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Microwaves in Postharvest Applications with Fresh Fruits and Vegetables

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ABSTRACT

Fruits and vegetables are an increasing part of our diets as they are a recognized source of health enhancing nutrients. The use of microwaves to ensure product quality for minimally processed fruits and vegetables is gaining popularity. Microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz. In this review we concentrated on research conducted at the 2450 MHz frequency. The special microwave-matter interaction mechanisms make microwaves a special format of energy that can bring many advantages to various applications in post-harvest handling of horticultural crops. The principal advantage in the use of microwave energy is the great reduction in processing time which often yields higher end-product quality. Microwave power has been used for high-temperature-short time thermal treatments of fresh commodities for disinfection, disinfestations, control of ripening, to impede on senescence and for the retention of phytochemicals. The study of the microwave permittivity of the produce can provide information on its quality, maturity and moisture content and can be used in sensing as a process control measure.

Keywords: blanching, cooking, extraction, microwave, phytosanitary, sensing

CONTENTS

INTRODUCTION

The principal goal of thermal processing of fresh fruits and vegetables is the elimination of microorganisms representing a potential health concern for human consumption. In addition, thermal processing may be considered to inactivate certain enzymes and to alter some chemico-physical properties of fresh commodities to prolong their shelf life and ensure their marketability.

Microwave heating technologies have been researched since the late 1940s with various levels of success. For the past 40 years, there have been investigations for the development of microwave heating processes in agriculture with target applications in grain drying (Bhartia *et al*. 1973; Shivhare *et al*. 1994) and insect control (Nelson 1973). Since then, numerous food applications have been studied with some successful industrial developments. Microwave processes were studied for food drying (Maurer *et al*. 1971; Sobiech 1980; Tulasidas *et al*. 1995; Ohlsson and Bengtsson 2001; Beaudry *et al*. 2003), for blanching (Chen *et al*. 1971; Avisse and Varaquaux 1977; Ramesh *et al*. 2002; Severini *et al*. 2004), for pasteurization (Lin and Li 1971; Jaynes 1975; Zhang *et al*. 2004), for cooking (Nykvist and Decareau 1976), and for microwave phyto-extraction (Hong *et al*. 2001; Williams *et al*. 2004; Liazid *et al*. 2007).

The basic requirements in successful microwave power applications are efficiency of power transfer, low cost and reliability of system operation. The most successful device for power application is the magnetron (Osepchuk 2002). Magnetrons operate in microwave ovens from 300 to 3000 W and in high power applications in the 5-100 kW range (Brown 1989). The supplied power is fed into a cavity known as the applicator. The most common applicator is the Multi-Mode Cavity popularized in our domestic microwave ovens.

By incorporating a mode stirrer (a rotating reflector) or continuously rotating the load on a turntable, temperature uniformity can be improved, by effectively smearing the electrical field distribution within the load.

In microwave heating, the thermal process is accomplished by absorption of microwave energy by rotation of the dipolar water molecule and translation of the ionic components of the product as it is subjected to an electromagnetic field which alternates at 2450 MHz, or 2450 million times per second. The reaction of the material subjected to microwaves is expressed by its dielectric properties. The imaginary component of permittivity ε'' represents energy losses and is called the dielectric loss factor. Hence the absorbed power is a function of the electric field strength and the material properties and can be calculated as:

Received: 17 January, 2007. Accepted: 19 April, 2007.

Invited Mini-Review

$$P = 2\pi f \varepsilon_0 \varepsilon'' E^2$$

where P is the power per volume (W/m^3);
f is the frequency (Hz);
E is the electric field strength (V/m);
ε_o is the absolute permittivity in vacuum (8.85 × 10^{-12} F/m);
ε'' is the dielectric loss factor (F/m).

MICROWAVE APPLICATIONS WITH FRESH PRODUCE

Industrial applications of microwaves are numerous in the processing of food. Applications are increasingly being perfected in tempering, vacuum drying, freeze drying, dehydration, cooking, blanching, baking, roasting, rendering, pasteurization, sterilization and extraction (Osepchuk 1984; Lew *et al*. 2002; Osepchuk 2002; Venkatesh and Raghavan 2004).

The adoption of microwave technology in a food application is usually a relatively slow process since there are economic, technological and safety issues (Buffler 1993). Microwave processing equipment has a considerable capital cost which is detrimental to equipment selection. Processing equipment needs to be designed precisely around an application and requires additional technical skills for proper maintenance and operation. Microwave energy use is also feared for safety reasons associated with radiation leakage and contaminants transferring to foods from susceptors and containers.

For most successfully adopted industrial application of microwave processing, the process produces a product with unique features not otherwise obtained by conventional processing.

This review article presents recent developments in the microwave treatment of fresh fruits and vegetables namely in cooking and blanching for minimal processing ensuring optimal product quality, phytosanitary treatment, extraction of phytonutrients and non-invasive microwave sensing.

Cooking and blanching

Cooking can cause partial or total loss of valuable nutrients depending on the process parameters and the type of fruits or vegetables (Kala and Prakash 2004). Research has demonstrated that many food vitamins are thermolabile and leach out during thermal processing. Over the years, microwave processing has demonstrated an advantage over traditional processing with reduced nutrient losses and rapidity of processing (Uherova *et al*. 1993; Finot 1996; Villanueva *et al*. 2000; Begum and Brewer 2001a, 2001b; Brewer and Begum 2003). However it is not always the case as microwave cooking at high intensity (5 min at 6 W/g) of broccoli inflorescence yielded the highest losses of flavonoids (97%) when compared to conventional boiling (80%), high pressure boiling (47%) and steaming (11%) in an experiment reported by Vallejo *et al*. (2003). On the other hand, milder microwave treatments (1 min at 10 W/g) were demonstrated to have improved the levels of health promoting components (total phenolic content) of certain vegetables such as green beans, sweet peppers and spinach (Turkmen *et al*. 2005, 2006).

Many quality deterioration mechanisms in fresh fruits and vegetables are attributed to enzymes such as peroxidase, ascorbic acid oxidase, polyphenol oxidase, etc. The oxidation degradation persists during cold and frozen storage. Blanching is commonly used prior to freezing to inactivate the enzymatic activity and thus maintain product quality. Microwave blanching is a thermal treatment aiming at inactivating oxidative enzymes such as polyphenol oxidase, peroxidase, lipoxygenase, etc. while maintaining nutrient levels. Peroxidase is a highly heat labile enzyme and is often used as an indicator of blanching efficiency (Soysal and Soylemez 2005). Enzymatic degradation of fruits and vegetables is detrimental to their marketability and overall quality (colour, nutritional content, etc.), through oxidative reactions. For example, peroxidase combines with H_2O_2 to produce an activated complex which reacts with a wide range of constituents including ascorbic acid, carotenoids and fatty acids. These reactions can cause significant changes in product quality (off-flavor, loss of aroma, color, nutrients). These enzymes are heat sensitive and are inactivated at temperatures greater than 80°C while their activity is decreased at temperatures above 50°C (Dorantes-Alvarez and Parada-Dorantes 2005). Hot water blanching is the preferred process for enzyme inactivation generally done by immersion in water at 88-99°C. Thermal inactivation of enzymes is dependent on a combination of time and temperature. While also affecting texture, blanching also eliminates surface microorganisms. In general blanching is conducted using hot-water or steam, however conventional methods yield losses in nutrients and consume considerable energy. Microwave blanching is proposed as a favourable alternative for achieving a balance between enzymatic inactivation and the retention of nutrients and physical attributes (Soysal and Soylemez 2005; Ahmed and Shivhare 2006).

Thermal treatments ranging from 35-75°C for exposures ranging from 0.5 to 180 min were compared with microwave treatments in a 700W microwave oven operating at 70, 210, 350 and 700 W for exposures ranging from 15 sec to 12 min (Soysal and Soylemez 2005). The impact of blanching treatments on carrot peroxidase inactivation was evaluated. Higher temperatures during thermal treatment achieved higher enzyme inactivation with greater loss in vitamin C, 44.3% loss for 10 min thermal treatment at 75°C. All microwave treatments resulted in greater retention of vitamin C while peroxidase was still inactivated.

An experiment by Brewer and Begum (2003) studied the effect of microwave blanching (700 W), where the ascorbic acid content was retained for broccoli, green beans and asparagus. Samples of 300 g were subjected to 30%, 55%, 70% and 100% power levels for 0, 1, 2, 3 and 4 minutes. The microwave treatments significantly affected the peroxidase activity with the intensity of the microwave power having the greatest effect. Microwave treatment at any power level for as little as 1 min exposure significantly reduced the peroxidase activity, thus promoting the product's quality in subsequent storage (Begum and Brewer 2003).

Chen *et al*. (1983) studied the blanching of spinach. The experiment compared microwave blanching of 25 g spinach at 650 W for 50 s with boiling water blanching for 3 min, followed by 20 weeks of frozen storage. The spinach was analyzed for folate (folacin) conservation. Microwave blanching caused a 13% loss of folacin whereas water blanching caused a 64% loss. The total folates remained stable during frozen storage for both water and microwave blanching. This confirms previous work conducted by Klein *et al*. (1981), where greater folacin retention was reported for microwave cooked spinach. They compared cooking of a 400 g sample with 100 ml water microwave cooked for 6.5 min at 585 W compared with cooking a 400 g sample with 100 ml water on a gas burner at 100°C for 7 min.

Kaur and Kapoor (2001) studied the effect of blanching on the subsequent quality of frozen green beans and carrots. Carrots and beans were blanched in boiling water for 5 min and 3 min respectively. Both carrots and beans were also blanched by immersion in 70°C water for 30 min or microwave blanching at 700 W for 3 min for carrots and for 4 min for beans. All blanched samples were subsequently stored at -18°C for 2 months. In terms of nutrient loss, ascorbic acid is highly heat labile. Ascorbic acid content decreases with increasing temperature and process time. Fresh ascorbic acid content was measured at 5 mg/100 g and 26 mg/100 g for carrots and green beans respectively. Microwave blanching had the highest retention of ascorbic acid with 76% retention, while immersion and water boiling had 42% and 34 % retention respectively. Total carotenoids was best retained during microwave blanching. Microwave blanching obtained the lowest residual peroxidase activity which maintained a better product quality during frozen storage.

Verkerk and Dekker (2004) studied the effects of microwave cooking on the glucosinolates and myrosinase activity of red cabbage. Glucosinolates are gaining popularity for their anticarcinogenic properties and their retention in foods during cooking is highly recommended. The protective health benefit of glucosinolates is governed by the myrosinase enzyme. Hence cooking methods must retain high levels of myrosinase and glucosinolates. During microwave cooking it appears that the myrosinase enzyme is denatured at high power intensities (900 W for a sample of 300 g) whereas for the same total energy inputs (lower power and longer time), during microwave cooking at lower applied power (180 W for 300 g), the enzymatic activity is retained. In fact, the myrosinase activity increases with moderate heat at temperatures up to 60°C while inactivation occurs at higher temperature. Overall, the microwave cooking of red cabbage retained high levels of glucosinolates and maintained acceptable myrosinase activity, making it a suitable method to provide nutritious and health promoting cooked foods (Verkerk and Dekker 2004).

In a study by Rehman *et al*. (2003), the effect of cooking by hot plate, pressure cooking and microwave cooking on the dietary fiber content of fresh vegetables was compared. Chopped vegetables in water (1 g per 4 ml) were subjected to microwaves at 550 W for 10 min and to pressure cooking at 15 lbs per in^2 for 10 min and hot plate heating for 10 min. All cooking methods significantly reduced the dietary fiber content of the vegetables with the microwave and hot plate cooking being acceptable processes with similar reduced losses when compared to pressure cooking.

Microwave blanching of tomatoes was investigated by Begum and Brewer (2001a) and compared to boiling water and steam blanching. Samples of 225 g were subjected to boiling water for 3 min, steam for 3 min, microwave heating (700 W) for 3 min. Steam blanched tomatoes were the lightest while boiled water tomatoes generally had the best appearance scores. Microwave blanched tomatoes retained the best nutritive value with acceptable colour and flavour scores. Following the same thermal treatment comparison as for the tomatoes presented above, Begum and Brewer (2001b) demonstrated that snow peas can be successfully microwave blanched prior to frozen storage. Microwave blanching inactivated peroxidase as well as other blanching methods while retaining more ascorbic acid. All blanching methods produced better quality frozen vegetables. Hence they recommend microwave processing to produce ready to freeze high quality snow peas with superior nutrient retention when compared with conventional water blanching. Similar recommendations were made for green beans and yellow squash (Lane *et al*. 1985); broccoli (Brewer *et al*. 1995); for asparagus (Begum and Brewer 1997) and Brussel sprouts (Viña *et al*. 2007).

Lin and Brewer (2005) studied the blanching of peas prior to frozen storage. 500 g samples were either steam blanched for 4 min, blanched for 4 min in boiling water or microwave blanched for 4 min at 800 W with 80 ml of water. The peroxidase activity in fresh unblanched peas was about 4000 units. Blanching regardless of method used, reduced the peroxidase activity by more than 97%. The ascorbic acid content was highest in fresh, unblanched peas at about 29 mg/100 g. Steam-blanched and microwave blanched peas retained the highest ascorbic acid content following treatment and frozen storage.

Microwave heating proved effective to inactivate oxidoreductase enzymes (polyphenoloxidase and peroxidase) in fruit purees while ensuring an acceptable impact on the qualitative and quantitative composition of carotenoids in papaya puree and anthocyanins in strawberry puree (de Ancos *et al.* 1999). Microwave treatments of 150 g purees at 285 W, 475 W, 570 W and 850 W were studied for treatment durations of 15, 30, 45 and 60 s. Inactivation of enzyme was ensured with 475 W for 45 s. Anthocyanin in strawberries was unaffected by the microwave treatments, whereas total carotenoids were very sensitive to the microwave treatments with 50% losses at 475 W for 45 s.

Ponne *et al*. (1994) studied microwave, microwave-steam, infrared, radio-frequency, steam and water blanching of spinach and endive. Their comparative analysis indicated that microwave and microwave-steam blanching yielded the best texture, vitamin C retention and general acceptability scores in terms of taste and colour.

Ramaswamy and Fakhouri (1998) compared microwave and hot water blanching of carrots and sweet potatoes. Full 700 W microwave power was applied for 30-60 s for 50 g samples, for 30-120 s for 100 g samples and 30-180 s for 150 g samples. 50 g samples were also blanched in boiling water for 30-180 s. Following blanching, the product was vacuum sealed and frozen stored for 7 months. Enzyme inactivation was faster for microwave blanching, whereas similar product quality in terms of texture was obtained with both methods.

Devece *et al*. (1999) studied the industrial microwave blanching of mushrooms to inactivate polyphenoloxidase activity which causes browning within a few days of storage. Mushroom samples of 200 g were subjected to microwaves with a power absorption of 113 W. Their results demonstrated that with proper applicator design, the microwave treatment can achieve complete enzymatic inactivation in a short time, ensuring minimal loss of antioxidant and moisture with minimal browning (Rodriguez-Lopez *et al*. 1999).

In an experiment conducted by Premakumar and Khurdiya (2002), bananas were blanched by immersion in 100°C water for 8 min and compared with microwave blanching on high power for 3 min (1200 W, 2450 MHz). The overall quality parameters (total soluble solids, tannins, total sugars, ascorbic acid, enzymatic activity, colour, flavour and texture) were all higher for microwave blanched bananas than for water blanched bananas. The prevention of banana browning can be ensured by blanching. Browning in banana occurs when polyphenoloxidase and peroxidase catalyze the oxidation of phenols. Microwave blanching can successfully inactivate both enzymes (Cano *et al*. 1990).

Huang *et al*. (2007) studied the effect of microwaves on green tea preservation quality. When compared with oven heating, the microwave treatments significantly promoted the retention of vitamin C while there was no significant differences in the retention of total chlorophyll and tea polyphenols from the two heating techniques. Furthermore the vitamin C level in microwave treated green tea decreased at a significantly lower rate during storage than the oven treated tea providing more stability during storage with significantly reduced losses.

Turkmen *et al*. (2006) compared water boiling (5 min), microwave cooking (1000 W/100 g samples for 1 and 1.5 min) and steaming (7.5 min) of various vegetables. Highest chlorophyll *a* and chlorophyll *b* losses were observed in boiled vegetables while best chlorophyll retention was reported in microwave blanched vegetables. These results support the work of Ihl *et al.* (1998) which studied chlorophyllase inactivation during blanching of artichokes. The chlorophyllase enzyme catalyses the cleavage of the phytol group from the chlorophyll. Microwave blanching ensured enzymatic inactivation while maintaining colour quality and limiting ascorbic acid losses from artichokes (Ihl *et al*. 1998).

In the case of certain vegetables, a blanching process is required to limit the presence of antinutritional factors such as oxalic acid, phytic acid and tannic acid as they impair absorption of other components such as calcium and iron. Cooking or blanching of such vegetables has proven effective in destroying most antinutritional factors. In a study presented by Mosha *et al*. (1995), microwave blanching was as effective as hot water blanching at reducing the antinutritional factors in cabbage, collard greens and sweetpotato in much reduced treatment time (1 min for microwave blanching versus 10 min for hot water).

Yoshida *et al*. (2005) studied the influence of microwave roasting of peanuts on their composition and their fatty acids distribution. The microwave treatments of 80 g samples were subjected to 0.5 kW power for treatment duration ranging from 6-30 min. The results indicated that during moderate microwave roasting (12 min or less), the unsaturated fatty acids were in a stable reducing oxidation thus ensuring product quality.

Baloch *et al*. (2003) studied the effect of microwave radiation on the ripening of Dhakki dates. There was a very positive effect of microwave heating, at 210, 360 and 480 W, on the ripening quality of the dates. The proposed microwave ripening process can allow harvesting of the fruits 2 weeks earlier. The sensory evaluation of the microwave treated dates rated them as superior. There is however an upper limit of the treatment at which point the radiation becomes harmful to the quality and shelf life.

High temperature blanching may disrupt cellular integrity, cell adhesion and reduce the firmness of the fresh product. Lower temperatures are recommended for highest firmness retention. In any case, thermal processing requires an optimal balance between the inactivation of microorganisms and specific enzymes and the retention of target quality parameters (Ahmed and Shivhare 2006). With longer treatment times there is an increase in weight loss from loss of moisture from the product's surface (Ramesh *et al*. 2002; Brewer and Begum 2003).

A great industrial advantage of using microwave blanching is the fact that there is no production of wastewater in the process. The higher cost of the microwave equipment has however slowed down its industrial adoption. Nonetheless, the operating costs are quite advantageous and when the process is combined with steam to ensure adequate surface heating, microwave blanching offers great industrial potential (Fito *et al*. 2005). Microwave blanching must be well controlled as there are disadvantages that may arise from microwave blanching, principally in the non-uniform heating which can cause uneven surface treatment and uneven enzymatic inactivation and product deterioration (Sumnu and Sahin 2005).

Microwave blanching/steaming will be gaining considerable interest for the greater nutritional quality of its products. Combination of hot water/steam blanching with microwave heating presents some advantages. The low cost hot water or steam can first be used to raise the surface temperature (for surface cleaning), while microwave power can be used for rapid internal blanching, thus achieving the best of both methods and reducing the incidence of negative impacts.

Microwave treatment for phytosanitary purpose

Microwave heating can offer high temperature and short time processing resulting in quality advantages. A recent focus has been in the microwave pasteurization of packaged foods. In a study by Lau and Tang (2002), pickled asparagus in glass jars were pasteurized using 915 MHz microwaves. The process produced uniform heating while reducing the process time by at least one-half compared to water-bath heating. Furthermore, the microwave pasteurization significantly reduced thermal degradation of asparagus. When using microwave heating for pasteurization, care must be taken to ensure the homogeneity of the thermal process within the product and that the target lethal temperature is maintained for a sufficient period of time to provide a safe product (Finot 1996).

Wang *et al*. (2003) studied the lethal effect of microwaves on different spores of *Bacillus*. Different strains in different environments exhibited various levels of tolerance to the microwave heating treatment. The properties of the material hosting the *Bacillus* strain had a significant effect on its tolerance to a microwave sterilization treatment. Higher power levels are recommended to accomplish lethality.

Karabulut and Baykal (2002) studied the use of microwave heating treatments for the control of postharvest disease of fresh peach. Growth of pathogens (*B. cinerea* and *P. expansum*) could be inhibited with microwave treatments at 2450 MHz for 2 min process duration at 400 W applied power for 2 medium sized peaches. The microwave treatment did not impair the fruit quality parameters such as firmness, total solids content, peel and flesh colour.

Ortega and Liao (2006) demonstrated the ability of microwaves to inactivate known parasites (*Cyclospora* and *Crytosporidium*) using treatment times of 45 s in microwaves operating between 650 and 1100 W with 5 ml samples. However, time should not be used as the control parameter to ensure parasitic inactivation. The target temperature reached is the governing process parameter. In a study by Celandroni *et al*. (2004), it was demonstrated that microwave treatments and conductive heating treatments were as effective in killing *Bacillus subtilis* spores with similar treatments times.

On the other hand, Heddleson *et al*. (1994) demonstrated that the single most important parameter to consider in microwave destruction of *Samonella* spp. is the temperature achieved by the product.

Zhang *et al*. (2006) investigated the combination of microwave treatment with a yeast antagonist *C. laurentii* on the quality and shelf life of wounded and *P. expansum* inoculated pears. The combination treatment was the most effective at reducing the percentage of decayed fruits while maintaining product quality better than either stand alone treatment.

Microwave treatments are being considered for lowering the microorganism contamination of spices and herbs. In general the level of contamination in herbs and spices can be as high as 10^5 to 10^8 microorganisms per gram. However, thermal processing is often associated with degradation of food properties. Nonetheless, in some cases, the thermal process can have a beneficial effect, which is the case with the formation of compounds with novel antioxidant properties. In a study conducted by Bertelli *et al*. (2004) samples of black pepper, oregano, basil and sage were subjected to microwave treatments of 30-70 W/kg for 15 min as a phytosanitary process. The total phenolic content in pepper, oregano and basil increased with microwave treatment, while it decreased only in the case of sage.

Microwave-assisted extraction (MAE)

Solvent extraction is a process using solvent to separate components that contains the target components from the solid matrix. The extraction rate and the quality of the extract depend on many factors, among which the most important ones are: the characteristic of the matrix, the distribution of the target components in the matrix, the solubility of the solvent to the target components and the interfering components, and temperature. Breakdown of the membrane system drastically accelerates the extraction process. Temperature is important in the extraction process because the higher the temperature is, higher is the diffusion rate and consequently higher is the extraction rate. In some extraction process, high temperatures over long extraction times are not desired due to the decomposition of heat-sensitive components.

The reduction of extraction time is one of the most attracting results attributable to the introduction of microwaves into phytochemistry. In 1986, Ganzler *et al*. first introduced microwave energy in the extraction system for crude fat, vicine, convicine, and gossypol from seeds, foods and feeds using organic solvents. With only 3.5 mins of microwave irradiation, the yields of these compounds were comparable to those obtained with a 3-hr Soxhlet extraction. Williams *et al*. (2002) reported the extraction of pungent principles capsaicin and dihydrocapsaicin from capsicum species showing that with 15 mins of microwave extraction the yields of both capsaicin and dihydrocapsaicin more than doubled compared to the results of reflux extraction for 2 hrs and 50% higher than shaken flask extraction for 24 hrs.

Besides the great acceleration effect, microwave-assisted extraction can also improve the product quality as a result of short processing time or due to the special characteristics of microwaves in the extraction method. For example, when a system of fresh plant material and a non-polar solvent is exposed to microwave radiation, microwave will travel freely through the solvent which is transparent to microwave energy and reach the sample. A significant fraction of microwaves is absorbed by the sample, mainly the water in the glandular and vascular systems, which results in a sudden temperature rise inside the sample with a dramatic expansion in volume leading to explosion at the cellular level. The substances located in the cells are then free to flow out of the cell to the surrounding solvent (Dai *et al.* 2001).

Solvent free microwave extraction is being developed as a green alternative method. Results obtained by Lucchesi *et al*. (2004, 2007) demonstrated rapidity, efficiency and cleanliness (no solvent) of the process for essential oil extraction from spices. Wang *et al*. (2006) are proposing an improved solvent-free microwave extraction method for dry materials such as herbs and spices. Their process involves the addition of a microwave absorbing medium to facilitate the absorption of energy around the dried plant material to favour the extraction. Carbonyl iron powders are suggested for this application. Wang *et al*. (2006) compared their solvent-free microwave extraction by combining 100 g of spice with 20 g of carbonyl iron powder, mixed in a reactor and heated at 85W for 30 min. Compared with microwave assisted hydrodistillation, and conventional hydrodistillation, the solvent-free microwave extraction process proved to be simple, quick and economical.

Liazid *et al*. (2007) studied the stability of phenolic compounds as affected by temperature during microwave assisted extraction from grape skin. Microwave assisted extraction with methanol was conducted at 50, 75, 100, 125, 150 and 175°C. Up to 125°C, 95% recovery of phenolic compounds is achievable. At higher temperature, there is a significant decrease in recovery at 34% at 175°C. Below 100°C, no degradation of phenolic compounds was observed.

Microwave sensing

On-line, real time sensing of material's properties is important to many food industries to ensure product quality and process optimization. The use of microwaves in sensing applications relies on the interactions between the electromagnetic wave and biological materials characterized by their dielectric properties. Dielectric based measurement methods are sensitive to the water content of the material, bound or free water (Nelson *et al*. 1998; Trabelsi and Nelson 2006). Moisture content can also be estimated from a temperature measurement when the amount of microwave energy absorbed by the sample material is proportional to its moisture content (Zhang and Brusewitz 1991). Permittivity measurements using an open-ended coaxial probe or free-space transmission connected to a network analyzer allow for non-destructive measurements of interest in sensing product properties (Trabelsi *et al*. 2000). The reflection coefficient at the dielectric interface between the probes and the material is governed by the permittivity of the material in contact with the probe or placed between the wave transmitter and receiver. Energy dissipation leads to an attenuation of the resonance of the circuit, yielding an exponential decay of the oscillation amplitude in time domain of a broadening of the resonance curve in frequency domain (Knochel *et al*. 2001). Significant variations in both the dielectric constant ε' and the loss factor ε'', the real and imaginary parts of the complex relative permittivity $\varepsilon = \varepsilon' - j\varepsilon''$, occur as a function of changing material's properties (Kent *et al*. 2001).

In a study conducted by Nelson *et al*. (1995), there were slight variations in the dielectric properties of peaches depending on their stage of maturity. The sensitivity of those slight variations is dependent on the frequency range of the testing measurement. Calibration methods can be formulated to provide flexibility in the interpretation of the dielectric measurements and their reading of product properties (Trabelsi and Nelson 2006).

Environmental stress can bring changes in physiological and physical properties of plant materials including fruits and vegetables. These changes may influence the dielectric properties which can be detected by measuring the complex dielectric properties of plant parts affected by water stress (Shimomachi *et al*. 2006). Non-invasive sensing using an open-ended coaxial probe connected to a network analyzer showed the capacity to monitor changes in protein, amino acids and ionic composition of tomato plants in response to degrees of water stress.

FUTURE AND INDUSTRY REQUIREMENTS

Due to their selective and volumetric heating effect, microwaves bring a lot of new avenues to various bioprocessing techniques such as: the increasing rate of the thermal treatment, improved product quality, increasing yield and extract quality in an extraction process. These advantages are to be considered in choosing an alternative to conventional processing methods.

For successful industrial applications of microwave energy there needs to be the understanding that any microwave operation will require initial product-specific design to meet the process objectives, and operator and maintenance staff training. Furthermore, for initial production initializing, the food company will have to fine tune the operating parameters in close collaboration with the microwave manufacturer to ensure that all production staff has acquired the confidence to operate the equipment in the small window of maneuverability to achieve product quality (Gerling 1986).

Research and development is underway to produce new magnetrons for widespread applications at 5.8 GHz. This will offer great new horizons for product and applications development especially in phytosanitary applications.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC) and from the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT).

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