling on 1 bar at 100°C, but if the pressure is lowered to 40 mbar, boiling temperature will be 28.96°C (Moran and Shapiro, 1996). The important feature of vacuum drying is virtual absence of air during dehydration, which makes this process attractive for drying of material that may deteriorate and/or be chemically modified as a result to air or high temperature exposure.

Compared to direct dryers, in whom the product is in direct contact with the drying medium, the vacuum dryer has a lower maximum drying temperature (Barbosa-Canovas and Vega-Mercado, 1996). All systems that have vacuum application consist of four main parts: vacuum chamber, heat supply, vacuum producing unit (pump) and device to collect water vapour (desiccators or condenser). Because of the high installation and operating cost, vacuum dryers are used only for high-value materials and to dry materials with low final moisture (Somogyi and Luh, 1986). Vacuum treatment is also useful in combination with some other processes, such as microwaves, osmotic dehydration (Argaiz *et al.*, 1994), or as a finishing drying method.

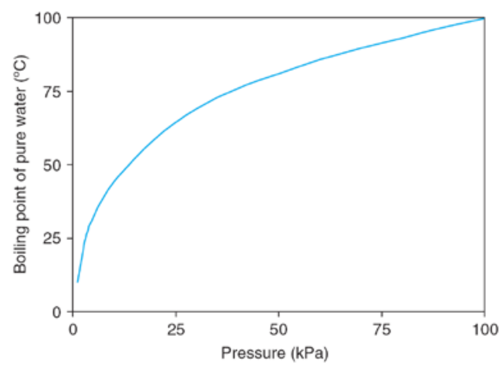

Fig. 1. Relationship between pressure and the boiling point of water.

The idea to combine fast heating of microwave and low temperature processing of vaccum has been investigated by a number of researchers. The results show that the vacuum-microwave drying is an alternative way to improve the quality of dried products. It has been used successfully for several products such as orange powder, cranberries, potatoes, bananas, and carrots (Attiyate 1979; Yongsawatddigul and Gunasekaran, 1996; Kubota *et al*., 1992; Drouzas and Schubert, 1996; Tein *et al*., 1998).

The main objective of this study is to review the research and development on microwave vacuum drying for food and agricultural products. It is hoped that this review may be useful for future development work.

Principle of microwave drying

Wavelengths of microwave range from 1 mm to 1m, corresponding to a frequency range of 300 MHz to 300 GHz (Sanga *et al*., 2000). The foundation of the electromagnetic wave theory was laid down by Maxwell in 1864 when he formulated equations describing electromagnetic phenomena. Hertz provided the first experimental proof of the existence of electromagnetic waves in 1888. Electromagnetic radiation was first used for communication (radio, radar, and television) in 1894 (Stuchly and Stuchly, 1980). Nowadays, many diversified applications of electromagnetic radiation are employed and are being studied extensively. Since a conventional dryer is limited by heat transfer to the core of product and mass transfer of water out of the material (Mujumdar and Menon, 1995), it would be expected that microwave drying would perform more uniformly and faster due to the volumetric heating. In microwave drying, heat is generated by directed transforming electromagnetic energy into kinetic molecular energy, thus the heat is generated within the material. Microwave drying has gained popularity as an alternative drying method in the food industry because it is rapid and energy efficient compared to conventional hot-air drying (Decareau and Peterson, 1986). During microwave heating, heat is generated by dielectric materials that absorb microwaves, but materials that are reflectors will not be heated directly. It is distinct from conventional drying which is driven by the difference in temperature between the outside and inside of the material. Microwave drying is not governed by temperature gradients but the heat arises from the oscillation of molecular dipoles and movement of ionic constituents respectively in response to alternating electric fields at high frequency. The resulting energy is absorbed throughout the volume of the wet material. The increase in internal pressure drives out the moisture from the interior to the surface of the material (Sanga *et al.*, 2000).

The property of the materials that defines their interaction with electromagnetic fields is the electric permittivity (ε). The electric permittivity defines the material behavior in the electric field, and consists of a real part, (ε') called the dielectric constant, and an imaginary part, called the loss factor (ε") (Stuchly and Stuchly, 1980). This can be represented by Equations 2.1 and 2.2.

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad \ldots\ldots\ldots\ldots\ldots(2.1)$$

$$\tan \delta = \varepsilon''/\varepsilon' \qquad \ldots\ldots\ldots\ldots\ldots(2.2)$$

Where $j=\sqrt{-1}$, which indicates a phase shift between the real (ε') and imaginary (ε") parts of the dielectric constant (Schiffmann, 1995). The dielectric constant (ε') governs the electromagnetic field distribution within the material and provides a measure of how easily energy can be stored by material. The loss factor (ε") describes the loss interactions and determines how easily energy can be dissipated into the material (Sanga *et al.*, 2000). These properties can be measured at various frequencies, and they are not constant; they are dependent on the temperature, moisture content, composition and particle density of the material. The dielectric properties of fruits and vegetables are shown in Table 1. The two basic physical phenomena that contribute to large values of the loss factor and that are responsible for the heating effect at microwave frequencies are ionic conduction and dipolar rotation. At room temperature, when an electric field is applied to a material containing ions, the ions spontaneously break down and collide with other molecules, and the kinetic energy is conversion process in which electric field energy is converted into a kinetic energy of the ion moving in a defined direction, and then the kinetic energy is converted into heat through multiple collisions (Stuchly and Stuchly, 1980). While there are a number of advantages of microwave drying over convection drying. Simultaneously, some limitations are also found in the process. Microwave heating and drying present the following advantage over conventional thermal heating/drying method (Mullin, 1995; Sanga *et al*., 2000; Tulasidas, 1994; Venkatachalapathy, 1998; Beaudry, 2001; Sunjka, 2003; Liang *et al*., 2003).

Table 1. Dielectric properties of fruit and vegetables at 23°C (Venkatesh and Raghavan, 2004).

Fruits and Vegetables	MC, % (w.b.)	Dielectric constant (ε') Frequency		Dielectric loss factor (ε") Frequency	
		915 MHz	2450MHz	915MHz	2450MHz
Apple	88	57	54	8	10
Avocado	71	47	45	16	12
Banana	78	64	60	19	18
Cantaloupe	92	68	66	14	13
Carrot	87	59	56	18	15
Cucumber	97	71	69	11	12
Grape	82	69	65	15	17
Grapefruit	91	75	73	14	15
Honeydew	89	72	69	18	17
Kiwifruit	87	70	66	18	17
Lemon	91	73	71	15	14
Lime	90	72	70	18	15
Mango	86	64	61	13	14
Onion	92	61	64	12	14
Orange	87	73	69	14	16
Papaya	88	69	67	10	14
Peach	90	70	67	12	14
Pear	84	67	64	11	13
Potato	79	62	57	22	17
Radish	96	68	67	20	15
Squash	95	63	62	15	13
strawberry	92	73	71	14	14
Sweet potato	80	55	52	16	14
Turnip	92	63	61	13	12

Heating is instantaneous due to radiative energy transfer, hence the surface-to-centre conduction stage is largely eliminated. Moreover, rapid, efficient and accurate control of heating rates can be achieved by controlling the output power of the generator. During conventional drying, moisture is initially evaporated from the surface while the internal water diffuses to the surface slowly. Under microwave drying, internal heat generation leads to an increase in internal temperature and vapour pressure, both of which promote liquid flow towards the surface, thus increasing the drying rate. More of the applied energy is converted to heat within the target material, because transfer of energy to the air, oven walls, conveyor, and other parts is minimal given their low dielectric constants. This can result in significant energy savings. Drying time can be shortened by 50% or more, depending on the products and the drying conditions.

Microwave drying equipment occupies less space and reduces handling time. Microwave drying improves product quality and, in some cases, eliminates case hardening, internal stresses, and other problems of quality such as cracking. The exposure to high temperature is shorter, resulting in less degradation of heat-sensitive components such as vitamins and proteins. Microwave can be conveniently combined with other methods of drying, such as hot air drying, freeze-drying, and the application of a vacuum. However, microwave-drying systems are not without disadvantages (Sanga *et al*., 2000). These disadvantages can be summarized as follows:

High initial cost for purchase and installation

Possible aroma loss in microwave-dried juice-powder and color change due to charring or scorching

Possible physical damages caused by localized areas of continually rising temperature

Specific sample sizes and shapes of products are usually required because of microwave's limits on penetration

Microwave vacuum drying

Microwave vacuum drying (MVD) systems are normally used for materials that can be damaged or decomposed at low temperature. Drying takes place at reduced boiling points that is achieved at low pressures. Rate of heat transfer is significantly increased when microwave energy is used compared to conventional heating where thermal convection is very low (Jones and Rowley, 1996). Higher electric field strengths normally would give rise to glow discharges or electrical arcing in the cavity. Materials to be dried are in the paste from spread on a conveyer belt and passed through a special applicator at a vacuum of between 1 to 20 torr. The microwave dryers are already in commercial use for production of fruit juice concentrates, tea powder and enzymes (Schiffmann, 1995). Most pharmaceutical products are heat sensitive. The products are of high moisture content and sometime contain a mixture of solvents and demands intensive drying. To avoid damage and degradation of product quality, local overheating and irreversible changes that might occur, pharmaceutical industries use MVD process. MVD is employed in the manufacture of table granulation (Jones and Rowley, 1996; Schiffmann, 1995). The systems are employed in the drying mixture of water, ethanol, or aceton and at relatively low temperature as compared to conventional drying.

Drying rate

The combination of vacuum and microwave allows solid food pieces to be dried more rapidly than with any other method, while maintaining the product temperature relatively low during most of the process. A comparison of the drying curves of replicate batches of 3 mm thick carrot slices treated by three drying technologies illustrates the rapid dehydration rate that can be achieved using MVD (Fig. 2) (Lin *et al*., 1998). Freeze-drying required approximately 3 days to reach the end point of 9.9 percent moisture (dry basis), air-drying required 8 hours, while MVD required 33 minutes. Drying time becomes a controllable variable in MVD, determined predominantly by the ratio of microwave power to the amount of water to be evaporated. Therefore, to increase the rate of drying, either the load size can be reduced or the microwave power can be increased. For example, drying avocado, mushroom and strawberry pieces at high power (850 W) versus low power (425 W) resulted in a faster drying rate and also higher rehydration rates for the dried product (Pappas *et al.*, 1999). Limitations are imposed only by the microwave power density (W/kg) within the chamber and the limits of microwave penetration into the load of wet food material. Excessively high power density may cause microwave arcing or plasma discharge in the vacuum chamber, particularly if the load of microwave absorbing material in the chamber is small. In practical terms, power densities greater than 10 000 W/kg frequently leads to arcing in moderate vacuum systems where absolute pressure is 4–10 kPa. In addition to microwave power and load size, chamber pressure can affect the rate of drying. For dehydration to occur, it is necessary to supply energy to raise the product temperature to the boiling point of water and to provide the latent heat of water vaporization. As pressure is decreased, the latent heat of vaporization increases slightly. This contributes to a slight decrease in the rate of drying at the same microwave power.

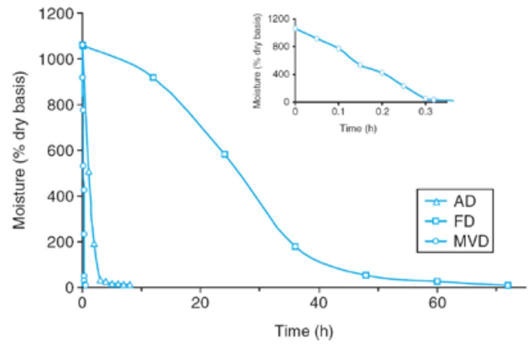

Fig. 2. Dehydration curves of air-dried (AD), microwave vacuum dried (MVD) and freeze-dried (FD) carrot slices. Inset: Expanded dehydration curve of microwave vacuum-dried carrot slices.

However, the lower the pressure in the drying chamber, the greater the driving force for water vapour diffusion from the product (Wei *et al.*, 1985). Therefore, moisture may be removed more rapidly at a lower operating pressure. The relative magnitude of these two opposing effects may depend on the configuration of the equipment used for the dehydration, as well as the characteristics of the sample. Cui *et al*. (2004) showed a slight positive relationship between chamber pressure and dehydration rates of thin carrot slices using equipment where the product was rotated but not thoroughly mixed. Under these conditions, the driving force of the pressure differential between the inside of the chips and the chamber may be less important than the influence of drying temperature which was increased with lower chamber pressure. However, there are many reports that document an inverse relationship between chamber pressure and drying rate (Wadsworth *et al*., 1990; Kiranoudis *et al.*, 1997; Drouzas *et al*., 1999; Lin *et al*., 1999; Pappas *et al*., 1999), suggesting that the pressure differential between the water vapour in the tissue and the drying chamber is the dominant effect. Kiranoudis *et al*. (1997) modelled the effects of microwave power (425–850 kW) and chamber pressure (2–7 kPa) on the drying kinetics of three different fruits (apple, kiwi, pear), in equipment where the product was static. Their results showed that microwave power had a direct relationship with the drying rate, while chamber pressure had a relatively minor and slightly negative effect. During dehydration of parboiled rice, the effect of pressure on drying rate was more pronounced at lower power levels (Wadsworth *et al.*, 1990). This was interpreted as an indication that the adsorption/ desorption rate of water on the surface of the sample was more important in determining the overall drying rate, rather than the diffusion rate of water to the surface. Drouzas *et al*. (1999) found that the drying rate constant increased significantly with decreasing pressure between 5 and 3 kPa and increasing microwave power from 640 to 710 watts. However, it was noted that the equipment and operating costs associated with the higher vacuum may not be justified for all products.

Retention of chemical components

Flavour, colour, nutrient, or other biologically active chemicals that are sensitive to thermal or oxidative degradation typically exhibit better retention after microwave vacuum-drying compared to air-drying (Table 2). Several studies with herbs have demonstrated enhanced retention of flavour volatiles. MVD sweet basil (*Ocimum basilicum* L.) retained 1.5 times more methylchavicol and 2.5 times more linalool, compared to samples air-dried at 48°C (Yousif *et al.*, 1999). The colour and rehydration rate of the MVD samples were superior to the air-dried product. Similarly, thymol, a key character impact compound in oregano (Lippia berlandieri Schauer) was significantly higher in microwave vacuum dried samples than in air-dried products and similar to fresh and freeze-dried samples (Yousif *et al*., 2000). However, four other volatiles (β-myrcene, β-terpinene, γ-terpinene and ρ-cymene) showed no difference in retention between air-drying and MVD. In another study, parsley dried by air or pulsed MVD was evaluated for colour, essential oil content and aroma by a sensory panel (Bohm *et al*., 2002). The microwave vacuum dried product was rated as having better colour and aroma than the air-dried and the essential oil content was approximately 94 per cent of the fresh content, while air-dried retained only 30 percent.

Processing of food products in superheated steam

Processing in microwave vacuum may impart physical changes upon the product in addition to any drying that may take place. These changes may be unique to microwave vacuum and may not be achieved any other way.

Carrots

The effect of blanching of the raw material on the properties of carrots obtained by various methods of drying was investigated by Mazza (1983) and Prakash *et al*. (2004). It was found that blanching of carrots before convective drying significantly affected the transport of moisture and the product quality (Mazza, 1983). Carrot dried in a fountain bed is characterised by better colour, better rehydration properties, and better retention of b-carotene compared to carrots dried by microwaves or by convection (Prakash *et al*., 2004).

Table 2. Retention of labile chemical components.

Reference	Source material	Chemical component	Retention	
			Air-dried	Microwave vacuum-dried
Bohm *et al.* (2002)	Parsley	Essential oils	30%	93%
Cui *et al.* (2003)	Garlic	Pyruvate[c]	54%	89%
Cui *et al.* (2004 b)	Carrot slices blanched	Total carotenes	86%	95%
	Carrot slices unblanched	Total carotenes	71%	96%
	Chiness chive	Total chlorophyll	38%	97%
Durance *et al.* (2000)	St John's wort	Hypericin	35[a]	45[a]
Kim *et al.* (2000a)	Echinacea purpurea flowers	Chicoric acid	254[a]	1120[a]
		Caftaric acid	61[a]	176[a]
Kim *et al.* (2000 b)	E. purpurea flowers	Alkamides	285[a]	307[a]
Kwok *et al.* (2004)	Saskatoon berries	Anthocyanins	50[a]	149[a]
	Thiessen variety	Phenoliecs	640[a]	890[a]
Lin *et al.* (1998)	Carrot slices	Ascorbic acid	38%	79%
		A + β carotenes	81%	97%
Mui *et al.* (2002)	Banana chips	Flavor volatiles	4.0[d]	6.4[d,e]
Vaghri (2000)	Blueberries	anthocyanins	198[a]	498[a]
	Hardy blue variety	Phenolics	2150[a]	3350[a]
		Ascorbic acid	ND[b]	7.5[a]
Yousif *et al.* (1999)	Sweet basil	Linalool	62[d]	157[d]
		Methylchavicol	65[d]	96[d]
Yousif *et al.* (2000)	Oregano	Thymol	23[d]	30[d]

[a]mg/100 g dry weight; [b]ND = not detectable; [c]enzymatically generated pyruvate as a measure of pungency; [d]relative peak area; [e]90% air dried _ 10% microwave vacuum dried.

Ghosh *et al.* (2004) examined the kinetics of mass exchange during the osmotic dehydration of carrot slices. They applied three different salt concentrations: 5%, 10% and 15%. The ratio of the raw material mass to that of the solution was 1:5. The decrease in the carrot moisture during dehydration varied nonlinearly, and was higher in the first stage of the process for all the solution concentrations than in the subsequent time intervals. A model was proposed that predicted the level of the total mass exchange, based on the experimental data acquired during the short time of osmotic dehydration. The possibility of using combined drying methods for food products was also examined. Litvin *et al*. (1988) dehydrated carrot slices by sublimation down to a 40% moisture content. They also applied microwaves for 50 s, and obtained a final moisture content of 5% by convective drying. They did not find significant differences in the colour of the product, the drying shrinkage, or in the rehydration properties between the combined method and the sublimation method. Studies on the kinetics of MVD of carrot slices were conducted by Zheng-Wei Cui *et al*. (2004). They proposed a theoretical model based on energy conservation of the sensible head, latent heat and source head of microwave power. The model was subjected to verification based on experimental data. The best fit was obtained at a dry-basis moisture content of 2%. The lower the water content, the greater the difference between the experimental data and the values calculated on the basis of their theoretical model. Wang and Xi (2005) performed investigations that allowed to determine the drying characteristics and to assess the quality of a product obtained as a result of a two-stage microwave drying. With decreasing thickness of the samples the energy consumption in the process decreased and the dehydration rate increased. The thickness of the carrot slices and the energy consumed in the first and second microwave drying stages significantly affected the content of b-carotene and the degree of dry mass rehydration. Tein *et al*. (1998) compared dried carrot slices using MVD with air and freeze drying on the basis of rehydration potential, colour, density, nutritional value and textural properties. Microwave vacuum dried carrot slices had higher rehydration potential, higher b-carotene and vitamin C content, lower density and softer texture than those prepared by air drying. Although freeze drying of carrot slices yielded a product with improved rehydration potential, appearance and nutrient retention, the microwave vacuum drying of carrot slices was rated as equal to freeze dried. Similar results were reported by Regier *et al*. (2005), where microwave vacuum dried carrots had the highest carotenoid retention compared to freeze-drying and convection-drying.

Banana

Vacuum drying of banana slices was studied in a domestic microwave oven by Mousa and Farid (2002). They show that banana temperature rises uniformly and rapidly to the saturation water vapor temperature corresponding to the vacuum used then rises slowly until most of the free moisture is lost. The thermal and drying efficiencies were found to drop from almost 100% at the beginning of the drying (high moisture content) to as low as 40% and 30% respectively at the end of drying. Both efficiencies were found to increase with the use of vacuum, especially at low moisture content. Retention of volatiles in banana chips was evaluated using a combination of airdrying and MVD (Mui *et al*., 2002). Chips were first air-dried to remove 60, 70, 80 or 90 per cent moisture (wet basis) and then subjected to MVD to 3 per cent moisture (dry basis). Samples that underwent more airdrying and less MVD, had higher levels of volatile compounds. This was attributed to the increased formation of an impermeable solute layer on the surface of the chips that may have reduced the volatile loss. However, banana chips that were exclusively air-dried had volatile levels significantly lower than the 90 percent air-dried/microwave vacuum-drying samples, attributed to volatile loss during the relatively long drying time. Krokida and Maroulis (1999) investigated the effect of microwave and microwave-vacuum drying on some quality properties such as density, porosity, color and viscoelastic behavior of dehydrated apple, banana, carrot and potato. It was concluded that microwave drying and moreover MVD tends to increase the product porosity and to prevent the color damages during drying. Microwave drying seems to decrease the maximum stress and maximum strain of dehydrated products, while it increases their elasticity and decreases their viscous nature.

Drouzas and Schubert (1996) investigated MVD of banana slices experimentally. This type of drying procedure is preferable to conventional drying techniques in order to avoid product degradation due to high temperatures encountered in convective drying. The drying process was examined by introducing pulse-generated microwave power in banana samples. The material temperature was monitored. Temperature peaks in the last stages of drying indicated that drying could be favoured if temperature was maintained below a maximum level, so that the final product should not be burned by hot spots during microwave drying. This procedure produced dehydrated products of excellent quality as examined by taste, aroma, smell and rehydration tests. The moisture content of some fruits and vegetables including apples, pears, strawberries, bananas, and avocados, potatoes, carrots, onions, lettuce, and cabbage, was determined using a microwave oven by Wenceslao (1988). The effect of sample weight was studied and the results were compared with those obtained by conventional and vacuum oven drying methods. For 20-g minced samples of fruits and vegetables, these three methods yielded equivalent results, but usage of a microwave oven substantially shortened the drying time required (30 minutes versus 15 hours).

Apple

Taking the main factors of apple processing by MVD into account, such as microwave power, vacuum level and initial moisture content, the predicted second-order regression model of the sensory quality of microwave vacuum dried apple slices was obtained according to the experimental data by using orthogonal rotatable central composite design, and effects of these variables and their interaction on the product quality were analyzed by response surface method (Han *et al*., 2009). To acquire higher quality of product, the ideal processing range of microwave power, vacuum level and initial moisture content were determined as 10.6-12.7 W/g, 0.083-0.094 MPa and 0.6-0.9 respectively. The optimal drying condition was found at microwave power 11.7 W/g, vacuum level 0.089 MPa and initial moisture content 0.75, with the maximum predicted sensory quality mark as 9.51, and the experimental validated mark as 9.42. The results prove that the regression model agrees well with the MVD process. Cui *et al*. (2008) investigated a combination of microwave-vacuum drying and freeze drying as potential means for drying carrot and apple chips. The sample was first dried by microwave-vacuum to dehydrate some amount of internal free water and then by freeze drying to a final moisture content of less than 7% (wet basis). Chemical properties (carotene and vitamin C retention) and physical properties (shrinkage, color, texture, and rehydration ratio) of carrot and apple slices dried by this method were evaluated and compared with those dried by freeze drying alone, MVD alone, and conventional hot air drying, respectively. The comparison showed that the carotene retention of carrot slices and the vitamin C retention of apple slices dried by the current method were close to those of freeze-dried carrot and apple slices and much better than those of conventional hot air-dried ones. The samples prepared by the current method exhibited very close rehydration capacity, color retention, and texture with those of the freeze-dried ones but with a little higher shrinkage. However, the samples still showed the attractive external appearance without marked warp.

The influence of air temperature, microwave application and vacuum impregnation or pulsed vacuum osmotic dehydration, as pre-treatments undertaken prior to convective drying, on the drying kinetics of apple and strawberry was studied by Contreras *et al.* (2008). Furthermore, the effect of the above pre-treatments on the optical and mechanical characteristics of dried samples was also investigated. Empirical equations (linear and page) were used to assess the effect of these factors on drying kinetics, with a good fit being observed between experimental data and model. The effect of microwave on the decrease in drying time was significantly greater than the effect of increasing the air temperature. A dehydrated product with less color change and a more rigid and firmer structure was obtained at higher air temperature or when applying microwave. However, the higher temperatures during microwave treatment increased pigment degradation. The increase in the liquid phase volume occurring with pre-treatments prolonged the convective drying time process and also implied greater colour changes in the samples. Nevertheless, they enhance the resistance to deformation and fracture of the dehydrated product. Compared with the convective air drying, the drying capacity, energy consumption, sensory quality, vitamin C content and scanning electron microscope of apple slices by MVD and puffing were analyzed by Han *et al*. (2008) systematically. They showed that, compared with the convective air drying, drying capacity of microwave vacuum was increased by 48.46% and energy consumption per kilogram water was decreased by 32.32%. The apple slices had better texture and flavor, more honeycomb network structure and larger pores, and the reservation rate of vitamin C content was 15.8% higher than that of air dried. The effects of microwave power, vacuum level, thickness of apple chips and the moisture content of pretreated apple chips on the drying characteristics and the expansion ratio were determined by Han *et al*. (2006). Furthermore, a group of optimum processing parameters were obtained, at microwave power of 12.0 W/g with absolute pressure of 15 kPa, the thickness of apple chips was 8 mm and the moisture content of pretreated apple chips was 37.5%, while apple chips were dried and puffed for 4 min, the expansion ratio reached its maximum and it was 321%. Contreras *et al*. (2005) dried apple slices, both vacuum impregnated (VI) with an isotonic solution and non-vacuum impregnated (NVI), at 30 and 50°C air temperature, with and without microwave application (0.5 W/g). MW application resulted in an increased water-soluble pectin fraction, especially in VI samples, ranging from 0.313 to 0.390 (expressed as g galacturonic acid/100 g fresh sample). The MW dried slices had a harder texture when dry (water content lower than 10 g water/100 g sample), but softer when rehydrated (to saturation): MW application also implied a slight increase (about 2°C) of glass transition temperature (Tg) in the samples, especially in the NVI samples. In contrast to the NVI samples, in which Tg changes from about 4 to 32°C when water activity increases from 0 to 0.22, the VI ones showed a very slight water plasticization effect (mean Tg 40°C). The changes in T g could be explained by the increase in the soluble pectin in the aqueous phase of the fruit during drying. There was no correlation between the mechanical properties and Tg.

Garlic

Whole garlic cloves, halved and sliced were subjected to MVD at three microwave power levels: 240, 480 and 720 W (Figiel, 2009). The process of drying was described by a sigmoid function. Slicing the cloves prolonged the time of drying. An increase in microwave power resulted in increased drying rate. The temperature of garlic samples measured in a vacuum flask amounted to 50 °C till the moisture content of 0.6 g/g dry matter. Further drying of garlic was associated with temperature increase to about 70 °C. Decreasing moisture content, till 0.6 g/g dry matter, was accompanied by decreasing relative volume of the dried material. On exceeding this value no further change in volume of the slices was observed, though for whole cloves and halves a marked increase in volume was observed. Lowering of moisture content below 0.6 g/g dry matter and increasing microwave power caused an increase in garlic cloves compressive strength. Increasing the degree of the material subdivision and microwave power resulted in increased water absorption capacity. Drying the garlic samples with the VM made the color brighter, shifting it towards red and blue, compared to fresh garlic cloves. The best retention of volatile oils was observed for garlic slices dehydrated with microwaves at 720 W.

Li *et al*. (2007) prepared garlic powder with high allicin content using microwave-vacuum and vacuum drying as well as microencapsulation in order to protect alliinase activity throughout the human stomach and improve the ratio of alliin transforming into allicin. The results showed that the optimal MVD condition was drying for 3 min under the microwave output power 376.1 W, then 282.1 W for 3 min, followed by 188.0 W for 9 min, and finally for 3 min under the output power 94.0 W. The thiosulfinates retention after drying was 90.2%. Following drying, garlic powder was microencapsulated by modified fluidized bed technique. Scanning electron microscope revealed good integrity and core materials that were embedded in microcapsules. Studies on the release kinetics of microencapsulated garlic granulates in vitro using simulated intestinal fluid indicated that release of garlic powder could be controlled in intestine by passing through human stomach conditions. Li and Xu (2007) also, prepared Garlic powder with high allicin content using microwave-vacuum and vacuum drying as well as microencapsulation to protect alliinase activity throughout the stomach and improve the ratio of alliin transforming into allicin. The results showed that the optimal drying condition was 376.1 W for 3 min, 282.1 W for 3 min, 188 W for 9 min, and 94 W for 3 min. The thiosulfinates retention after drying was 90.2%. Following drying, the garlic powder was microencapsulated by modified fluidized bed technique. Scanning electron microscope revealed good integrity and core materials that were embedded in the microcapsules. Studies on the release kinetics of microencapsulated garlic granulates in vitro using simulated intestinal fluid indicated that release of garlic powder could be controlled in the intestine by passing stomach conditions.

Combination of microwave-vacuum drying and air drying was investigated as a potential mean for drying garlic slices by Cui *et al*. (2003). The sample was dried by microwave-vacuum until the moisture content reached 10% (wet basis), and then by conventional hot-air drying at the temperature of 45°C to final moisture content less than 5% (wet basis). Pungency, color, texture, and rehydration ratio of garlic slices dried by this method were evaluated and compared with those dried by freeze drying and conventional hot-air drying. The comparison showed that the quality of garlic slices dried by the current method was close to that of freeze dried garlic slices and much better than that of conventional hot-air dried ones. The lab microwave-vacuum dryer which the materials to be dried could be rotated in the cavity was developed by the authors.

Conclusion

This review paper is focused on the drying of food product in microwave vacuum. Author presented a comprehensive review of the various benefits and limitations of using MVD for different products. Drying principles of microwave vacuum were completely descripted. Processing of Carrots, Banana, Apple and Garlic in microwave vacuum also was comprehensively descripted. It was found that benefits of microwave vacuum over HA are many. Energy consumption is often lower, smaller equipment may be used, reduced risks for fires and explosions, harmful emissions may be eliminated, and quality of product is often higher. The eventual objective of employing these appropriate drying technologies is to significantly improve the agricultural returns for farmers in appreciation of the hard effort they have devoted in crop cultivation.

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