ABSTRACT

KOSKINIEMI, CRAIG BENJAMIN. Development of a 915 MHz Continuous Microwave Process for Pasteurization of Packaged Acidfied Vegetables. (Under the direction of Dr. Van-Den Truong.)

The development of packaged acidified vegetables such as broccoli, red bell pepper, and sweetpotato was studied in order to improve the levels of beneficial phytonutrients compared to traditional pickled cucumbers. In addition, the application of continuous microwave processing to acidified vegetable products could reduce energy usage and water consumption, and thereby improve the sustainability of acidified vegetable production. This research sought to provide a comprehensive examination of: (1) the dielectric properties of acidified vegetables, (2) methods to improve heating uniformity during continuous microwave processing of packaged acidified vegetables, and (3) the microbial stability and changes in color and texture conferred by the pasteurization process over storage in acidified vegetable packs.

The effects of salt, acid, and equilibration time on the dielectric properties at 915 MHz of acidified broccoli, red bell pepper, and sweetpotato were studied in order to understand and assist in the design of a continuous microwave heating process. The addition of salt significantly increased the loss factors (ε'') among vegetables and was concentration dependent, but did not change the dielectric constants (ε'). Citric acid (0.5 – 2.0% w/v) did not significantly influence ε' nor ε''.

In part 2, the influence of salt level and distribution in acidified vegetable packs during 915 MHz continuous microwave processing was evaluated through heating uniformity studies. The presence of 1% salt in the cover solution adversely affected microwave heating of the vegetable pieces. However, pre-equilibration of vegetable pieces to 1% salt and

placement into a 0% salt cover solution improved heating. Changes in product composition were not enough to overcome the challenge of heating the cold spot to temperatures greater than 74°C, the industry standard for pasteurization of pickled cucumbers. The design and implementation of a cup rotation apparatus improved the heating uniformity in the packages, and pasteurization temperatures greater than 77°C in the liquid and vegetable pieces were obtained during microwave processing.

In part 3, the quality of vegetable packs subjected to continuous microwave pasteurization was evaluated. After processing, no significant changes were observed in the color of the vegetables, but tissue firmness decreased. Over a two-month storage period, no signs of microbial spoilage were observed. Broccoli, red bell pepper, and sweetpotato softened over storage, but to varying degrees. Broccoli color degraded due to chlorophyll degradation, but much of the brilliant red and orange color of red bell pepper and sweetpotato remained after storage.

This research successfully demonstrated the applicability of continuous microwave processing to produce shelf-stable, packaged acidified vegetables.

Development of a 915 MHz Continuous Microwave Process for Pasteurization of Packaged Acidfied Vegetables

by
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DEDICATION

To the most important people in my life

BIOGRAPHY

Craig Benjamin Koskiniemi was born October 12, 1984 in Fort Wayne, Indiana to Robert and Shirley Koskiniemi. Craig spent his entire childhood in Fort Wayne growing up with his older brother, Barry. Summer and winter vacations were, and still are on occasion spent enjoying the beautiful Keweenaw Peninsula of Michigan with his family. In high school, Craig's life was largely consumed by music, playing his beloved saxophone in every musical ensemble possible. After graduating from Northrop High School in 2003, he attended Purdue University in West Lafayette, Indiana as a food science major from the very beginning.

It did not take long for Craig to realize that food science was the right career choice for him. During his undergraduate career, Craig interned with Cargill Corn Milling in Dayton, Ohio as a quality assurance chemist. While the internship was a great experience, it also served as a motivation to pursue a career more research-based. Craig more seriously considered continuing on to graduate school at the suggestion of one of his professors, Dr. Lisa Mauer. Craig was determined to further his education, but first committed to a six-month internship in product development with the Kellogg Company in Battle Creek, Michigan before beginning his graduate studies at North Carolina State University.

During a visit to NC State, Craig was captivated by Dr. Den Truong's and Dr. Josip Simunovic's enthusiasm for microwave processing. This was all it took for him to decide NC State was the perfect place to pursue his Master's degree. Craig began his Master's degree in January 2008, and will finish in December 2009. He was very active in the Food Science Club, serving as the Activities co-chair and competing in the IFTSA College Bowl competition. Craig was also lucky enough to find his beautiful, loving girlfriend—a Wisconsin girl no less—here at NC State. Soon after the completion of his Master's degree, Craig will begin his professional career in January 2010 as a Sr. Food Scientist for Unilever in Englewood Cliffs, New Jersey. He is excited to see where the road of life will take him.

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First, I would like to thank Dr. Truong for advising me the past two years. I have learned many things, and I have come out of this experience a better scientist, thanks in part to him. I also thank Dr. Josip Simunovic for his infectious enthusiasm for microwave processing. Talking with Josip always left me feeling reinvigorated and excited about my research, not to mention laughing many times. And I thank Dr. McFeeters for his helpful guidance with all things acidified.

I thank all my friends in the department, past and present, who have made my time here much more fun. A special thanks goes out to the dwellers of room 330 for keeping things interesting… you know who you are.

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Last, but certainly not least, I thank the most important people in my life: my family for all of the love and support they have given me my entire life, and Leann for being such an amazing person. I would not be the person I am today without them.

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INTRODUCTION

In order to stay competitive in today's marketplace, the development of new products and sustainable processes must be explored. This is especially true for the pickle industry, which has not seen much change or growth over the past few decades. To this end, the development of packaged acidified vegetables such as broccoli, red bell pepper, and sweetpotato would improve the levels of beneficial phytonutrients compared to traditional pickled cucumbers, and may open new market opportunities for the pickle industry. Furthermore, the use of acidulants other than acetic acid (vinegar) would expand the possibilities for new products and move away from the "pickled" image. Aside from new products, there is also a need for new pasteurization technologies that would reduce energy costs and water consumption. In contrast to steam pasteurization, which has been used by the pickle industry for over 50 years, microwave processing is a new technology that may provide energy and water savings, and possibly quality improvements.

The application of microwave processing technology to acidified vegetables pairs one of the newest preservation technologies with one of the oldest. Fermentation of vegetables has been used as a preservation method for at least the past 3,000 years (Hutkins, 2006). While the term "acidified vegetables" strictly refers to vegetables where acid has been added, the preservation mechanism (lowering pH) remains the same. Today, the term "fresh-pack" is used to refer to vegetables (most often pickles) which have been packed in jars, filled with vinegar and flavorings, then pasteurized to produce a shelf-stable product. This method of acidification which requires pasteurization has been used in the pickle industry since the 1940s.

Recently, the pickle industry has shown an interest in microwave processing technology due to its potential advantages over traditional pasteurization procedures. Some of the potential benefits include: improved product quality, faster processing times, reduced water usage, reduced energy consumption, and bulk storage capabilities. These advantages stem from the efficiency of energy conversion in the product resulting from rapid, volumetric heating. Traditional pasteurization methods require longer heating times since heat is transferred by conduction and convection from outside to inside the food product, oftentimes resulting in overcooked food near the periphery.

Furthermore, food industry-wide trends involve packaging foods such that they are convenient, and presented in appropriate portions to the consumer. The presence of such products that require thermal processing presents an opportunity for the application of continuous microwave processing. It is the goal of this study to demonstrate the application of continuous microwave processing to produce pasteurized, shelf-stable acidified vegetable packs with high levels of beneficial phytonutrients and antioxidant activities.

Objectives

The objectives of this research were:

1) to determine the effects of acid, salt, equilibration time, blanching and temperature on the dielectric properties of broccoli, red bell pepper, and sweetpotato,
2) to develop a continuous microwave pasteurization process for the pasteurization of packaged acidified vegetables through heating uniformity studies, and
3) to evaluate finished product quality during storage with regards to color, texture, and microbial stability.

CHAPTER 1

LITERATURE REVIEW

1.1 Processing of acidified vegetables

Acidified vegetables are classified as acidified foods by the United States Food and Drug Administration (FDA). According to the United States Code of Federal Regulations Title 21 (21CFR), part 114, acidified foods are defined as, "any low-acid foods to which acid(s) or acid food(s) are added. […] They have a water activity (a_W) greater than 0.85 and have a finished equilibrium pH of 4.6 or below" (United States Code of Federal Regulations, 2008). Additionally, 21CFR states that,

> Acidified foods shall be thermally processed to an extent that is sufficient to destroy the vegetative cells of microorganisms of public health significance and those of nonhealth significance capable of reproducing in the food under the conditions in which the food is stored, distributed, retailed and held by the user. (United States Code of Federal Regulations, 2008)

However, acidified vegetables which use acetic acid as acidulant and have an equilibrated pH of 3.3 do not require thermal processing if the vegetable have been held for 48 hours at ≥ 25 ºC to ensure sufficient killing pathogenic microorganisms (Breidt and Costilow, 2004). These regulations are based on previous research and have been set in place to assure the safety of acidified vegetables. As a result, acidified vegetables which do not use acetic acid as acidulant must be thermally processed to render them safe and shelf-stable.

1.1.2 Pasteurization of acidified vegetables

Pasteurization of acidified vegetables serves to destroy all vegetative pathogenic microorganisms, prevent spoilage by lactic acid bacteria and yeasts, and to improve overall keeping quality (Jones et al., 1941; Etchells and Jones, 1942). The majority of heat penetration studies of acidified vegetables have focused on pickled cucumbers (Etchells, 1938; Monroe et al., 1969). The work done in the early 20th century still serves as the industry standard for pasteurization processes. The standard pasteurization process for fresh-pack pickles involves heating the vegetables to 74°C and holding for 15 minutes. Currently, this process is accomplished through the use of steam to heat the product in glass jars by convection. This process consumes a lot of water and is both time and energy intensive. Microwave technology has the potential to heat products more rapidly due to volumetric heating, and thereby reduce processing times and save energy. The efficiency of energy conversion from electromagnetic energy into heat is highly beneficial to thermal processes.

1.2 Microwave processing technology

1.2.1 Components of a microwave heating system

Microwave heating systems contain three major components: a microwave generator (usually a magnetron), waveguide, and applicator. These components are discussed below.

1.2.1.1 Magnetron

Magnetrons are the most economical, reliable and most widely used source of microwaves (Kitagawa and Kanuma, 1986). There are five main components which make up a magnetron: anode, cathode, resonant cavities, magnets, and an antenna (Figure 1); all of which are enclosed in a vacuum envelope. The cathode consists of a tungsten filament at the center of the anode. When a current is applied, the cathode is heated to a high temperature (~ 1300ºC) and loosely bound valence electrons are emitted from the cathode via thermionic emission (Meredith, 1998). As a result, a strong electric field is created between the cathode and the anode. Instead of a direct path from cathode to anode, the electrons follow a circular path due to the perpendicular magnetic field imposed by the magnets and an electron cloud is created. The resonant cavities serve to interrupt the flow of electrons and impose an oscillation in the electron cloud. The operating frequency of the microwave is determined by the size of the resonating cavities (Thostenson and Chou, 1999). It is of great importance to note that proper cooling of the anode during and after operation is essential to extend the life of the magnetron.

The power (watts) of a plane wave is the product of *E* (volts per meter) x *H* (amperes per meter). In dimensional terms, this relationship is described as the power flux density p (watts per square meter), where *E* and *H* are vectors:

$$\mathbf{p} = \overline{\boldsymbol{E}} \times \overline{\boldsymbol{H}} \text{ watts per square meter} \qquad \text{(Meredith, 1998)}$$

Power output in continuous flow microwave operations is controlled by different mechanisms based on the maximum power output of the magnetron. Power is controlled in low power (< 15 kW) magnetrons by adjusting the cathode current, whereas high power magnetrons (15 – 100 kW) rely on adjustment of the magnetic field of the magnetron through use of electromagnets (Meredith, 1998). The wave energy is then coupled to the waveguide by an antenna where it is transmitted to the microwave cavity or applicator.

1.2.1.2 Waveguide

Rectangular waveguides made of conducting materials such as aluminum are commonly used in continuous microwave processing due to their efficiency in conveying power with low loss (Meredith, 1998). Proper selection of waveguide dimensions is dependent on the free-space wavelength which is determined by the operating frequency. In order to achieve wave propagation in the TE_{10} (transverse electric) mode, the width of a rectangular waveguide must be at least half the free-space wavelength, and the resulting aspect ratio is always 2:1 (Meredith, 1998).

The waveguide and microwave applicator used in the work of this thesis was a longitudinal TE_{10} waveguide. TE mode means that there is no electric field in the direction of wave propagation; i.e. the electric field is perpendicular to the direction of propagation. Furthermore, since the conductivity of the waveguide walls is high, the electric field tangential to the surface E_{tan}, equals 0 (Meredith, 1998). This means that the maximum electric field intensity and therefore maximum heating occurs at the center of the waveguide. This theory is consistent with the work of Cha-um et al. (2009), which experimentally examined heating profiles of water and porous mediums at different locations in a rectangular waveguide.

1.2.1.3 Conveyor-type microwave applicator

Conveyor-type microwave applicators are typically used in drying, heating/baking, polymerization, pasteurization, tempering, and thawing processes (Meredith, 1998). The direction of product flow may be concurrent or countercurrent, and is dependent on the type of material being processed. For example, drying operations use countercurrent flow to place the low-loss dry product in the highest field intensity (Meredith, 1998). Concurrent flow is typical for foods where the dielectric properties change with temperature, and the potential for thermal runaway would be increased if exposed to high field intensity at the exit of the conveyor.

When a workload is placed into the applicator, reflections occur and the electromagnetic field behaves in an unpredictable fashion. In order to reduce reflection, impedances of the load must be matched to the impedance of the waveguide. This is usually accomplished by adjusting a three-stub tuner.

1.2.1.4 Choking tunnels

In conveyorised continuous microwave systems, the microwave applicator contains two apertures to allow passage of the product. In order to prevent exposure of microwaves to humans, choking tunnels are placed at both ends of the microwave applicator to attenuate, or “choke” the microwaves. Many techniques can be used to attenuate any microwaves that may not have been absorbed by the workload. Reactive or reflective choking is a simple, commonly used method that uses lossless cylindrical posts to create a high reflection coefficient and reflect waves back into the oven (Meredith, 1998). Other methods include lining the choke tunnel with a lossy dielectric, placing a dielectric diffuser to spread leakage over a wide area, using a diode to detect leakage levels and cut off the generator above a set threshold, or implementing a microwave fuse to shut off the generator when the current is interrupted (Meredith, 1998).

1.2.2 Microwave heating of foods

The use of microwave processing technology is rapidly becoming a viable method of pasteurization and sterilization for high and low-acid foods, respectively. Previous studies have utilized continuous flow microwave processing to aseptically process and package fruit and vegetable purees (Coronel et al., 2005), as well as in-pack sterilization of prepared meals (Tang et al., 2008). Improved color (Coronel et al., 2005; Sun et al., 2007; Steed et al., 2008) and antioxidant activities (Sun et al., 2007; Steed et al., 2008) have been reported using 915 MHz microwaves. These improvements in quality have been attributed to the rapid come-up time due to volumetric heating provided by electromagnetic microwave energy. In addition, the adoption of microwave processes present potential energy savings, as well as opportunities to reduce water usage.

Continuous, tunnel-type microwave systems have received little attention with regards to their potential to pasteurize in-pack foods. Previous works (Burfoot et al., 1988) used a tunnel microwave system operating at 896 MHz to pasteurize in-pack spaghetti bolognaise, and to compare experimental heating profiles of mashed potatoes in trays to prediction models (Burfoot et al., 1996). Uniform heating of the spaghetti bolognaise to at least 80ºC was achieved using 896 MHz, but not 2450 MHz microwaves (Burfoot et al., 1988).

Foods with high salt contents, such as acidified vegetables present difficulties in microwave heating due to dramatically reduced penetration depths. Fresh-pack acidified vegetables such as cucumbers and peppers are typically packed in salt brines to achieve equilibrated salt concentrations in the vegetable tissue at 2-5% (Potts et al., 1986; Daeschel et al., 1990; Passos et al., 2005). While industrial microwave processes utilize 915 MHz microwaves for their relatively high penetration depth, the addition of salt dramatically reduces the penetration depth. When the distance to the center of a material exceeds the penetration depth, the microwave energy is rapidly attenuated, and the food material will not heat volumetrically and surface heating will predominate (Datta and Anantheswaran, 2001).

Only one study has examined the use of microwave-assisted pasteurization of acidified vegetables. Lau and Tang (2002) examined heating uniformity and textural degradation kinetics of pickled asparagus packed in 1.8 kg (64 oz.) glass jars heated to 88°C using a batch microwave system at 915 MHz. The authors were able to reduce heating time by 50% compared to heating in a water bath and the product had less textural degradation (Lau and Tang, 2002). However, the asparagus was hot-filled at 80°C brine and equilibrated to a temperature of 70°C in a water bath before further heating to 88°C by 915 MHz microwaves. It should also be noted that the study did not include dielectric property information of the asparagus or cover solution containing 1% NaCl. Omission of this information prohibits a thorough understanding of the electromagnetic energy interactions with the food product.

In the case of food matrices containing solid and liquid phases, the differences in dielectric and thermophysical properties between these phases influence the heating characteristics. A study by Cha-um et al. (2009) examined microwave heating of a saturated porous medium consisting of 0.15 mm glass beads immersed in water. Inclusion of low loss glass beads increased penetration of microwaves into the water and bead mixture, resulting in higher temperatures at the bottom of the sample. In addition, it was observed that conduction was the predominant mode of heat transfer in the saturated porous medium, while convection prevailed when no beads were in the sample (Cha-um et al., 2009). This research suggests that the pairing of high and low loss materials could produce desirable heating patterns.

1.2.2.1 Non-uniform heating

Non-uniform heating remains a major technical challenge for microwave heating of foods and may arise due to a number of factors. Thickness, geometry, dielectric properties, and thermophysical properties are the main intrinsic properties of the food that determine its heating behavior. Dielectric properties of a food material are a principle factor in understanding microwave heating, as these properties characterize how microwave energy will interact with the food. Additionally, thermophysical properties (thermal conductivity, density, specific heat, and thermal diffusivity) of the food components determine how much energy is required to heat a material to a given temperature, and how fast this phenomenon will occur. Variations in the electromagnetic field are also responsible for non-uniform heating. Kelen et al. (2006) attribute electromagnetic field variations to cavity effects, which encompasses microwave design, and workload interactions such as the dielectric properties, thickness, shape, and size of the food.

Previous studies have sought to accurately predict and validate the microwave heating behavior of foods based on their dielectric properties (Peyre et al., 1997; Lobo and Datta, 1998; Zhang et al., 2001; Anantheswaran and Swanderski, 2002; Sakai et al., 2004; Rakesh et al., 2008; Wang et al., 2008), as well as their size and shape (Prosetya and Datta, 1991; Ryynänen and Ohlsson, 1996; van Remmen et al., 1996; Vilayannur et al., 1998; Ni et al., 1999; Zhang and Datta, 2005a, 2005b). All of the studies which examined the influence of dielectric properties on the heating behavior of various foods and food simulants manipulated the salt content, since salt has a marked effect on the loss factor and consequently the penetration depth. All of the above studies were consistent in observing that focusing was a phenomenon in the materials where no or little salt was added, and surface heating predominated when the salt concentration produced penetration depths less than the radius of the material, usually a cylinder or sphere. However, Zhang et al. (2001) showed that adding salt to ham at 1.6%, an intermediate concentration, could mitigate focusing and surface heating effects to improve heating uniformity during microwave sterilization to 121 ºC at 2450 MHz.

Aside from compositional modifications, the effect of physical movement of foods during microwave processing, such as rotation, to improve heating uniformity has received little attention despite its ubiquitous presence in domestic microwave ovens. A study by Geedipalli et al. (2007) has modeled the effect of rotation and experimentally quantified the improvement in heating uniformity contributed by rotation. The researchers found that rotation improved heating uniformity by 37-43% when using the coefficient of variance as the quantifiable response. However, it was noted that uniformity did not increase across different horizontal layers of the food, and that movement of the food from top to bottom during processing could greatly improve heating uniformity (Geedipalli et al., 2007). Heating improvements due to rotation were also observed by Oliveira and Franca (2002). Quantifiable results were not discussed, although the authors noted that rotation in combination with power cycling improved heating uniformity to a greater extent than either method alone.

1.2.2.2 Focusing of microwaves

Focusing of microwaves in foods is responsible for volumetric heating and is largely dependent on their shape and dielectric properties, as well as the microwave frequency and wavelength in the food (Zhang and Datta, 2005a; Zhang and Datta, 2005b). Slabs, spheres, and cylinders have been studied most frequently due to their simplified shape and ability to model the heating behavior and electromagnetic field distributions. It has been shown that these shapes contribute their own geometric effects, which are also a function of their dielectric properties. For example, the corners of slabs are subject to overheating due to the convergence of microwaves from multiple directions (Zhang and Datta, 2001). In the case of spheres and cylinders, focusing can occur when the diameter is approximately 1.5 times the penetration depth (Buffler, 1993; Decareau, 1985).

Zhang and Datta (2005a) have shown the wavelength of microwaves and the penetration depth in the food to be major determinants in understanding the focusing effect in foods. Zhang and Datta (2005a) point out that for most foods, penetration depth is largely dependent on ε'' and wavelength of microwaves in the food is dependent on ε'. Microwave focusing can be accurately predicted in spherical foods based on the wavelength of microwaves in the food (based on dielectric properties) and the size, or radius of the sphere. Contrary to previous work, Zhang and Datta (2005a) found that maximum focusing occurs in spheres when $r = 2*D_p$., where r is the radius. Lastly, the authors found that microwave focusing does not occur when $r < 0.5$ cm at 2450 MHz.

1.3 Dielectric properties

1.3.1 Fundamentals of electromagnetic waves

Electromagnetic waves are made up of two components, an electric and a magnetic component which are perpendicular to each other. "Two fundamental components are necessary for a propagating [electromagnetic] wave to exist: an electric field (*E*, volts per meter) and a magnetic field (*H*, amperes per meter)" (Meredith, 1998). When an electromagnetic wave comes in contact with a dielectric material, parts of the wave will be reflected and others will be transmitted through the material. How the wave interacts with the material is dependent on the dielectric properties of the material as well as the angle of the incident waves (Coronel, 2005).

1.3.2 Dielectric properties of food materials

Dielectric properties of food materials influence the efficacy of microwave heating. Dielectric properties of a material describe how well electromagnetic radiation interacts with the material, and is characterized by two components: the dielectric constant (ε') and dielectric loss factor (ε''). The dielectric properties of a given food material are influenced largely by the chemical composition, temperature, frequency, and physical structure of the material (Ryynänen, 1995). A thorough understanding and analysis of the dielectric properties of the material of interest is critical to develop an efficient microwave heating operation.

1.3.2.1 Dielectric constant and loss factor

The dielectric constant (ε') describes the ability of a material to store electromagnetic energy when placed in an electromagnetic field, whereas the dielectric loss factor (ε''), an imaginary quantity, is indicative of the conversion of electromagnetic energy into thermal energy. These two components make up the complex relative permittivity ε_r, where

$$\varepsilon_r = \varepsilon' - j\varepsilon''$$

and $j = \sqrt{-1}$. The dielectric loss factor ε'' is proportional to the amount of thermal energy converted in the food, and seen as a rise in temperature (Schubert and Regier, 2005). The dielectric loss factor takes into account both dipolar rotation and ionic conductivity effects:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_0 \omega}$$

where subscripts d and σ refer to contributions from dipolar rotation and ionic conductivity, respectively. σ (S m^{-1}) is the ionic conductivity, ε_0 is the permittivity of free space (8.854 x 10^{-12} F m^{-1}), and ω (rad s^{-1}) is the angular frequency (Tang, 2005). Dipolar rotation is important at high frequencies, whereas ionic conduction prevails at low frequencies (Ryynänen, 1995).

Two other often-used descriptive parameters are the loss tangent and penetration depth. The loss tangent (tan δ) is defined as

$$\tan\delta = \varepsilon''/\varepsilon'$$

This parameter is useful in applications where the dielectric constant of a food may change as a function of temperature. In such a case, the loss tangent is a better estimate of power dissipation in the material as it accounts for the dielectric constant, as opposed to only examining the loss factor. A material with a higher loss tangent will heat faster than a material with a lower loss tangent when exposed to microwave radiation at the same frequency. However, to accurately compare heating rates, thermophysical properties (specific heat, density, thermal conductivity) of the materials must be taken into consideration (Gabriel et al., 1998).

Penetration depth (d_p) is defined as the distance at which the power drops to 1/*e* (37%) of its value at the surface of the material, and can be written as

$$d_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]^{-1/2}$$

where λ_0 is the free space wavelength and $\lambda_0 = c/f$. c is the speed of light (3 x 10^8 m/s) and f is the frequency of the microwave. From the equation, it is evident that penetration depth is dependent on the dielectric properties of the material as well as the frequency or wavelength of the incident microwave. It follows that increasing the frequency, and thereby decreasing wavelength results in reduced penetration depths.

Calculation of the penetration depths of materials is useful in predicting heating characteristics of food materials. Materials with high loss factors will dissipate energy very rapidly and confine heating to the surface, whereas in materials with lower loss factors microwave energy will penetrate farther into the material (Datta and

Anantheswaran, 2001). At a distance greater than the penetration depth, conversion of electrical energy into thermal energy is negligible.

1.3.2.2 Dielectric heating mechanisms

Dipolar rotation

Dielectric properties of materials are determined largely by their chemical composition. Water content is a major determinant of microwave heating. When placed in an oscillating microwave field, the positively and negatively charged regions of the dipole try to align with the changing electrical field. This changing alignment results in intermolecular friction that is dissipated as heat and is known as dipolar rotation or orientation polarization (Ryynänen, 1995). It is important to realize that this heating mechanism is not attributed to a single molecule; rather, it is a bulk phenomenon (Gabriel et al., 1998).

Ionic conduction

Ionic species also influence the dielectric properties of both aqueous solutions and solid food materials by ionic conduction. Ionic conduction results from ions attempting to align with the oscillating electrical field, which in turn results in friction and heat. The degree of ionic conduction is dependent on the operating frequency and ionic size (De Los Reyes et al., 2007). The higher is the molecular weight of an ion; the lower is its contribution to ionic conductivity at a given frequency. Generally, as frequency increases, ionic conduction decreases as seen in Figure 2.

1.3.3 Factors affecting dielectric properties

Dielectric properties are influenced by both intrinsic properties of a material and extrinsic factors. Chemical composition and structural characteristics of foods are critical factors which influence dielectric properties; especially water and salt contents. Extrinsic factors to the food include frequency and temperature; these factors also influence dielectric properties of the food, and thus its microwave heating properties.

1.3.3.1 Frequency effects

Dielectric properties of a given material change with frequency. Many studies have examined the effect of frequency on the dielectric properties of water and ionic solutions (Hasted et al., 1948; Haggis et al., 1952; Lyashchenko and Zasetsky, 1998), as well as agricultural commodities (Nelson, 2005). At the fundamental level, frequency determines which mechanism of heating predominates: ionic conduction or dipolar rotation (Figure 2). Below microwave frequencies (< 200 MHz), ionic conduction plays a major role. At normal microwave operating frequencies (915 and 2450 MHz), both ionic conduction and polarization mechanisms occur (Tang, 2005). At very high frequencies, the ability of molecules to orient with the rapidly changing field decreases, and therefore both ε' and ε'' decrease.

The loss factor of a given molecule peaks when the critical frequency (f_c) is reached, and is related to the relaxation time (τ) of the molecule by equation

$$f_c = 1/2\pi\tau$$

An example is given for water in Figure 3. Generally, larger molecules have longer relaxation times since they are less mobile. Therefore, the critical frequency decreases with increasing molecular size. A major effect that influences dielectric properties of biological materials deals with the state of water. Free water is very mobile with a short relaxation time (0.0071 ns), whereas the mobility of bound water is reduced and effectively increases the relaxation time, lowering the critical frequency. This becomes important when processing foods with low water activities (more bound water); lower frequencies would be more beneficial in heating.

1.3.3.2 Temperature effects

The effect of temperature on the dielectric properties of food materials is very important for thermal processing of foods and is largely dependent on the composition. The effect of temperature on dielectric properties has been studied for water and model systems such as aqueous solutions with varying salt contents (Hasted et al., 1948), as well as for food products (Tong et al., 1994; Sun et al., 1995; Nelson, 2003; Sipahioglu and Barringer, 2003; Guan et al., 2004; Brinley et al., 2008). Even though food systems are highly complex, the dielectric properties of foods still show good correlations with water, salt and/or ash contents.

It is known that increasing the temperature of solutions results in increased Brownian motion and reduced viscosity (Von Hippel, 1954). Assuming molecules are spherical, relaxation time (τ) can be related to the volume of the molecule (V), viscosity of the solution (η), the Boltzmann constant (k), and absolute temperature (T) by the following equation:

$$\tau = V\frac{3\eta}{kT}$$

From the equation, it can be seen that as the molecular size and viscosity increase, so does the relaxation time. Increasing the temperature reduces the relaxation time. Since temperature influences molecular relaxation times, temperature also influences the critical frequency ($f_c = 1/2\pi\tau$). Increasing the temperature and the resultant reduction of the relaxation time would then shift the peak ε'' and critical frequency to a higher frequency (Tang, 2005). When ions such as Na^+ and Cl^- are introduced into the system, a positive relationship between temperature and ε'' is observed at low frequencies due to the predominant role of ions (Roebuck and Goldblith, 1972). As a result, runaway heating often occurs in high salt foods.

1.3.4 Dielectric properties of fruits and vegetables

To date, no literature exists which has examined the dielectric properties of acidified vegetables, although the dielectric properties of many raw fruits and vegetables have been determined. Very limited data has been collected on the dielectric properties of organic acids commonly used to acidify vegetables, such as acetic and citric acids. Many studies have focused on developing predictive models of the dielectric properties of fruits and vegetables as functions of temperature, moisture content, ash, density, plant constituents (e.g. starch, pectin, polysaccharides), and combinations thereof.

The dielectric properties of fruits and vegetables have been measured as functions of frequency, also known as dielectric spectroscopy (Nelson et al., 1994; Nelson, 2003; Guo et al. 2007; Nelson et al., 2007). Dielectric spectroscopy provides the advantage of understanding the underlying dielectric heating mechanisms of a material. Nelson (2003) found a low correlation between moisture content and dielectric properties of fruits and vegetables, although ε' generally increased as moisture content increased. The differences in dielectric properties were attributed to tissue structure, density, and the degree of water binding (Nelson, 2003). Further work by Nelson et al. (2007) which measured the dielectric properties of the external surface and inner tissue of watermelon supported the role of tissue structure. Ionic conduction was observed in the inner tissue, whereas dipolar relaxation predominated near the external surface. The authors hypothesized that the unexpected dominance of dipolar relaxation was a result of different mechanisms (e.g. Maxwell-Wagner, bound water, molecular cluster, and ion-related phenomena) (Nelson et al., 2007). While dielectric spectroscopy provides insight to the behavior of materials at a range of frequencies, other factors play a major role at the frequencies of interest for microwave heating.

1.3.4.1 Water and ash content

Water, salt/ash content, and temperature play major roles in the dielectric properties—and microwave heating characteristics—of fruits and vegetables. Sipahioglu and Barringer (2003) measured a variety of fruits and vegetables at 2450 MHz and found moisture content to be positively associated with both ε' and ε''. The dielectric constant decreased with temperature for all fruits and vegetables, whereas ε'' decreased then increased due to a transition from ionic to dipolar heating mechanisms (Sipahioglu and Barringer, 2003). Increased ash content was associated with higher values of ε''. The findings of Sipahioglu and Barringer were consistent with those of Funebo and Ohlssen (1999), who used density in addition to temperature and moisture content to develop predictive models.

1.3.4.2 Chemical composition

The least understood determinant of dielectric properties is perhaps the complex chemical composition of food materials. Even though water and salt/ash are the major components which directly interact with the electromagnetic field (Sun et al., 1995), their interactions with sugars, starch, pectin, and other plant polysaccharides influence their ability to reorient with the oscillating field. Ndife et al. (1998) observed differences in dielectric properties between six different species of starch, but could not relate the differences to the structural differences of the starches used. However, varying degrees of water binding were likely responsible for the observed differences, according to the theory of Roebuck and Goldblith (1972). Similar to the findings of Ndife were the findings of Brinley et al. (2008) which showed varying dielectric properties of sweet potato purees produced from different cultivars.

Soluble solids such as sugars have also been shown to increase ε″ due to their conductive properties. However, this property has not been shown to be a reliable predictor of dielectric properties, and vice versa (Funebo and Ohlssen, 1999; Guo et al., 2007). Pectic substances have been shown to bind water and reduce the dielectric properties of fruits, thereby masking the predicted effect due to sugars (Funebo and Ohlssen, 1999).

Dielectric property prediction models have been developed with varying degrees of success. Accurate models can be produced for specific products, as demonstrated by Brinley et al. (2008) who found moisture, sugar and starch to be the critical factors for dielectric property modeling of sweet potato purees. It is apparent that the complexity and variability of food matrices makes accurate modeling difficult. More dielectric property data are still needed in order to advance the utility of predictive models.

1.3.5 Dielectric properties of organic acids

One study by Bohigas and Tejada (2009) studied the dielectric properties of acetic acid and vinegar as a function of acid concentration and frequency and found that ε′ decreases and ε″ increases as concentration increases from 1 to 8 GHz. Acetic acid was found to be the critical factor in measuring the dielectric properties of different types of vinegars, as other minor components did not mask the effect of acetic acid. This finding has enabled the use of dielectric spectroscopy to measure the acetic acid content of vinegars up to 10% w/v acetic acid. No data exists in the literature for citric acid, although Marcotte et al. (2000) found no significant contribution of citric acid to electrical conductivity during the ohmic heating of foods.

1.3.6 Measurement of dielectric properties

Open-ended coaxial probe technique

The open-ended coaxial probe technique is a simple and efficient method for dielectric properties measurement of food and other biological materials. This measurement technique employs the use of a coaxial cable, which is put in contact with the material under test (MUT). The coaxial cable is connected to a network analyzer. When a measurement is triggered, a sine wave signal at a specified frequency is incident on the MUT. Once in contact with the MUT, the wave can be transmitted through the MUT, absorbed by the MUT, and/or reflected by the MUT. Dielectric properties of the material are determined by the phase and amplitude of the reflected signal read by the network analyzer (Venkatesh and Raghavan, 2005).

Use of the open-ended coaxial probe technique is appropriate for food materials because of its robustness. Liquids and solids are easily measured, and proper sample cell design enables dielectric properties measurement over a wide range of temperatures, including commercial sterilization temperatures as high as 130 ºC (Guan et al., 2004; Kumar et al., 2007; Brinley et al., 2008).

1.4 Color and texture in food quality

1.4.1 Color measurement systems

Over the course of the 20th century, three tristimulus colorimetry systems have evolved: the CIE system (1931), the Hunter Lab system (1958), and most recently the CIE L^*, a^*, b^* (CIELAB) system (1976). Today, the CIELAB system is most commonly used in the food industry for objective color measurements (MacDougall, 2002). The CIELAB system provides a uniform color space, where lightness is denoted by L^*, red/green by a^*(+/-), and yellow/blue by b^*(+/-). Measurement of these three values produces a distinct coordinate in color space.

Two useful values can be derived from a^* and b^*: they are hue angle and chroma. Hue angle (H°) is defined as:

$$
\begin{aligned}
&H° = \tan^{-1}(b^*/a^*) && \text{when } a^* > 0 \text{ and } b^* \geq 0 \\
&H° = 180° + \tan^{-1}(b^*/a^*) && \text{when } a^* < 0 \\
&H° = 360° + \tan^{-1}(b^*/a^*) && \text{when } a^* > 0 \text{ and } b^* < 0
\end{aligned}
$$

Hue angle refers to the perceived color, whereas chroma (C*) is a measure of the color intensity, where

$$C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

Lastly, a third parameter (ΔE) is also commonly used to compare the total color difference, where

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

All of the aforementioned color parameters continue to be useful for quality monitoring of fresh and processed foods.

1.4.2 Color degradation of vegetables

Broccoli

The green color of broccoli and other green vegetables is attributed to the presence of chlorophyll in chloroplasts. Chlorophyll can be degraded by heat, acid, and enzymatic activity (Heaton and Marangoni, 1996). Each of these mechanisms displaces the magnesium ion (Mg^{++}) from the center of the porphyrin ring of chlorophyll, which is replaced by two hydrogen ions (H^+), and produces olive-brown pigments called pheophytins and pheophorbides. This process is generally referred to as pheophytinization. Regardless of the type of green vegetable under study, green color degradation is related to processes that affect coloring compounds, such as chlorophyll and chlorophyllides (Tijskens et al., 2001a). It follows that an understanding of these processes related to chlorophyll degradation be understood.

Heat. Previous studies have examined the impact of blanching (Barrett et al., 2000; Tijskens et al., 2001a), cooking methods (Turkmen et al., 2006), and pasteurization and sterilization processes (Shin and Bhowmik, 1994) on chlorophyll degradation in green vegetables. Green color degradation is observed with prolonged exposure to heat. Tijskens et al. (2001a) conducted a comprehensive study of blanching times and temperatures with regards to the color of green beans and broccoli. It appeared that the green color described by the ratio of –a*/b* increased as blanching temperature increased from 40 ºC to 90 ºC. However, color increased only within the first minute of blanching and then decreased due to chemical decay and leaching into the blanch water (Tiljskens et al., 2001a). The reason for the increase in green color during the initial stages of blanching is still controversial. Early work by Mackinney and Weast (1940) and Meyer (1960) postulated that the increase in green color was due to the elimination of intracellular air and ingress of blanch water and cellular fluids as a result of cell disruption. While this mechanism is widely accepted, others suggest additional or alternative mechanisms such as the conversion of non-colored precursors during blanching as being responsible for brightening of the green color (Tijskens, 2001a).

pH. Compared to process operations such as cutting and heating of green vegetables, lowering of the pH is the fastest mechanism of color degradation. The conversion of chlorophyll to pheophytin as affected by pH has been studied since the early 20th century by Mackinney and Joslyn (1938, 1940a, 1940b). The effect of pH on the green color degradation of blanched broccoli has been studied by Gunawan and Barringer (2000) and Tijskens et al. (2001b). Pheophytinization is a first order reaction and is a function of hydrogen ion concentration (Joslyn and Mackinney, 1938; Gold and Weckel, 1959; Canjura et al., 1991). It follows that increasing the acid concentration for lowering the pH results in a faster rate of color degradation since more dissociated hydrogen ions are available to replace Mg^{++}. It should be noted that increasing the temperature and duration of acid treatment also increases the rate of color change.

The rate of color decay is not solely a function of acid concentration. Gunawan and Barringer (2000) found that the color degradation rate of blanched broccoli was also dependent on the polarity of the acidulant. Poorly soluble benzoic and phthalic acids degraded chlorophyll the fastest, whereas the polar acids consisting of acetic, citric and malic acids degraded the green color at a slower rate. It was postulated that the hydrophobic nature of benzoic and phthalic acids imparted by their benzene ring components could easily diffuse through the lipid membrane and displace Mg^{++} with newly dissociated hydrogen ions (Gunawan and Barringer, 2000). It should be noted that diffusion rates of acid into the vegetable tissue were not examined in the study by Gunawan and Barringer. While color change could be indicative of diffusion rates, equilibration time of the broccoli with the surrounding solution needs to be taken into account.

Red bell pepper

A wide variety of carotenoids are responsible for the color of red bell peppers; however, the major pigments include capsanthin (35%), β-carotene (12%), and capsorubin (6%) (Curl, 1962). Carotenoids are stable in the undisturbed vegetable tissue, although degradation may occur once mechanical or thermal processes have disrupted the tissue. The main mechanisms of color degradation are related to oxidation, heat, and light, as these promote oxidation of highly unsaturated carotenoids (Minguez-Mosquera and Hornero-Mendez, 1994). The impact of dehydration on peppers has been studied extensively, and the effects of thermal processing to a lesser extent. Interestingly, a recent study noted steady decreases in red color of red bell peppers after fermentation, heating at 85°C for 15 minutes, and subsequent storage for 30 days (Di Cagno et al., 2009).

Sweetpotato

The color of orange sweetpotatoes is attributed to their high β-carotene content. Subjecting sweetpotatoes to processes such as heating causes changes in color. Compared to the color of raw orange sweetpotato flesh, the color after cooking is observed to be a deeper, brighter orange color. The change in color stems from the disruption of chromoplasts during heating. When the cellular structure is damaged, carotenes are released and become dissolved in other cellular lipids (Purcell et al., 1969). The temperature, length of heating, and mode of heating were shown to significantly alter the isomeric forms of β-carotene, as well degrade β-carotene to a lesser extent, but the changes in color were not examined (Chandler and Schwartz, 1988). Colorimetry information is limited with regards to the effects of heating and storage on sweetpotato color. However, microwave-assisted aseptic processing of sweetpotato puree did not cause any significant color changes compared to unheated controls (Coronel et al., 2005).

1.4.3 Texture of fruits and vegetables

Texture is a multi-dimensional aspect of foods, and has been defined by Szczesniak (2002) as “the sensory and functional manifestation of the structural, mechanical, and surface properties of foods detected through the senses of vision, hearing, touch, and kinesthetics”. With respect to fruits and vegetables, texture is one of the most important quality attributes (Waldron, 2004). Maintenance of acceptable texture is a veritable challenge in that texture is an ever-changing property during maturation, post-harvest handling, processing, and storage. In order to control changes in texture, it is important to understand the underlying processes and properties of fruits and vegetables responsible for texture.

1.4.3.1 Tissue structure and components

Van Dijk and Tijskens (2000) attributed texture to the following processes and mechanisms:

1. turgor pressure inside intact living cells and the associated tissue tension,
2. special compounds inside cells possibly generating strength (e.g. starch),
3. cohesive forces within a cell: chemical properties of the cell wall,
4. adhesive forces between cells: chemical properties of the pectin,
5. overall structure and shape of separate cells,
6. overall structure and shape of tissue: strength and distribution of stronger shaped vascular tissue. (Van Dijk and Tijskens, 2000)

Changes in texture can result from changes to any of these physical or chemical properties. Edible plant tissue is primarily made up of unspecialized parenchyma cells, and is collectively called parenchymatous tissue or parenchyma. Parenchyma cells contain at least one vesicle responsible for turgor pressure, as well as cytoplasm, a plasma membrane, cell wall, and middle lamella (Van Buggenhout et al., 2009). It follows that the composition of parenchyma cells plays a major role in the perceived texture of fruits and vegetables.

The cell walls of parenchyma cells primarily consist of an inter-woven cellulose-hemicellulose matrix, with a small amount of pectin (~ 30% dry weight) (Van Buggenhout et al., 2009). The middle lamella can be thought of as an extension of the cell wall and primarily consists of pectic material. Cross-linking of pectin between the middle lamellae of adjacent cells is responsible for cellular adhesion, and is a major contributor of tissue strength in addition to cell wall strength imparted by the cellulose-hemicellulose matrix (Van Dijk and Tijskens, 2000). The molecular structure of pectin is very complex. Pectin molecules may contain several domains, although homogalacturonan (HG) and rhamnogalacturonan (RG) are the most predominate regions (Van Buggenhout et al., 2009). HG is the simplest and most useful pectin, which has been reflected by the amount of research focused on HG and its industrial use as a texturizing and/or gelling agent (Duvetter et al., 2009). HG is a linear chain polymer of α-1,4-linked D-galacturonans and up to 70 – 80% of carboxyl groups may be methyl-esterified (Van Buggenhout et al., 2009). It is in fact the degree of esterification (DE) of pectin molecules in the middle lamella that dictates the adhesive strength between cells.

Enzymes, namely pectinases play a major role in the texture of vegetables. Pectin methylesterase (PME) and polygalacturonase (PG) are the two most studied pectinases endogenous to plants (Duvetter et al., 2009). PME functions by hydrolyzing methyl esters from O6 of galacturonic acid in HG, and releasing methanol and H_3O^+. Oftentimes, the action of PME is beneficial to maintenance of vegetable texture. The demethoxylation process aids in the removal of bulky methyl ester groups, and thereby facilitates the association and crosslinking of HG chains. PME is heat labile, although its optimum activity range is usually between 50 and 65°C. This trait has been exploited by the use of low temperature blanching to increase tissue firmness of vegetables (Truong et al., 1998; Anthon et al., 2005; Ni et al., 2005; Abu-Ghannam and Crowley, 2006).

Contrary to the beneficial effects of PME on vegetable firmness, PG activity can be detrimental to vegetable texture. PG acts on HG by hydrolysis of the α-1,4-D galacturonan linkages, resulting in shorter HG chains. Reduction in the degree of polymerization breaks up the pectin network, reducing intercellular adhesion, and therefore increasing tissue softening.

1.4.3.2 Thermal effects on vegetable texture

The application of heat to vegetables is closely linked to the endogenous enzymatic activity.

Broccoli

Lin and Chang (2005) used a puncture test on broccoli stems and used peak force as the texture index. Compared to the raw sample, cooking in distilled water for any time up to 60 minutes at 50-70ºC increased the peak force. However, peak forces were highest after 10 minutes of cooking. Cooking at 80 and 100ºC decreased the peak force, which decreased further as cooking time increased to 60 minutes. Precooking the broccoli at 50ºC for 10 minutes prior to cooking for 8 minutes in boiling water increased the relative peak force to 120% of its raw value. This phenomenon was likely due to the well-documented increased activity of pectin methylesterase (PME) at moderate temperatures (45-60ºC) which de-esterifies pectin, leaving more carboxyl groups to be bridged by calcium ions, and increase tissue strength.

Red bell pepper

As it relates to acidified red bell peppers, there is limited information on the effects of pasteurization treatments on texture. The effect of pasteurization on the texture of brined cherry peppers and jalapeno peppers was previously studied by Fleming et al. (1993), but not for red bell peppers. Fleming et al. (1993) found that pepper firmness decreased after pasteurization; however, no decrease in firmness was observed after pasteurization when calcium chloride was added. In fact, more studies have focused on the effects of blanch pretreatments (Papageorge et al., 2003; Ni et al., 2005) and the effects of pH and chemical addition (Papageorge et al., 2003; McFeeters et al., 2004) on the texture of red bell pepper. Firmness was best retained when blanched at 75°C for 3 minutes and the final pH was in the range 3.4 -3.8. Below pH 3.4, firmness was significantly lowered (Papageorge et al, 2003). The presence of oxygen was also shown to accelerate softening, but was inhibited when sulfite was added (McFeeters et al., 2004).

Sweetpotato

Much of the research related to the textural properties of sweetpotato has involved the development of methods to maintain or improve firmness of canned or French fry-type products. More specifically, various acid and base pretreatments have been evaluated. Walter et al. (1992, 1993) found both tissue acidification and alkalization to increase firmness compared to untreated controls of a French fry-type product after frying. Walter et al. (1998) were able to maintain firmness in canned sweetpotatoes for 10 months by using the alkali-neutralization process. Most recently, the application of a low temperature blanching procedure (62°C for 30 or 45 minutes) was also found to result in improved firmness of canned sweetpotatoes (Truong et al., 1998).

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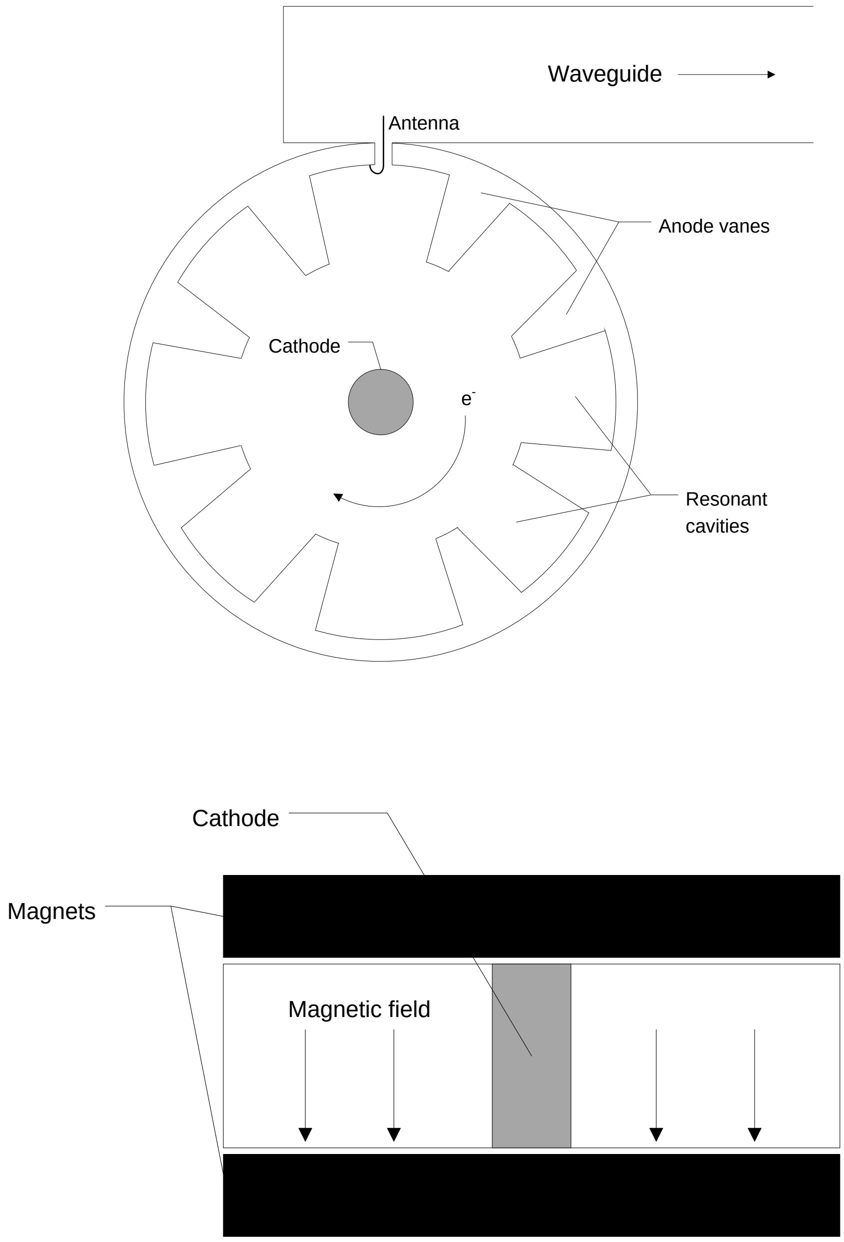

Figure 1. Magnetron schematic. Top view (top) and side view (bottom).

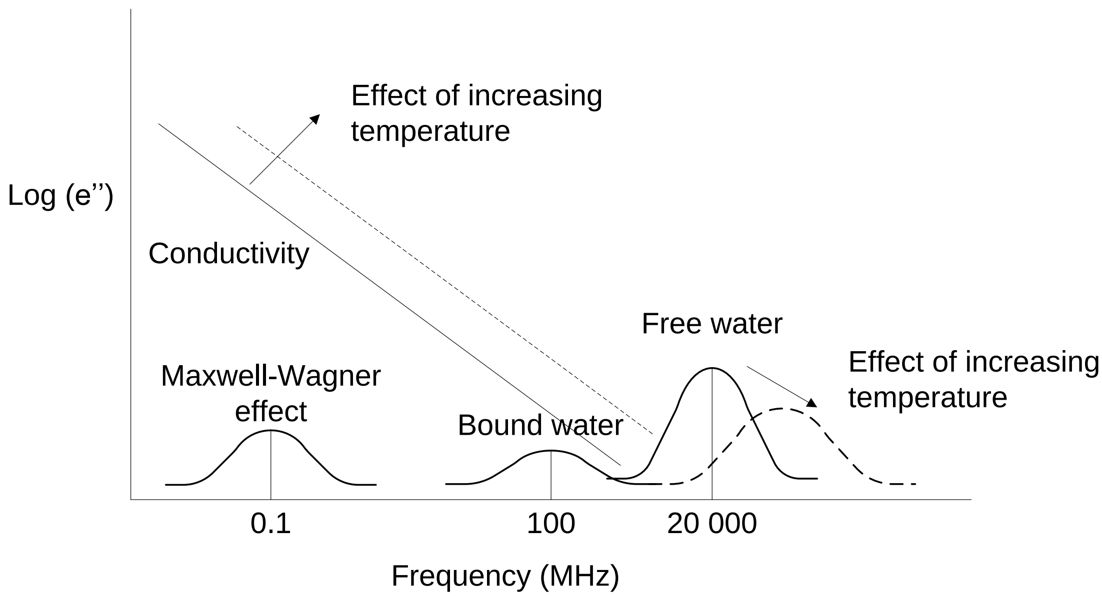

Figure 2. Simplified diagram of indicating the frequencies at which dielectric loss mechanisms occur for moist materials. Effects of temperature are also noted. (adapted from Tang, 2005)

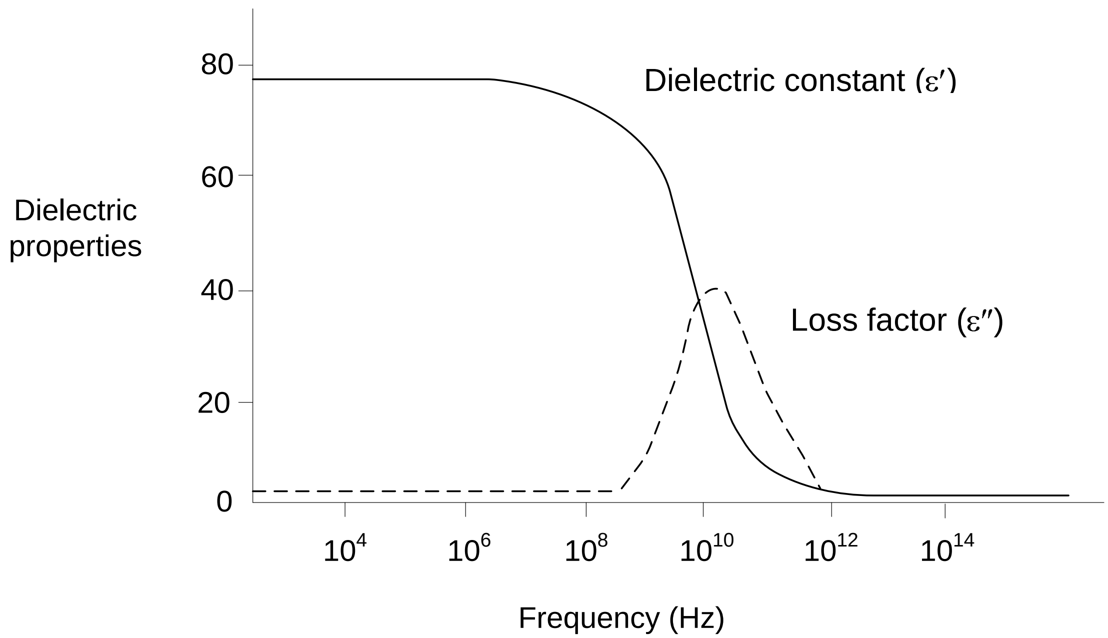

Figure 3. Dielectric properties of free water as a function of frequency. (Adapted from Ryynänen, 1995).

Chapter 2

Effects of Acid, Salt and Equilibration Time on the Dielectric Properties of Acidified Vegetables

2.1 Abstract

Knowledge of the dielectric properties of foods is a critical aspect to any microwave process, as it characterizes the ability of materials to store and convert electromagnetic energy into heat. In order to design a continuous microwave process for pasteurization of acidified vegetables, equilibration phenomena must be examined with regards to changes in dielectric properties. The objective of this study was to examine the effects of acid and salt concentration on the dielectric properties of acidified vegetables. Broccoli florets and sweet potato cubes (1.2cm) were blanched to facilitate acid and salt equilibration by heating for 15 seconds in boiling de-ionized water, then cooling in an ice-water bath. Red bell pepper cubes were not blanched. The vegetable samples were then acidified in solutions of 1-2% NaCl with 0.5-2% citric acid. Dielectric properties were measured in duplicate at 915 MHz from 25 to 100 °C after 0, 4, and 24 hr equilibration periods in the solutions using an open-ended coaxial probe connected to a network analyzer. Acid and salt concentration had no significant effect on the dielectric constant (ε'). However, ε' was significantly different among vegetables (p<0.05). Dielectric loss factor (ε'') was not affected by acid, but significantly increased with salt concentration. Equilibration occurred within 4 hours of salting and acidification. This research shows the changes in dielectric properties of vegetables that occur when acid and salt are added. These results provide necessary information to apply microwave processing technology to acidified vegetables.

2.2 Introduction

The use of microwave processing technology for pasteurization of acidified vegetables presents potential advantages over conventional thermal processing techniques. The application of microwave energy provides rapid heating of both liquid and particulate phases based on dielectric properties, as opposed to conventional methods, which rely on heat transfer by convection and conduction. As a result, microwave energy can potentially shorten heating times, minimize over-processing, and reduce water and energy usage (Thostenson and Chou, 1999). Therefore, microwave processing technology is well-suited to thermal processing of acidified vegetables. However, one of the first steps in determining the feasibility of microwave processing for any food involves the determination of dielectric properties.

Dielectric properties provide insight with regards to the conversion of electromagnetic energy into heat. Collectively, the term "dielectric properties" refers to the dielectric constant (ε') and dielectric loss factor (ε''). The dielectric constant is a real quantity indicative of the capacity of a material to store electromagnetic energy. The dielectric loss factor is an imaginary quantity, and indicates the ability of a material to convert the absorbed electromagnetic energy into heat. Both ε' and ε'' of a food may change as a function of temperature, frequency, moisture content, salt/ash content, density, structure and other compositional differences (Nelson and Datta, 2001).

Oftentimes, foods undergo treatments prior to thermal processing. Thus, it is important to understand the influences of these treatments on the dielectric properties of food materials. In the case of acidified vegetables, such pretreatments include blanching and equilibration of the product in a solution containing acid and salt. Within these treatments, factors such as acid and salt concentrations, as well as the equilibration time may affect dielectric properties, and in turn influence microwave heating. To date, there is no literature available on the dielectric properties of acidified vegetables. With regards to acidulants used in food systems, two studies have examined the dielectric properties of different vinegars (Tanaka et al., 2002; Bohigas and Tejada, 2009) and found detectable differences in dielectric spectra as a function of acetic acid concentration. On the other hand, Lau and Tang (2002) used 915 MHz microwaves in a batch process to pasteurize pickled asparagus with improved textural properties. However, no dielectric property information was presented, and so a full-understanding of the role of dielectric properties in liquid-solid mixtures could not be gained. The objectives of this study were to determine the effects of salt and acid concentrations, and equilibration time on the dielectric properties of broccoli, red bell pepper, and sweetpotato.

2.3 Materials and Methods

Vegetable preparation

Broccoli, red bell pepper, and orange-fleshed sweetpotato (cultivar *Covington*) were used in this study.   Broccoli florets were prepared by cutting into pieces of 3 ± 1cm in length, and 2 ± 1cm in width. Red bell peppers were cored and sweet potatoes were peeled prior to dicing into 1.2 cm cubes using a 3/8 inch slicer plate and 3/8 inch dicer plate of a Hobart food processor (Model FP150, Hobart, Troy, OH).

Titration of vegetable materials

Titration of vegetable tissues with citric acid was necessary in order to determine the quantity of acid required to achieve an equilibrated pH of 3.8. Vegetable tissue and de-ionized water (1:1 w/w ratio) were blended in a Waring blender (Model 700S, Waring Product Corp., New York, NY) for 2 minutes then titrated with 2.70 M citric acid.

Blanching

In order facilitate the acidification of the vegetables to pH 3.8 within 24 h, blanching was evaluated. Broccoli, red bell pepper, and sweetpotato were cut and diced and separated into two groups: unblanched and blanched. Blanching involved submersion of the vegetables in 90 ºC water for 15 s, and then cooling in an ice bath for 2 minutes. The vegetable pieces were submerged in citric acid and NaCl solutions at a 50:50 w/w ratio for red bell pepper and sweetpotato and 30:70 w/w ratio for broccoli. The pH of vegetable samples was measured after 4 and 24 hr equilibration periods. Preliminary experiments indicated that blanching of broccoli and sweetpotato was required to reduce pH to 3.8 within 24 hours. Blanching was not required for red bell pepper. Therefore, based on the rate of acidification, the present study focused on the dielectric measurements of blanched broccoli and sweetpotato, and unblanched red bell pepper.

Equilibration

Food grade citric acid (Thermo Fisher Scientific, Inc., Waltham, MA) and sodium chloride, NaCl, (Sigma Aldrich, St. Louis, MO) were used in the cover solutions to acidify and salt the vegetables. Cover solutions were prepared by weighing NaCl and citric acid monohydrate into a volumetric flask, and diluting to volume with deionized water. The concentrations of NaCl and citric acid used are shown in Table 1. Sweetpotato and red bell pepper (500g), and broccoli (300g) were placed in separate glass jars. Cover solution (500g) was then added to sweetpotato and red bell pepper, and 700g of cover solution added to the broccoli. Jars were then capped and allowed to equilibrate at 20 ± 2 °C.

Measurements of Dielectric properties

Two 25 g vegetable samples were drawn after 0, 4 and 24 hours of holding in the cover solution at 20 ºC for dielectric property measurements. Table 1 shows the treatment summary for determining the effects of salt and acid concentrations. Samples were mashed and placed into a test cell. Dielectric constants and loss factors were measured at 915 MHz using a network analyzer (HP 8753C, Agilent Technologies, Palo Alto, CA) with an open-ended coaxial probe (HP 85070B, Agilent Technologies, Palo Alto, CA) in a pressurized test-cell. The test cell was submerged in an oil bath (Model RTE111, Neslab Instruments Inc., Newington, NH) and the dielectric properties of duplicate samples were measured in 15 ºC intervals from 25 – 100 ºC. The experimental design is illustrated in Figure 1.

Statistical Analysis

Statistical analysis was performed using the mixed procedure (PROC MIXED) in SAS version 9.1 (SAS Institute Inc., Cary, NC). Type three analysis of variance was used to determine differences in ε' and ε'' with respect to vegetable type, salt and acid levels, temperature, equilibration time, and their interactions.

2.4 Results and Discussion

Dielectric properties of raw vegetables

The dielectric properties of raw broccoli, red bell pepper, and sweetpotato were measured to establish an initial time point prior to acidification. The dielectric constants (ε') and loss factors (ε'') as a function of temperature are shown in Figure 2. Dielectric constants for red bell pepper were the highest, followed by sweetpotato and broccoli. Conversely, red bell pepper had the lowest values of ε'', followed by broccoli and sweetpotato. Statistical analysis (Table 2) showed that ε' and ε'' were significantly different between vegetables over the temperature range from 25 - 100ºC. For each vegetable, ε' decreased and ε'' increased with increasing temperature. These findings were consistent with previous reports (Kumar et al., 2007; Brinley et al., 2008), which showed the same trends in ε' and ε'' for vegetables at 915 MHz as temperature increased.

Interestingly, ε″ of sweetpotato was markedly greater than both red bell pepper and broccoli. The greater values of ε″ for sweetpotato were likely a result of the higher sugar content (Brinley et al. 2008) or other chemical constituents contributing to the ionic loss, since the moisture content of sweet potato was lower (79.5% f.w.b.), compared to 88.4% and 92.8% moisture for broccoli and red bell pepper, respectively.

Effect of equilibration time on dielectric properties

The diffusion of intracellular solutes into the cover solution and migration of salt and citric acid into the vegetable tissue is a dynamic, time-dependent process. Preliminary experiments showed that the pH of unblanched tissues of broccoli and sweetpotato could not be lowered to pH 3.8 within 24 hr when equilibrated in a cover solution at room temperature. Therefore, a blanching step was implemented to disrupt the cellular structure and facilitate the movement of salt and citric acid into the vegetable tissue to more rapidly lower the pH. The blanching procedure was used for broccoli and sweetpotato; however, no blanching step was used for red bell pepper since its pH was lowered to pH 3.8 within 24 hours.

Dielectric properties of salted, acidified vegetables were measured after 4 and 24 hours of soaking in a 2% NaCl, 2% citric acid cover solution to monitor the equilibration process. The dielectric constants of each vegetable did not change significantly from their raw values over the 24 hr equilibration period (Table 2, Figure 3). In Figure 3, 0% NaCl refers to ε′ measured at time 0 (unsoaked). The datasets labeled as 1% NaCl refer to vegetable pieces soaked in a 2% NaCl solution; i.e the equilibrated concentration of NaCl in the vegetable pieces was 1%. As expected, dielectric loss factors increased significantly compared to initial values due to ionic losses contributed by NaCl (Figure 4). This finding was consistent with previous works (Herve et al., 1998; Mao et al., 2003) that showed no change in ε' at 915 MHz when sodium chloride was added in the range of 0 to 3% to surimi and cottage cheese, but significant increases in ε'' were observed and closely related to salt concentration. The current study showed no significant differences in ε'' between 4 and 24 hours for each vegetable, and loss factors of different vegetables were not significantly different (Table 2). However, Figure 4 shows that the variability of loss factors between vegetables was reduced between 4 and 24 hr, as shown by the closer grouping of loss factors. These results indicated that vegetables should be soaked for about 24 hr prior to microwave processing to reduce variability in dielectric properties and subsequent heating by microwaves.

Another useful term used to compare dielectric properties is the loss tangent ($\tan\delta$) where $\tan\delta = \varepsilon'/\varepsilon''$. The loss tangent provides a better comparison of dielectric properties because it takes into account both ε' and ε''. Comparing $\tan\delta$ results showed that after soaking, the dielectric properties of the vegetable samples were largely dependent on the salt concentration and very similar to a 1% w/v NaCl solution (Figure 5). This finding suggested that food matrix effects on dielectric properties were minimized when the equilibrated salt content was near 1%. Differences in the loss tangents between vegetables were similar before and after equilibration with salt and acid. This indicated that the addition of salt appeared to have an additive effect on the loss tangents of the vegetables.

While no literature has examined equilibrium phenomena with regards to changes in dielectric properties of salted, acidified vegetables, Sarang et al. (2007) matched the electrical conductivities of different solid food components by blanching them in a highly conductive sauce prior to ohmic heating, thereby producing uniform heating during ohmic heating. Since electrical conductivity is conferred by the presence of ions, it is closely related to the ionic conductivity term of ε″ and linked to dielectric properties. It follows that the equilibration of a variety acidified vegetables to the same salt content would produce more uniform heating among vegetable pieces during microwave processing, enabling more efficient heating of a multi-component product.

Effect of salt concentration on dielectric properties

Vegetables were soaked in cover solutions containing 1% and 2% NaCl to establish the relationship between salt concentration and dielectric properties. After 24 hours of soaking, ε′ of each vegetable did not change significantly from that of the unsoaked samples, regardless of salt concentration (Table 2). However, differences in ε″ with respect to salt concentration were substantial. Figure 6 shows the dielectric loss factors of each vegetable after 24 hours soaking with 0.5 and 1% equilibrated salt concentrations, as well as the unsoaked vegetables. As salt concentration increased, so did ε″ in a linear fashion. Again, this finding was consistent with the work of Harve et al.

(1998) and Mao et al. (2003), as previously discussed. The addition of more salt increased the conductivity, and produced a positive correlation between salt concentration and dielectric loss.

Effect of citric acid concentration on dielectric properties

Different concentrations of citric acid were tested in the presence of NaCl to determine the importance of acidulant levels on the dielectric properties of acidified vegetables. For this experiment, the equilibrated salt concentration was held constant, and the citric acid concentrations varied according to each vegetable. Treatment 1 involved soaking the vegetables in cover solutions containing 2% NaCl and 2% citric acid. For comparison, treatment 2 involved soaking each vegetable in a cover solution containing 2% NaCl and their titration-determined amount of citric acid required to lower the tissue pH to 3.8 (Table 1). For red bell pepper, sweetpotato, and broccoli these amounts were 0.5, 1.0, and 1.5% w/v citric acid, respectively.

Citric acid concentrations ranging from 0.5 – 2.0% w/v in the cover solution had no significant effect on ε', but nearly had a significant effect on ε'' at the 0.05 significance level when salt was present at an equilibrated level of 1% (Table 2). Figure 7 shows this effect graphically by examining the loss factors of each vegetable at their respective citric acid concentrations compared to all vegetables at the same citric acid concentration of 2%. The minimal contribution of citric acid to the dielectric properties of the vegetables was likely due to its molecular structure and the narrow range of concentrations tested.

The degree of interaction of a molecule to a microwave field depends on its size, polarity, and conductivity (Gabriel et al., 1998; De Los Reyes et al., 2007). Small, highly conductive ionic compounds such as NaCl readily dissociate in solution and are very mobile when exposed to 915 MHz microwaves. Citric acid is a larger molecule and has only one charged carboxyl group at pH 3.8. Therefore, due to its lower charge and larger size, citric acid cannot interact as readily to the oscillating electric field, so its contribution to dielectric loss is less. Therefore, when both NaCl and citric acid were present in the system, the contribution of NaCl overshadowed any measureable effect of citric acid. These results showed that concentrations of citric acid typically used in acidified vegetables had little effect on the dielectric properties when salt was added at an equilibrated level of 1%.

2.5 Conclusion

This research showed that salt was the major contributor to changes in dielectric properties of acidified vegetable products. Salt concentration had no significant effect on the dielectric constant of acidified vegetables, but was significantly associated with the dielectric loss factor. Variability in dielectric properties decreased as equilibration time increased. Citric acid was found to have minimal effects on the dielectric properties of acidified vegetables when used in conjunction with sodium chloride at levels of 0.5 – 2.0%. Furthermore, these findings provide food formulators flexibility in acidulant levels when designing foods for microwave processing.

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Table 1. Cover solution compositions and vegetable:solution ratios

	Treatment 1		Treatment 2		Treatment 3		
Vegetable	Citric acid (% w/v)	NaCl (% w/v)	Citric acid (% w/v)	NaCl (% w/v)	Citric acid (% w/v)	NaCl (% w/v)	Vegetable:solution ratio
Broccoli	1.5	2.0	1.5	1.0	2.0	2.0	30:70
Red bell pepper	0.5	2.0	0.5	1.0	2.0	2.0	50:50
Sweetpotato	1.0	2.0	1.0	1.0	2.0	2.0	50:50

Table 2. Analysis of variance for ε′ and ε″

Effect [a]	**Dielectric constant, ε'** **Pr > F**	**Loss factor, ε''** **Pr > F**
Veg	0.0020	<0.0001
Acid(Veg)	0.3772	0.0615
Salt(Veg)	0.9049	<0.0001
Time	0.2653	<0.0001
Temp	<0.0001	<0.0001
Time*Temp	0.0365	<0.0001
Veg*Time	0.5120	0.0615
Time*Acid(Veg)	0.8079	0.1928
Time*Salt(Veg)	0.9934	0.0019
Temp*Acid(Veg)	0.5197	0.0248
Temp*Salt(Veg)	0.5493	<0.0001
Time*Temp*Salt(Veg)	0.9866	0.0008
Time*Temp*Acid(Veg)	0.4549	0.0448

[a] Veg = vegetable type; Temp = temperature

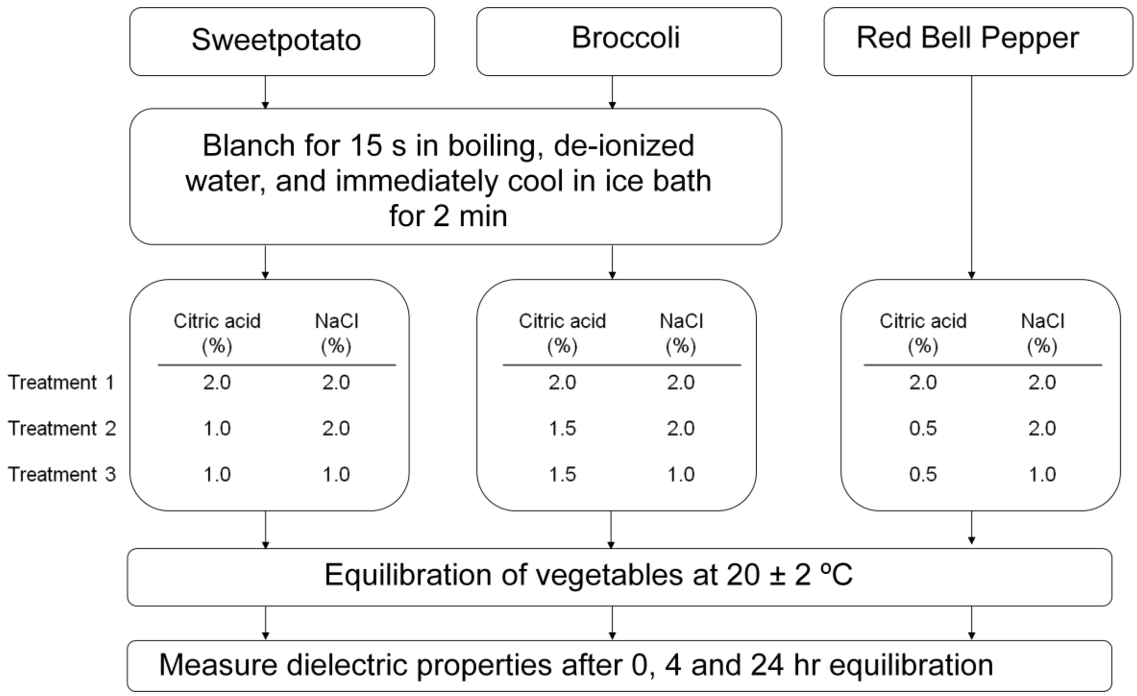

Figure 1. Diagram of experimental procedure.

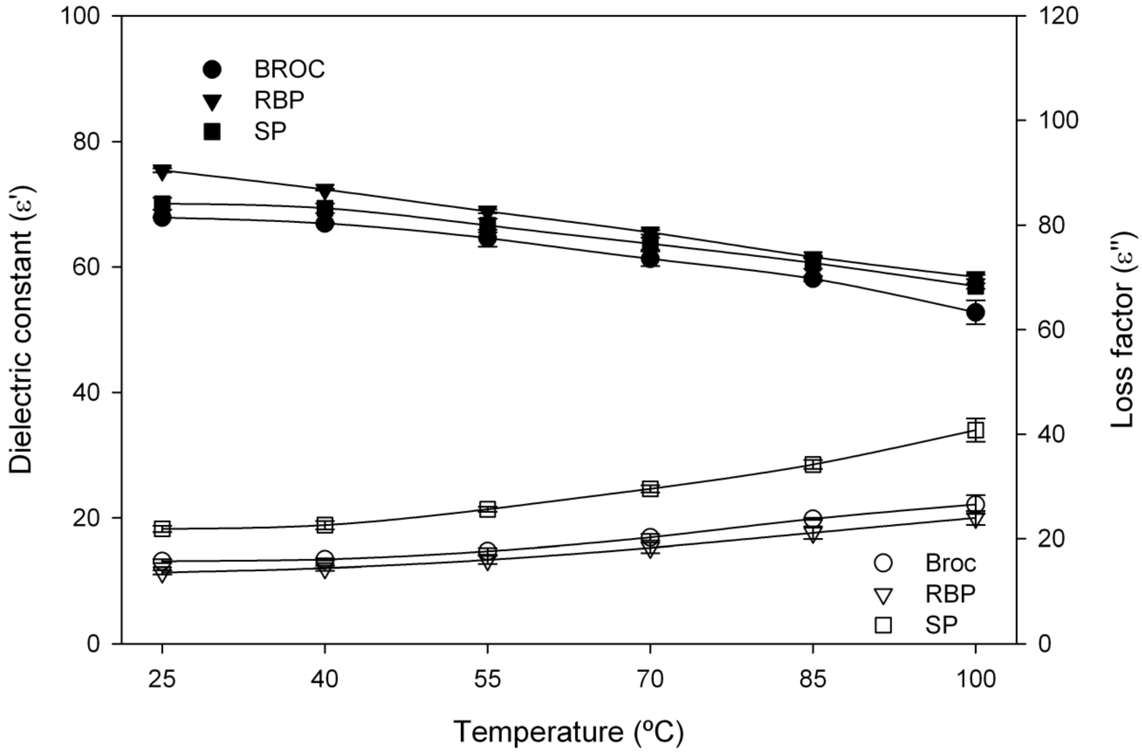

Figure 2. Dielectric constants (closed symbols) and loss factors (open symbols) as a function of temperature for broccoli (BROC), red bell pepper (RBP), and sweetpotato (SP).

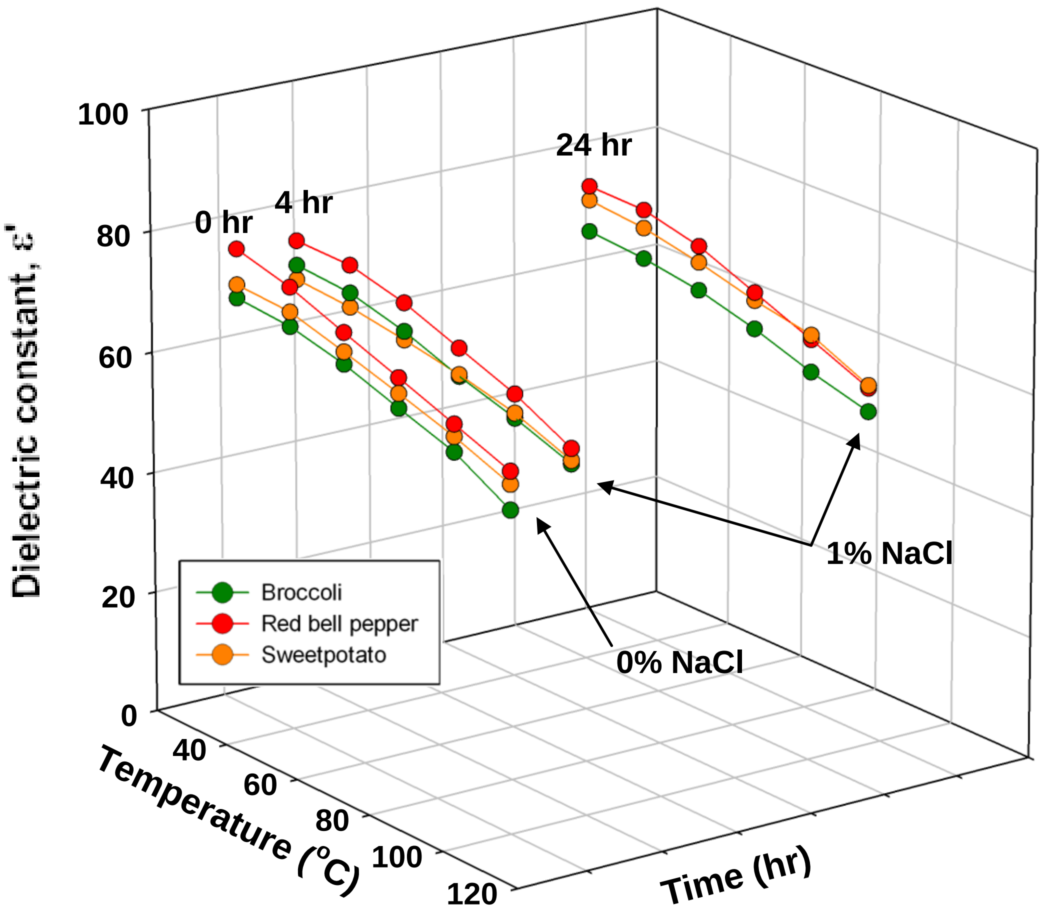

Figure 3. Dielectric constants ε′ of broccoli, red bell pepper and sweetpotato measured at 915 MHz as functions of temperature and equilibration time (0, 4, and 24 hr) in a 2% NaCl (w/v), 2% citric acid (w/v) solution.

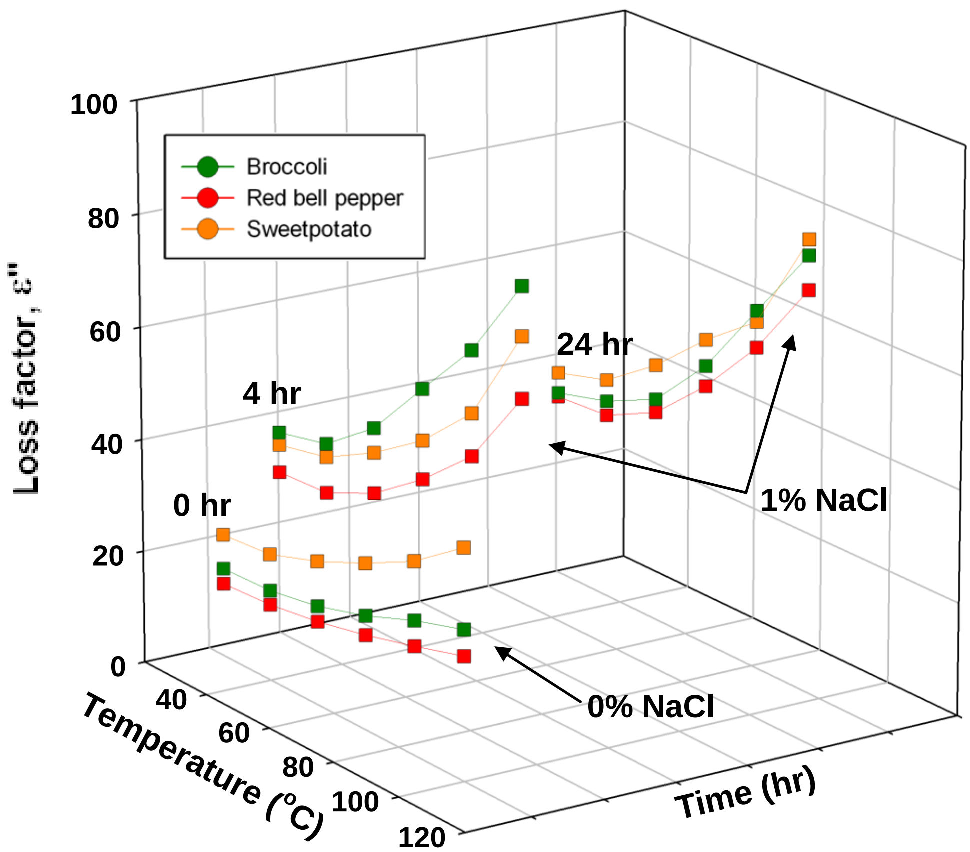

Figure 4. Loss factors ε′′ of broccoli, red bell pepper and sweetpotato measured at 915 MHz as functions of temperature and equilibration time (0, 4, and 24 hr) in a 2% NaCl (w/v), 2% citric acid (w/v) solution.

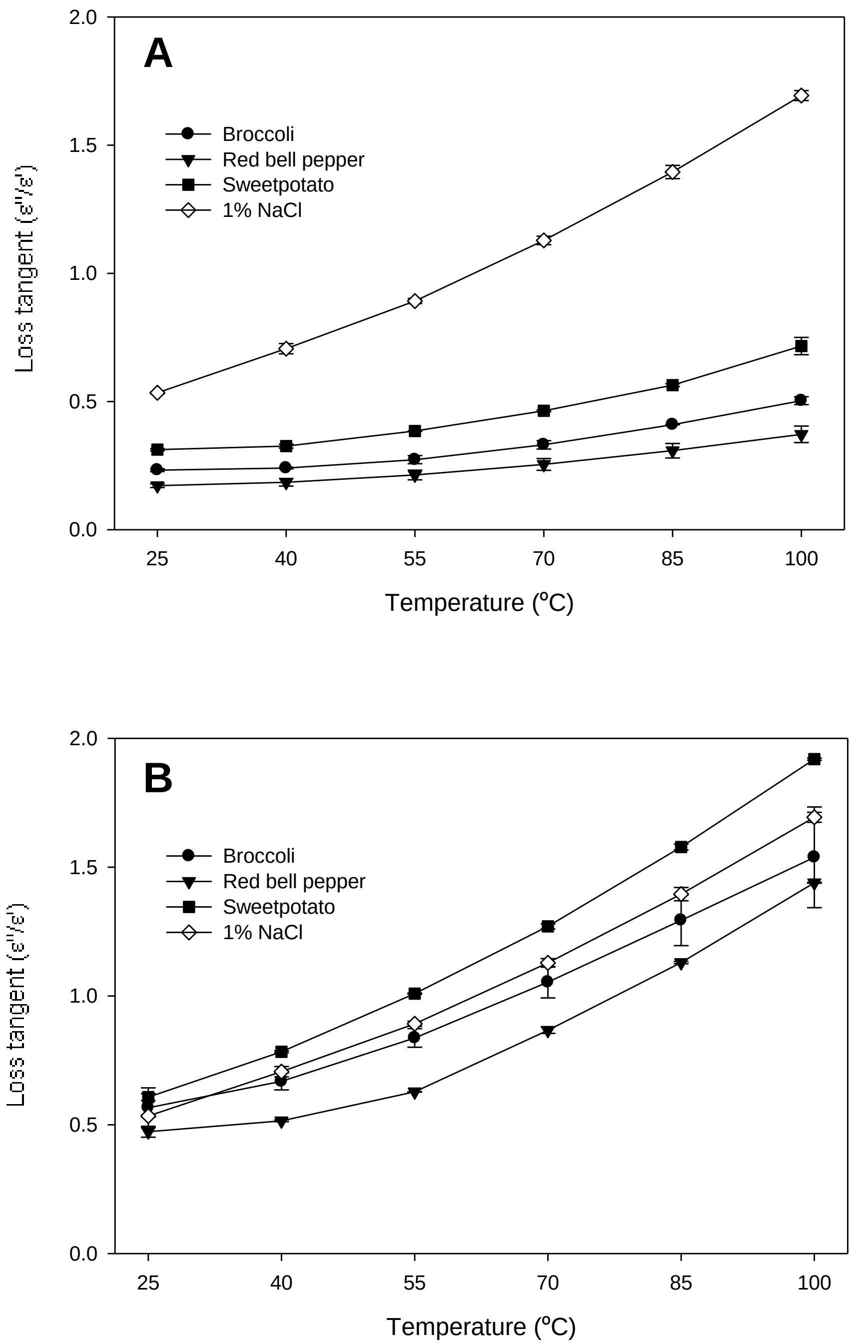

Figure 5. Loss tangents of vegetables before (A) and after (B) equilibration in a 2% NaCl, 2% citric acid cover solution for 24 hr. Loss tangent of 1% NaCl solution is included as a reference. Error bars represent one standard deviation (n = 2).

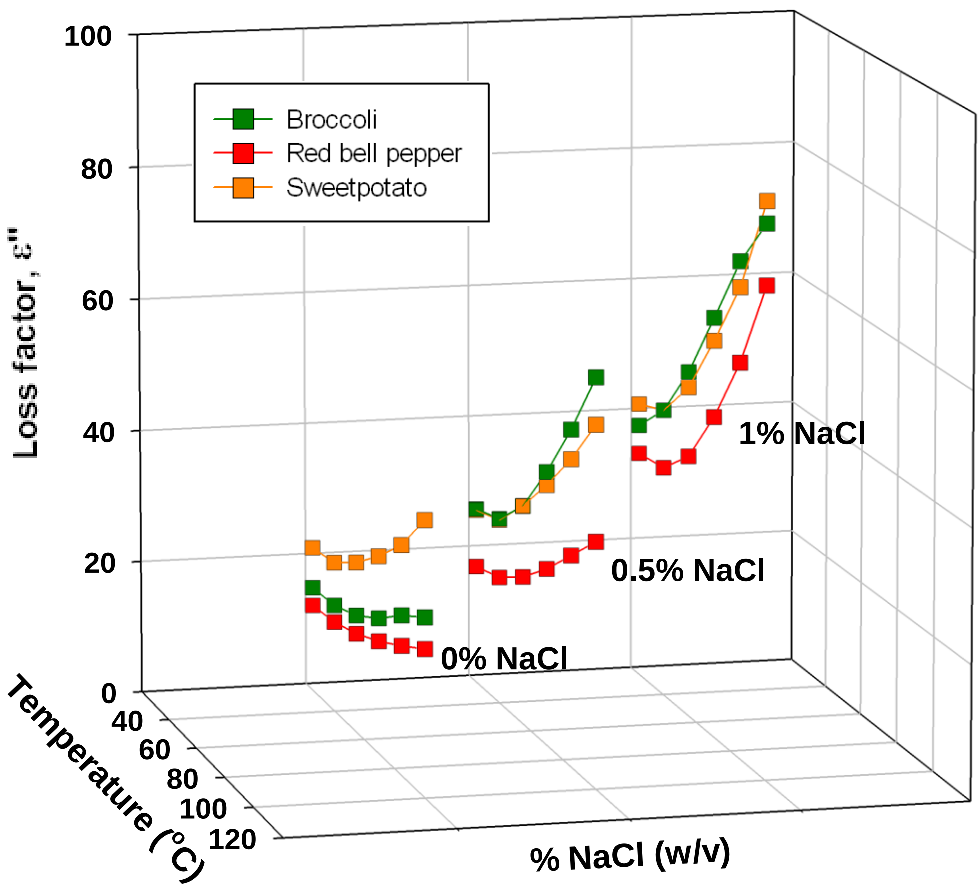

Figure 6. Dielectric loss factors ε′′ of broccoli, red bell pepper, and sweetpotato after a 24 hr equilibration period in 1 and 2% NaCl solutions. Unsoaked vegetables at time 0 are labeled as 0% NaCl.. Each vegetable was acidified with its titration-determined amount of citric acid in the cover solution.

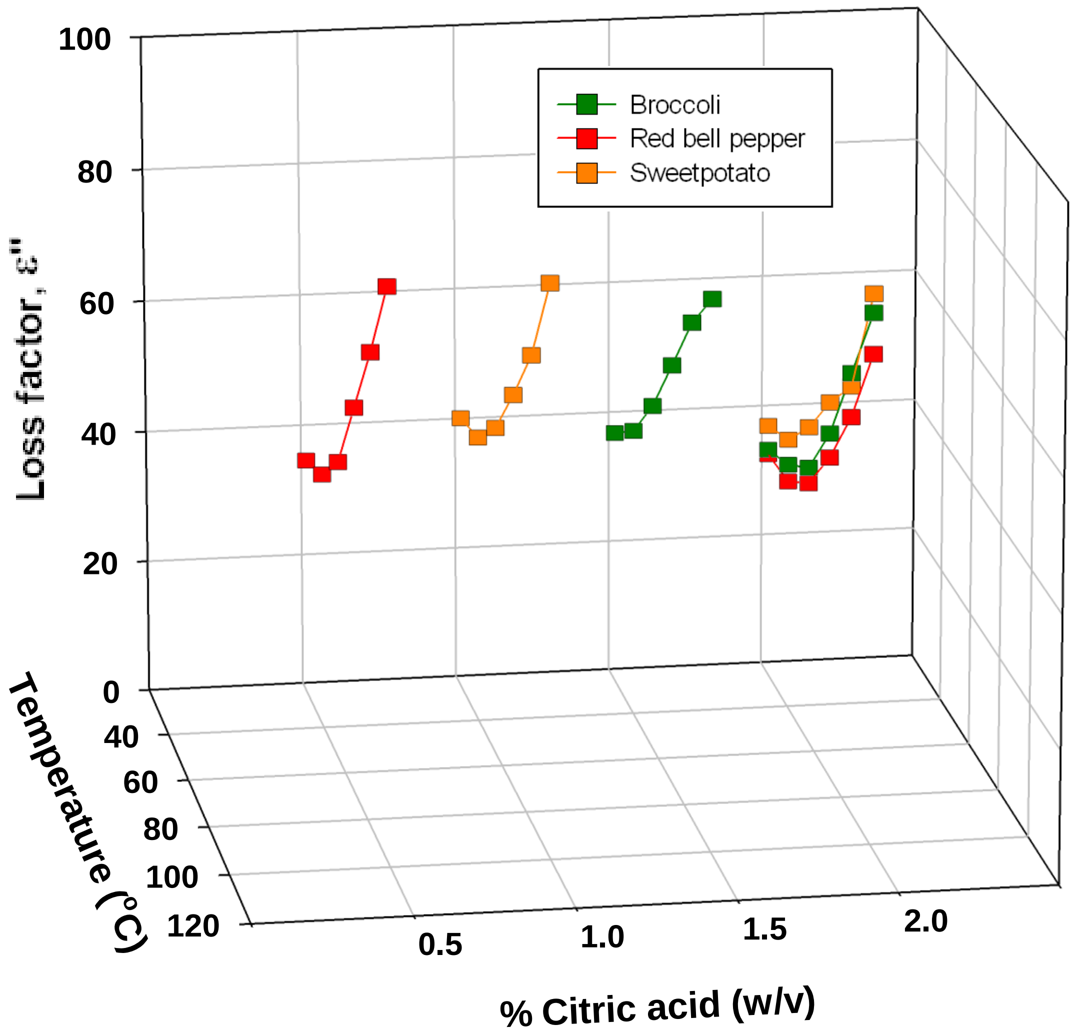

Figure 7. Dielectric loss factors ε′′ of vegetables after 24 hr equilibration in a 2% w/v NaCl solution with varying citric acid concentrations (0.5, 1.0, 1.5, and 2%).

Chapter 3

Improvement of Heating Uniformity in Packaged Acidified Vegetables Pasteurized with a 915 MHz Continuous Microwave System

3.1 Abstract

Continuous microwave processing of packaged foods with moderate to high salt contents poses serious challenges in pasteurization processes due to reduced microwave penetration depths and non-uniform heating. The effects of formulation changes with regards to salt levels and process modifications were studied to assess the feasibility of using a continuous microwave pasteurization process to produce shelf-stable, acidified vegetable packs. Raw sweetpotato, red bell pepper, and broccoli were placed in 109mL cups and acidified to pH 3.8 with a solution containing citric acid with 0% NaCl (treatment 1) and 1% NaCl (treatment 2). Treatment 3 involved placement of vegetables pre-equilibrated to 1% NaCl into a 0% NaCl solution. Unsealed vegetable packs were placed on a conveyor belt and passed through a microwave tunnel operating at 915 MHz and 4 kW (residence time = 4 min). To evaluate heating uniformity during processing, time-temperature heating profiles of vegetable pieces at 5 locations in the package were measured using fiber optic temperature sensors. Vegetable pieces in treatment 3 reached higher temperatures (mean = 84°C) than in treatment 2 (mean = 73°C), due to the presence of salt in the particles versus salt in the cover solution. However, heating was non-uniform in all packages with a cold spot (approximately 60°C) at the location in the container farthest from incident the microwaves. These challenges were overcome through the design and implementation of a two-stage rotation apparatus to rotate vegetable packs 180° during processing. After implementation, the temperature at the cold spot increased from 60°C to 77°C, above the industrial standard of 74°C for in-pack

pasteurization of acidified vegetables, and heating uniformity was improved. This work has shown that 915 MHz continuous microwave processing can be used for the pasteurization of packaged acidified vegetables.

3.2 Introduction

The use of microwave processing technology is rapidly becoming a viable method of pasteurization and sterilization for high and low-acid foods, respectively. Previous studies have utilized continuous flow microwave processing to aseptically process and package fruit and vegetable purees (Coronel et al., 2005), as well as in-pack sterilization of prepared meals (Tang et al., 2008). Improved color (Coronel et al., 2005; Sun et al., 2007; Steed et al., 2008) and antioxidant activities (Sun et al., 2007; Steed et al., 2008) have been reported using 915 MHz microwaves. These improvements in product quality have been attributed to the rapid come-up time due to volumetric heating provided by electromagnetic microwave energy. In addition, the adoption of microwave processes present potential energy savings, as well as opportunities to reduce water usage.

The use of continuous, tunnel-type microwave processes is widely used in industry for drying processes (Meredith, 1998); however, it has received little attention with regards to its potential to pasteurize packaged foods. Previous work (Burfoot et al., 1988) used a tunnel microwave system operating at 896 MHz to pasteurize spaghetti bolognaise trays, and to compare experimental heating profiles of mashed potatoes in trays to prediction models (Burfoot et al., 1996). Uniform heating of the spaghetti bolognaise to at least 80ºC was achieved using 896 MHz, but not 2450 MHz microwaves (Burfoot et al., 1988).

Microwave heating relies largely on the conversion of electromagnetic energy into heat via friction of dipolar molecules and ionic species which try to follow the oscillating electrical field, as opposed to conventional heating, which relies on heat transfer through conduction and convection (Thostenson and Chou, 1999). The manner and degree to which foods heat by exposure to microwave energy is largely determined the dielectric properties of the food and the penetration depth of microwaves into the food.

Foods with moderate to high salt contents, such as acidified vegetables present difficulties in microwave heating due to dramatically reduced penetration depths. Fresh-pack acidified vegetables such as cucumbers and peppers are typically packed in salt brines to achieve equilibrated salt concentrations in the vegetable tissue from 2-5% (Potts et al., 1986; Daeschel et al., 1990; Passos et al., 2005). While industrial microwave processes utilize 915 MHz microwaves for their relatively high penetration depth, the addition of salt significantly reduces the penetration depth. This can present challenges when processing foods. When the dimensions of a material exceed the penetration depth, the microwave energy is rapidly attenuated, and the food material will not heat volumetrically and surface heating will predominate (Datta and Anantheswaran, 2001).

Only one study has examined the use of microwave-assisted pasteurization of acidified vegetables. Lau and Tang (2002) investigated heating uniformity and textural degradation kinetics of pickled asparagus packed in 1.8 kg (64 oz.) glass bottles when heated to 88°C using a batch microwave system at 915 MHz. The authors were able to reduce heating time by 50% compared to heating in a water bath and reduced textural degradation (Lau and Tang, 2002). However, the asparagus was hot-filled with 80°C brine and equilibrated to a temperature of 70°C in a water bath before heating to 88°C with 915 MHz microwaves

In the case of food matrices containing solid and liquid phases, the differences in dielectric and thermophysical properties between these phases influence the heating characteristics. A study by Cha-um et al. (2009) examined microwave heating of a saturated porous medium consisting of 0.15 mm glass beads immersed in water. Inclusion of low loss glass beads increased penetration of microwaves into the water and bead mixture, resulting in higher temperatures at the bottom of the sample. In addition, it was observed that conduction was the predominant mode of heat transfer in the saturated porous medium, while convection prevailed when no beads were in the sample (Cha-um et al., 2009). This research suggests that the pairing of high and low loss materials could produce desirable heating patterns.

In the present study, the inclusion of liquid and solid phases presented the opportunity to manipulate the composition of these phases to improve microwave heating of high-salt, acidified vegetables. It was hypothesized that the absence of salt in the cover solution would promote higher penetration depth of microwaves into the vegetable particles, resulting in higher heating rates of the vegetable particles. Conversely, the presence of 1% NaCl in the cover solution would preferentially heat the solution, and primarily transfer heat via convection to the vegetable particles. The objectives of the study were to: (1) compare the heating profiles of sweetpotato, red bell pepper, and broccoli, (2) determine the effects of salt and its distribution on heating, and (3) to improve heating uniformity of packaged acidified vegetables using a 915 MHz continuous microwave system.

3.3 Materials and Methods

Sample preparation

Broccoli, red bell pepper, and orange-fleshed sweetpotato (cultivar *Covington*) were used in this study. Broccoli florets were prepared by cutting into pieces of 3 ± 1cm in length, and 2 ± 1cm in width. Red bell peppers were cored and sweet potatoes were peeled prior to dicing into 1.2 cm cubes using a 3/8 inch slicer plate and 3/8 inch dicer plate of a Hobart food processor (Model FP150, Hobart, Troy, OH).

Acidification and Salting

Three different treatments in Table 1 were designed to examine the level and distribution of salt within each vegetable system in order to best understand and optimize microwave heating uniformity. The vegetable to solution ratio was 50:50 for red bell pepper and sweet potato cubes, and 33:67 for broccoli florets. Unblanched vegetables were combined with a solution containing 0.75% w/v citric acid and 0% NaCl (treatment

1) or 1% w/v NaCl (treatment 2). The blanching treatment (treatment 3) involved submersion of the vegetables in 95ºC water for 30 seconds, followed by immediate cooling in an ice-water bath for 2 minutes. A 2% w/v NaCl, 0.75% w/v citric acid soaking solution was then added to the vegetables in their respective vegetable to solution ratios, and equilibrated for 24 hours at 20 ± 2ºC. After 24 hours, vegetables were removed from the soaking solution, placed in 109 mL cups, covered with a 0.5% w/v citric acid solution and immediately put on the conveyor belt of a microwave system for pasteurization. The blanching and soaking of vegetables in a citric acid and salt solution served to increase the salt content of the vegetables. Treatment 1 evaluated time-temperature profiles of the vegetables during microwave heating when no salt was added to the system. Formulations without salt were tested to contrast any positive or negative influences of added salt in treatments 2 and 3. The net weight of each cup was 90 g.

Measurements of dielectric properties

Dielectric constants (ε′) and loss factors (ε″) were measured at 915 MHz using a network analyzer (HP 8753C, Agilent Technologies, Palo Alto, CA) with an open-ended coaxial probe (HP 85070B, Agilent Technologies, Palo Alto, CA). Vegetable samples were mashed and placed into a pressurized test cell. The test cell was submerged in an oil bath (Model RTE111, Neslab Instruments Inc., Newington, NH) and the dielectric properties of were measured in 15 ºC intervals from 25 – 100 ºC. The dielectric constants and loss factors were used to calculate the penetration depth (d_p) of microwaves into the material with the following equation:

$$d_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]^{-1/2}$$

where λ_0 is the wavelength of 915 MHz microwaves.

Continuous microwave system

A 5-kW microwave generator operating at 915 MHz transmitted microwaves through a traveling wave applicator by means of an aluminum waveguide (Industrial Microwave Systems, Morrisville, NC). A simplified schematic of the system is shown in Figure 1. A conveyor belt traveled through the geometric center of the applicator at a rate of 0.711 m/min. The microwave generator was controlled through a computer interface (HP34970A, Agilent, Palo Alto, CA) with a program written in LabView (National Instruments Corp., Austin, TX). Power diodes (JWF 50D030+, JFW Industries, Inc., Indianapolis, IN) measured the transmitted power, reflected power, and lost forward at different points in the microwave system and were recorded in LabView. Generator power was set to 4 kW during microwave trials which examined compositional effects and 3.5 kW for cup rotation experiments.

Food simulant

During continuous microwave processing, a constant mass flow rate must be maintained in the traveling wave applicator to minimize drastic changes in the electric field. In order to reduce the amount of vegetable material used to obtain time-temperature heating profiles through the microwave system, a food simulant with similar dielectric properties to the acidified vegetables was developed. The dielectric properties of a solution consisting of 0.5% w/v pre-hydrated carboxymethylcellulose (CMC) (TIC Gums, White Marsh, MD) and 0.5% w/v NaCl were found to closely match those of the acidified and salted vegetables. CMC was included in the food simulant to increase the viscosity of the solution, such that spillage during handling of the cups would be minimized. Dummy cups were filled with 90 g of the food simulant and placed edge-to-edge to maintain a constant mass load in the microwave. For implementation of the two-stage rotation apparatus, cups were spaced 4 cm apart.

Fiber optic temperature sensor measurements

Vegetable and brine temperatures were continuously monitored during microwave processing at different locations within a cup by inserting precalibrated fiber optic temperature sensors (FOT-L/ 10M, Fiso Technologies, Inc., Quebec, Canada) through the walls of the polypropylene cup. The sensing portion of the probe was inserted into the center of vegetable pieces as well as in the cover solution at the locations shown in Figure 2. The fiber optic temperature sensors were connected to a 4-channel fiber optic signal conditioner (Model UMI 4, Fiso Technologies, Quebec, Canada) controlled by FISOCommander software (FISO Technologies, Quebec, Canada), and measured the temperature in 0.6 s intervals.

The cup with fiber optic temperature sensors was surrounded on both sides by cups that contained the food simulant. Upon startup of the microwave system, dummy cups were run through the system until conditions were equilibrated in the microwave. Then the cup with fiber optic temperature sensors was placed on the conveyor belt, the cover solution added, and dummy cups placed on the belt until the fiber optic cup appeared at the end of the conveyor belt. At this point, microwave power was shut-off, and the cup was placed in an insulating mold made out of polyurethane.

Infrared imaging

Thermal images of the cup surfaces were recorded at the end of the conveyor belt by a Thermovision Alert N infrared camera (FLIR Systems AB, Danderyd, Sweden). The infrared camera was controlled remotely by Thermovision Remote Software (FLIR Systems AB, Danderyd, Sweden) installed on a laptop computer. Infrared images were analyzed using Thermovision Researcher 2000 software (FLIR Systems AB, Danderyd, Sweden).

3.5 Results and Discussion

Dielectric properties and penetration depth

The effects of salt on the dielectric properties of foods have been widely documented (Ahmed et al., 2007). It is known that salt decreases the dielectric constant while simultaneously increasing the loss factor (Chapter 2). Therefore, the addition of solvated sodium and chloride ions to a food system decreases the penetration depth of microwaves as a consequence of increasing the conductivity component of the dielectric loss factor. Figure 3 clearly illustrates this phenomenon. The unblanched samples had high penetration depths, 2.0 – 3.5 cm at 25°C and 1.5 – 2.5 cm at 100°C, which were significantly different among the vegetables. For the samples that were blanched and equilibrated to a salt content of 1%, the penetration depth was around 1 cm and not significantly different among the vegetables. The penetration depths of the blanched, equilibrated vegetables were not significantly different than a 1% w/v NaCl solution. Previous work (Chapter 2) showed that the highest concentration of citric acid that might be used in an acidified vegetable product was 2% due to its high degree of sourness, so penetration depths of a 2% citric acid solution are included in Figure 3. This shows that the dielectric properties of vegetables were equalized by soaking in a salt solution. However, this equalization of dielectric properties among the vegetables resulted in reduced penetration depths, which is not always desirable for microwave processes. In order to overcome the disadvantage of low penetration depths of acidified vegetables with salt contents in the range of 1% w/v NaCl, different formulations were tested (Table 1).

Microwave heating profiles

A series of time-temperature heating profiles and contour plots are presented to illustrate the heating behavior of vegetable pieces in different locations in acidified vegetable packs. Figure 2 shows the location of continuous temperature measurements during microwave processing. Time-temperature heating profile graphs are accompanied by contour plots to better visualize the cross-sectional temperature distribution. Contour plots show the maximum temperature reached during processing at each location, red being the hottest, and blue being the coldest spots (Figures 4-6). All contour plots were generated using the same temperature scale. It is important to keep in mind that the long-standing procedure for pasteurization of acidified vegetable products is heating to 74°C and holding for 15 minutes (Etchells and Jones, 1942). The primary goal of the presented work was to reach temperatures greater than 74°C in all measured locations using a continuous microwave system.

Treatment 1 – Unblanched, 0% NaCl cover solution. Volumetric heating was readily apparent in the unblanched, 0% NaCl treatment for all vegetables. The penetration depth of the 0.75% citric acid cover solution with no salt was approximately equivalent to the measured penetration depth of the raw vegetable (Figure 3). The absence of salt effectively increased the penetration depth and created a heating profile where the center of the cup heated the fastest. This was evidenced by vegetable particles in the center of the cup reaching 100ºC (Figures 4a, 5a, 6a).

Compared to sweetpotato and broccoli, red bell pepper particles in the top half of the cup (locations A and B) were heated to a lesser extent. Red bell pepper particles A and B reached maximum temperatures of 76.8 and 78.4 ºC (Table 2, Figure 5a), and maximum heating rates of 1.9 and 0.7 ºC/s (Table 3), respectively. In comparison, the maximum temperatures of particles A and B of sweetpotato and broccoli ranged from 97 – 100ºC, and the heating rates of particles A and B were at least 0.6 ºC/s and 2.5 ºC/s greater than red bell pepper, respectively.

Locations D and E in the bottom of the cup showed different heating profiles compared to the center and upper locations. For all vegetables, locations D and E displayed the lowest maximum temperature. Red bell pepper saw the lowest maximum temperature at location E with a temperature of 59.4ºC. Location E was also the cold spot for broccoli, and reached a maximum temperature of 73.8ºC during heating. For sweetpotato the cold spot was at location D and reached 79.1ºC.

The highest heating rates were measured in vegetable particles located in the center of the cup (location C) (Table 3). It is interesting to note that red bell pepper particles in the center (location C) exhibited the slowest heating rate of 3.5 ºC/s, compared to sweet potato and broccoli which achieved heating rates of 9.8 and 10.2 ºC/s, respectively. These results were consistent with the dielectric properties of the unblanched vegetables (Figure 3). Red bell pepper had the highest penetration depth and lowest loss tangent (Chapter 2), indicating a slower rate of heating. Sweet potato and broccoli were able to rapidly convert the microwave energy into heat due to their higher loss factors (Chapter 2). This was also supported by comparing the heating rates (Table 3) and maximum temperatures (Figures 4a, 5a, 6a) achieved by the vegetable particles in locations A and B.

While heat must be delivered to the center of each particle, heating characteristics of the cover solution must also be taken into consideration. In general, heating of the 0% NaCl cover solution in treatment 1 followed the same trend as the vegetable particles. The cover solution in the upper half of the cups reached higher maximum temperatures for all vegetables (Table 2). A similar spatial heating pattern of water contained in cylinders was observed by Prosetya and Datta (1991). The observed heating effect may be the result of convective fluid flow from the rapidly heated, and less dense, center of the cup upwards due to buoyant forces, as well as the exposure of the unshielded cups to microwave energy. It followed that the cold spot was observed at the bottom of the cups due to a combination of insufficient microwave penetration and buoyancy-driven fluid flow.

The heating profile results showed that the vegetable particles were preferentially heated. This was evidenced by greater temperatures and heating rates, except for red bell pepper in location B (Tables 2 and 3). These results were also consistent with the measured dielectric properties (Chapter 2). The temperature gradient between particles and solution was minimized in the bottom half of the cup due to less microwave exposure. Compared to the vegetable particles, heating was more uniform in the cover solution due to convection currents and higher penetration depth of microwaves into the citric acid cover solution.

These results indicated that when NaCl is not present, pasteurization temperatures of at least 74°C could be achieved using continuous microwave processing for sweetpotato and broccoli. Red bell pepper presents challenges to microwave pasteurization because its dielectric properties are not as conducive to microwave heating as sweetpotato and broccoli.

Treatment 2 – Unblanched, 1% NaCl cover solution. Volumetric heating was not observed when unblanched vegetables were combined with a 1% w/v NaCl cover solution. The maximum temperature was achieved at location A for all vegetables. Location A is closest to the incident microwaves, so the microwave energy is rapidly absorbed and converted into heat in the 1% NaCl cover solution. Similar to treatment 1, higher particle temperatures were achieved in the upper half of the cup, although the maximum temperature achieved at any location in treatment 2 was lower than temperatures recorded in treatment 1 (Table 2). This may be explained by the rapid attenuation of microwaves in the 1% NaCl cover solution, rather than in the vegetable particles. As a result, the amount of electromagnetic energy converted into heat within the particle decreased and the amount of heat transferred to the particle by convection increased. This observation was supported by the small difference in temperatures between the cover solution and vegetable particles at the same measurement location (Table 2). This heating effect was different from treatment 1 in which the vegetable pieces were clearly heated preferentially to the surrounding solution, creating a large temperature gradient between the particle and solution at the same location. Overall, treatment 2 resulted in improved heating uniformity as seen by the decrease in range between maximum and minimum temperatures within the cup, but the average temperature within the cup was lower than treatment 1.

Treatment 3 – Blanched, 1% NaCl equilibrated vegetables in 0% NaCl solution. It was hypothesized that increasing the dielectric loss by equilibrating the blanched vegetables to a 1% w/v NaCl content and placing them in a citric acid solution (0.5%) of lower dielectric loss would increase the maximum temperature of the vegetable particles during microwave processing. Blanching was used in order to facilitate the penetration of acid and salt into the vegetable material within 24 hr (Chapter 2). It would follow that the vegetable pieces would be preferentially heated, and greater penetration of microwaves into the cup would occur. It was found that the hypothesis held true for each vegetable. The maximum temperatures for each vegetable particle in treatment 3 were greater than each of the corresponding pieces in treatment 2 (Table 2). Heating rates of the vegetables also increased, but the heating rates of the cover solution remained unchanged (Table 3). These results indicated that greater penetration of microwaves was achieved.

The equilibration of blanched vegetables with NaCl had the most significant effect on red bell pepper. Heating of red bell pepper particles A, B, C, and D showed significant improvement compared to treatment 2. The maximum temperature reached by particles A, B, C, and D increased by approximately 15ºC, compared to treatment 2. The compositional change did not improve heating of particle E for red bell pepper or broccoli, but increased the maximum temperature of sweetpotato in location E by 8ºC.

Comparison of compositional effects

Salt had a significant impact on the heating profiles of vegetable particles when added to the cover solution. The addition of salt to the cover solution clearly produced surface heating effects, as opposed to volumetric heating, which was observed when no salt was added to the cover solution. This finding was consistent with previous work on microwave heating of salt solutions in cylindrical containers (Anantheswaran and Swanderski, 2002). A remarkable feature of vegetables heated in a 0% NaCl solution was the rapid rise in temperature at the center of the cup. The cylindrical cup used in this study lent itself to favorable convergence of microwaves, which resulted in higher electric field intensity near the center of the cup. Focusing of microwaves only occurs if the radius of the cylinder does not exceed the penetration depth (Peyre et al., 1997). This explains why focusing was not observed in treatment 2. The penetration depth of the salted vegetables and 1% NaCl solution was approximately 1 cm (Figure 3), and the radius of the cup was 3.4 cm, so microwaves could not reach the center of the cup to converge and produce a focusing effect.

For all product compositions, the coldest location during microwave processing was in the bottom part of the cup. This finding was consistent with previous works (Prosetya and Datta, 1991; Anantheswaran and Swanderski, 2002). Anantheswaran and Swanderski (2002) found that the cold spot of water and salt solutions was at the bottom of cylindrical containers during microwave heating at 2450 MHz in a domestic microwave oven. Surface heating near the top of 1 and 2% NaCl aqueous solutions was observed, whereas volumetric heating was apparent in distilled water during microwave heating.

Process design improvements

Regardless of compositional differences, a temperature greater than 60ºC could not be achieved in location E, farthest away from incident microwaves. Upon this finding, it was hypothesized that rotating the cups 180º during processing could increase the temperature at location E and improve heating uniformity. In order to accomplish 180º rotation, a two-stage rotation apparatus was designed and implemented. Figure 7 illustrates the two-stage rotation apparatus and movement of the cups through the applicator. Based on the established time-temperature heating profiles (Figures 4, 5, and 6), it was shown that heating of the vegetables to their maximum temperature occurred within the first 30-60s, or approximately 0.5m into the microwave cavity. Therefore, it was determined that the two-stage rotation apparatus be placed 0.25m from the beginning of the microwave applicator to maximize exposure of the entire cup to microwave energy. Beads of silicone provided a ribbed surface and added friction to the bumpers such that the cups consistently rotated 90º after each bumper, for a complete 180º rotation.

In order to successfully implement the rotation apparatus, other processing parameters had to be adjusted. Preliminary trials showed that when cups were placed side-by-side on the conveyor belt, forces applied to cups by trailing cups resulted in inconsistent and unpredictable rotation. Therefore, 4 cm spacing of the cups on the conveyor belt was necessary to consistently rotate the cups. Spacing the cups by 4 cm prevented cup-to-cup contact and produced reliable cup rotation. As a result of the spacing, the mass load in the microwave was reduced, thereby necessitating operation at a lower power level so that the cover solution would not boil. Heating profiles of red bell pepper (treatment 3) were obtained with rotation at 2, 3, 3.5, and 4 kW. 3.5 kW was deemed an appropriate operating power level, so all subsequent trials with rotation were conducted at 3.5 kW.

Installation of the two-stage rotation apparatus into the microwave applicator improved heating uniformity and increased the mean temperature at the exit of the microwave as seen in Figure 8. Comparing the bottom cup locations (D and E) of sweetpotato and red bell pepper clearly showed two-stage heating curves corresponding to the 180º rotation of the cup (Figure 9). Prior to rotation (stage 1: 0 – 0.2 m), vegetable particles at location D heated more rapidly due to its closer proximity to incident microwaves. A transitional stage occurred from approximately 0.2 to 0.4 m in the applicator, during which the cup rotated. After 180º rotation (stage 2: 0.4 m onward), a marked increase in the heating rate of location E was observed due to its increased exposure to microwave energy, since locations D and E have reversed. Interestingly, the heating profiles at location E were similar to the findings of Geedipalli et al. (2007). Geedipalli et al. (2007) investigated the heating uniformity contributed by a rotating turntable in microwave ovens at 2450 MHz and observed a stepwise-like increase in temperatures corresponding to the angle of rotation. The temperature of the hot spot would rise rapidly, then slowly, corresponding to each 180º turn of the food, indicating the uneven electrical field distribution in the microwave cavity.

While a crossover in temperatures and heating rates was observed at locations D and E for sweetpotato and red bell pepper, the same was not observed for broccoli. A two-stage heating curve was also observed for broccoli, although not as pronounced. It is thought that the results were not as obvious for broccoli due to the different vegetable:solution ratio (30 g broccoli, 60 g cover solution), compared to the other vegetables (45 g vegetable, 45 g cover solution). As a result, inclusion of a higher amount of a low-loss citric acid cover solution enabled greater microwave penetration into the broccoli pieces, as well as more convection in the cup.

To further support the observed heating improvement by rotation, the effect of rotation was captured by infrared imaging of the food simulant during startup (Figure 10). Figure 10a shows heating of the food simulant with no rotation, and Figure 10b with rotation. With no rotation, lower temperatures were seen in the half of the cup most distant to incident microwaves. With rotation, each half of the cup received near-equal exposure to incident microwaves, and thus improved heating uniformity.

As a final measure of the overall improvement in heating uniformity, time-temperature heating profiles of red bell pepper (treatment 3) were measured at each measurement location while processing at 3.5kW with 4 cm spacing and rotation. Compared to microwave processing at 4 kW with no rotation (Figure 5c), the process modifications with rotation dramatically improved heating uniformity and effectively heated the cold spot (Figure 11). The range in maximum temperatures at the hot and cold spots decreased from 37.9ºC to 17.5ºC, and a temperature of 77ºC was achieved at the cold spot in the cup to meet the required pasteurization temperature of 74ºC. These results showed that the addition of rotation and other process modifications significantly improved microwave heating characteristics of acidified vegetable packs.

Effects of process modification on microwave power

An important aspect of any thermal process is the efficiency of energy transfer, or energy conversion, especially in the case of microwaves. To this end, forward and reflected microwave power was also recorded. Table 4 shows the forward, reflected, and lost forward power during microwave processing at 4 and 3.5 kW. Forward power is the total amount of energy transmitted into the waveguide, reflected power is that which was directed back towards the circulator, and the lost forward power was the amount of microwave energy not absorbed by the product at the end of the microwave cavity. By looking at the reflected and lost forward power as a percentage of forward power, one can compare the effects of product arrangement in the microwave applicator. The results showed that reflections were greater when vegetable packs were spaced apart, as opposed to being placed adjacent to one another. Furthermore, Figure 12 shows that the fluctuations in reflected power were much greater when cups were spaced apart than when adjacent. It appeared that cup spacing and lateral movement involved during rotation of the cups increased the relative amount of reflected power. While these reflections did not impede the heating process, energy conversion could be optimized through tuning of the microwave system.

3.5 Conclusions

The level and distribution of salt in acidified vegetable packs was found to play a significant role in microwave heating. When no salt was added, a pronounced focusing effect was observed for all vegetables. Addition of salt to the cover solution lowered microwave penetration into vegetable pieces and resulted in lower temperatures during processing. Pre-equilibrating vegetable pieces to 1% NaCl improved microwave heating due to increased dielectric properties, and, coupled with a low loss cover solution increased microwave penetration into the vegetable packs.

Rotation of vegetable packs by 180º during continuous microwave processing was shown to reliably and significantly improve microwave heating by increasing exposure of the packs to incident microwaves. This is the first report, to our knowledge, of the implementation of a two-stage rotation apparatus in a continuous microwave tunnel. This work has contributed to a better understanding of the influence of salt addition and distribution during dielectric heating of solid/liquid mixtures. Furthermore, this study has demonstrated the feasibility of using 915 MHz continuous microwave processing for the pasteurization of acidified vegetables.

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Table 1. Treatment key for acidified broccoli, red bell pepper, and sweetpotato

		Soaking solution[a]		Filling solution	
Treatment	Unblanched (UB) or blanched (B)	Citric acid (% w/v)	NaCl (% w/v)	Citric acid (% w/v)	NaCl (% w/v)
1	UB	--	--	0.75	0
2	UB	--	--	0.75	1
3	B	0.75	2	0.5	0

[a] Blanched vegetables were placed in a soaking solution for 24 h at 20 ± 2ºC

Table 2. Maximum temperatures of vegetable particles and cover solutions at each measured location.

		Maximum temperature (ºC)					
		Sweetpotato		Red bell pepper		Broccoli	
Treatment[a]	Location[b]	Particle	Solution	Particle	Solution	Particle	Solution
Treatment 1	A	100.0		76.8		96.9	
Unblanched	B	96.9	87.0	78.4	86.5	100.0	92.3
0% NaCl solution	C	99.2	86.4	98.7	70.6	99.7	94.3
	D	79.2	73.7	64.9	65.4	86.5	86.1
	E	85.4		59.4		73.8	
Treatment 2	A	85.0		82.3		90.2	
Unblanched	B	79.9	80.2	68.6	73.7	76.7	70.2
1% NaCl solution	C	74.4	72.9	73.9	73.1	81.6	78.7
	D	70.3	67.4	59.6	58.4	65.8	64.5
	E	61.9		61.4		65.7	
Treatment 3	A	96.3		99.4		100.0	
Blanched (1% eq. NaCl)	B	80.6	77.8	83.4	83.4	84.0	74.4
0% NaCl solution	C	83.3	77.5	99.4	78.0	100.0	81.5
	D	82.2	65.4	83.7	67.6	68.1	65.9
	E	70.4		61.5		69.0	

[a] Refer to Table 1 for complete treatment description

[b] Refer to Figure 2 for fiber optic temperature probe location diagram

Table 3. Heating rates of vegetable particles and cover solutions at each measured location.

Treatment[a]	Location[b]	Heating rate (ºC/s) Sweetpotato Particle	Sweetpotato Solution	Red bell pepper Particle	Red bell pepper Solution	Broccoli Particle	Broccoli Solution
Treatment 1 Unblanched 0% NaCl solution	A	4.4		1.9		2.5	
	B	3.4	1.9	0.7	1.8	3.2	1.8
	C	9.8	1.2	3.5	1.2	10.2	1.6
	D	1.0	0.7	0.7	0.4	3.1	1.1
	E	3.4		1.1		0.9	
Treatment 2 Unblanched 1% NaCl solution	A	1.7		1.4		2.2	
	B	1.1	1.7	0.8	1.5	1.4	1.8
	C	2.2	1.0	1.4	1.2	2.2	1.4
	D	0.9	0.7	0.7	0.7	0.9	0.8
	E	1.5		0.7		1.1	
Treatment 3 Blanched (1% eq. NaCl) 0% NaCl solution	A	3.8		6.2		5.0	
	B	1.7	1.5	1.6	1.2	2.0	1.7
	C	3.0	1.3	4.3	1.0	6.8	1.5
	D	1.9	0.7	2.0	0.8	1.4	0.8
	E	2.0		1.7		1.9	

[a] Refer to Table 1 for complete treatment description

[b] Refer to Figure 2 for fiber optic temperature probe location diagram

Table 4. Effect of cup arrangement on microwave power efficiency during processing

	Mean power[a] (kW)		% of forward power[b]	
	Adjacent[c]	Spaced[d]	Adjacent	Spaced
Forward power transmitted	4.04	3.70	--	--
Reflected (reverse) power	0.07	0.12	1.66	3.34
Lost forward power	0.02	0.03	0.54	0.78
Net power absorbed	3.96	3.55	97.80	95.88

[a]Means are the process means of at least 8 runs

[b]Percentages of forward power lost were significantly different ($p < 0.05$) between adjacent and spaced treatments

[c]Adjacent cups (no rotation) were processed at a nominal power level of 4 kW

[d]Spaced cups (with rotation) were processed at a nominal power level of 3.5 kW

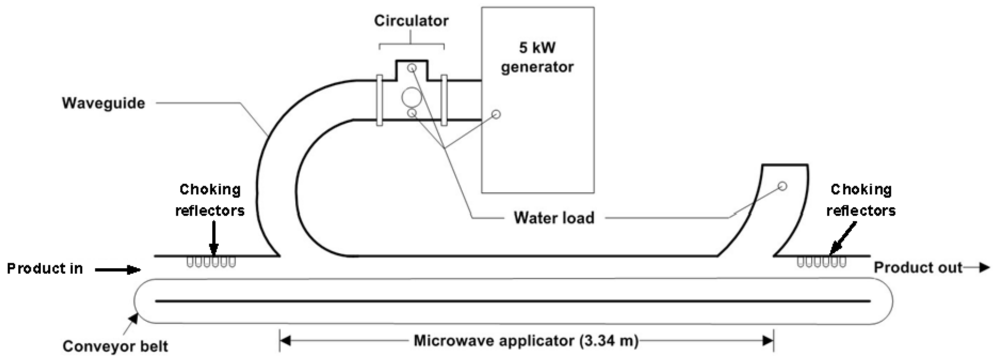

Figure 1. Simplified schematic of 915 MHz, 5 kW continuous microwave processing tunnel.

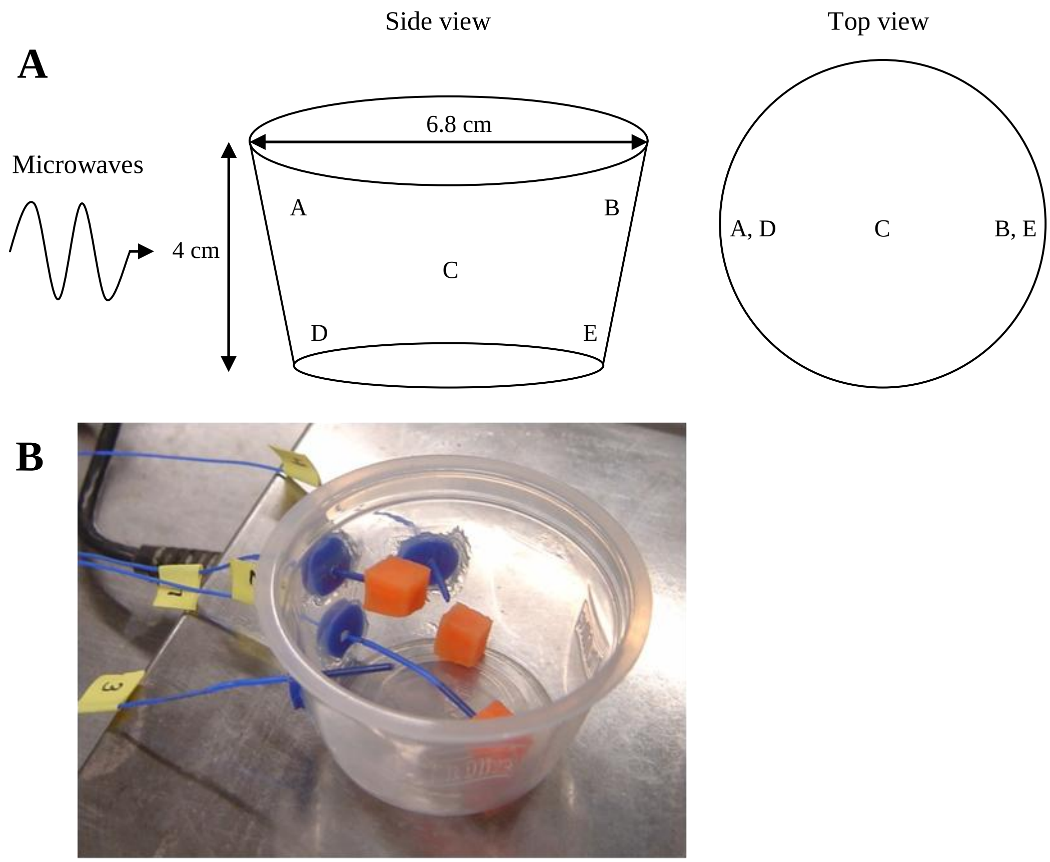

Figure 2. Schematic representation of fiber optic temperature probe placement (A), and picture of fiber optic probe insertion (B). Microwave energy moves from left to right in (A).

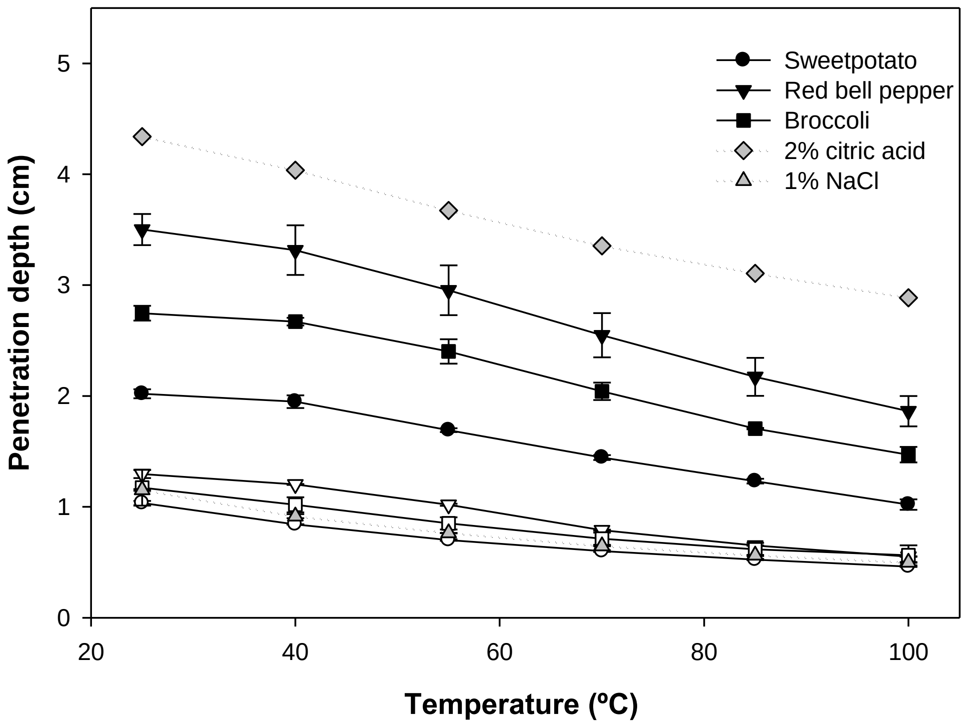

Figure 3. Penetration depth of 915 MHz microwaves as a function of temperature for vegetables and cover solutions. Closed symbols represent unblanched vegetables; open symbols represent blanched, equilibrated vegetables to 1% w/v NaCl.

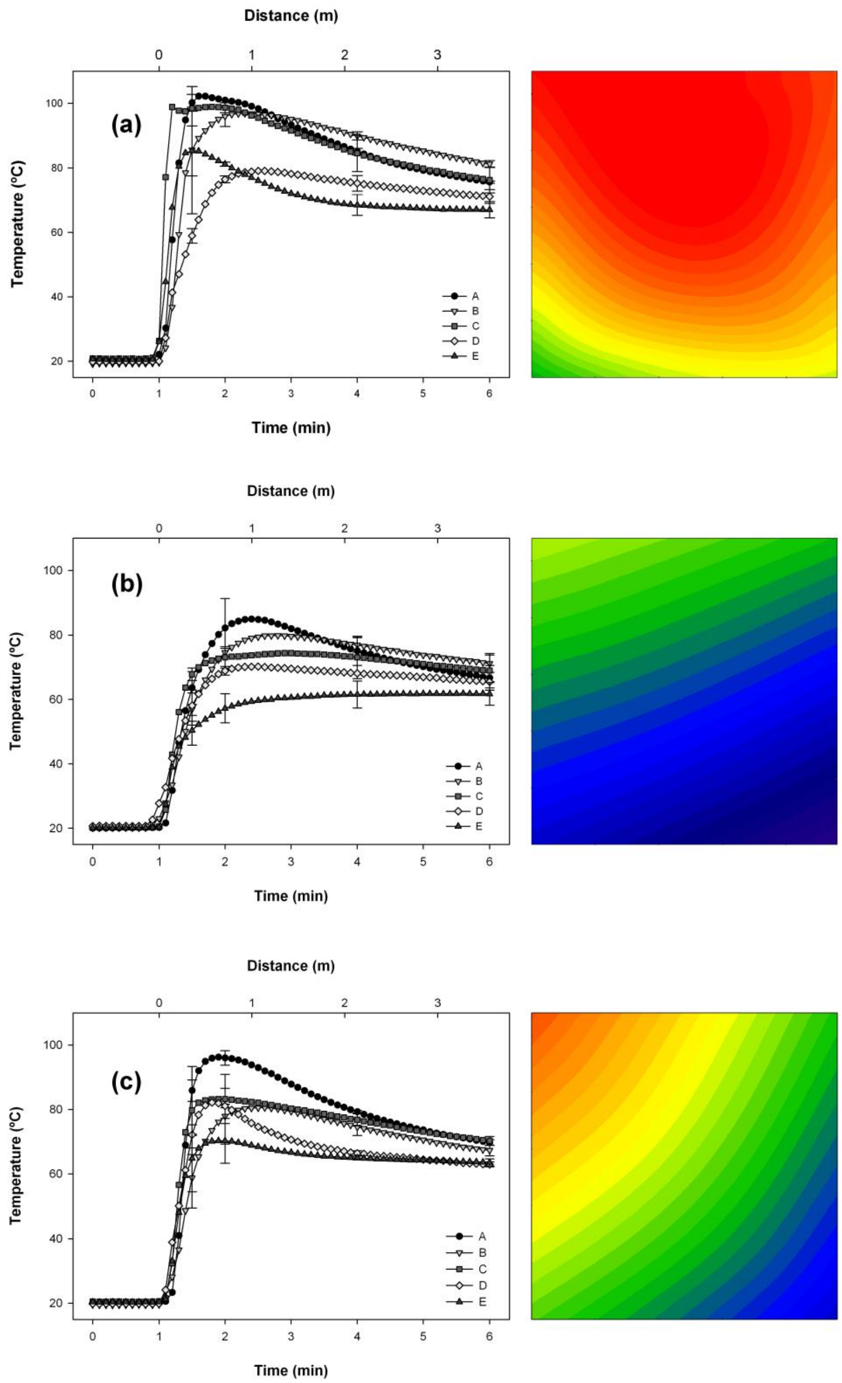

Figure 4. Time-temperature heating profiles (left) and maximum temperature contour plots (right) during 915 MHz continuous microwave processing: (a) unblanched sweetpotato cubes in 0% NaCl cover solution, (b) unblanched cubes in 1% NaCl cover solution, and (c) blanched, 1% NaCl equilibrated cubes in 0% NaCl cover solution. Error bars represent 1 standard deviation (n = 2). Refer to Figure 2 for locations of A, B, C, D, and E.

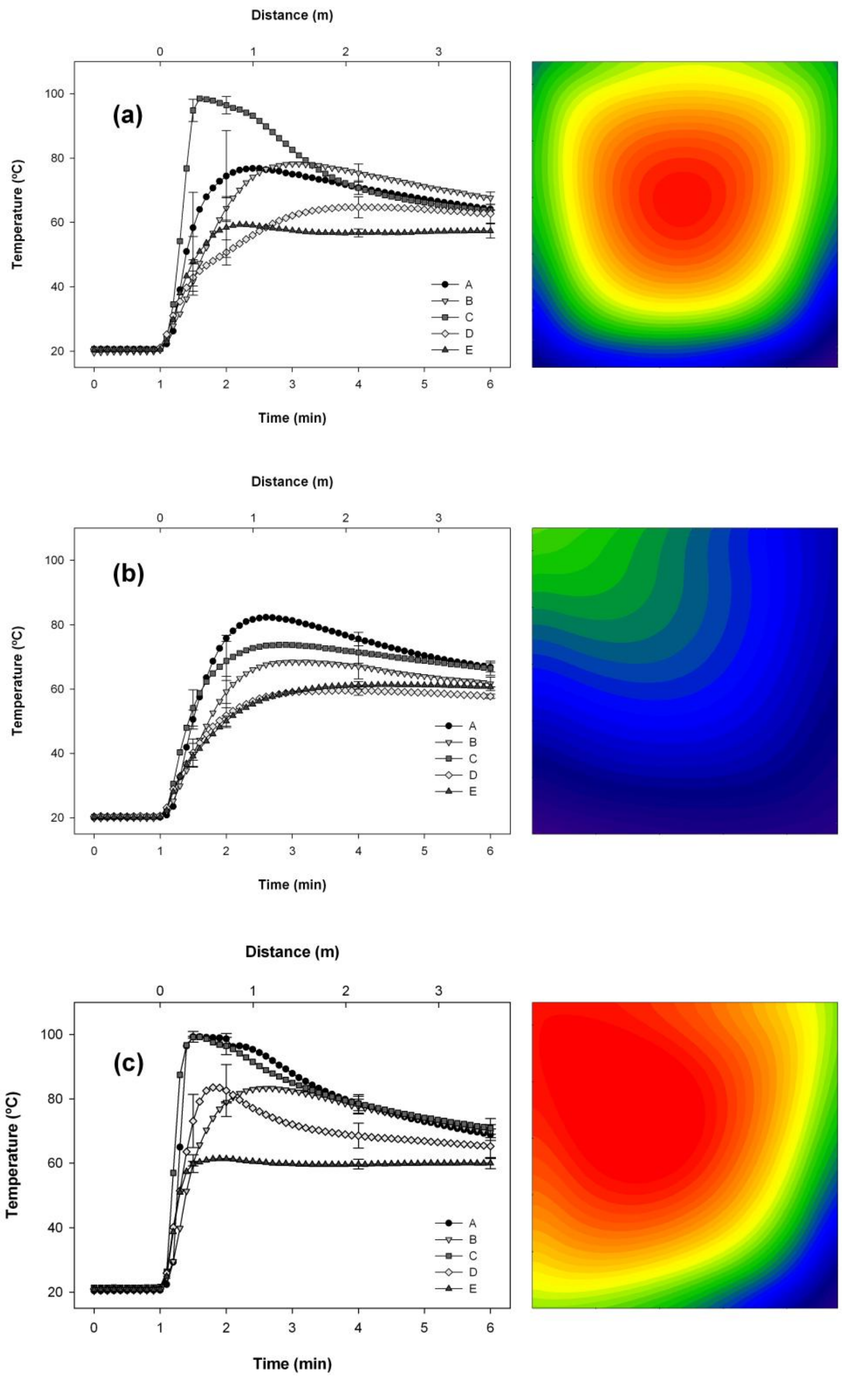

Figure 5. Time-temperature heating profiles (left) and maximum temperature contour plots (right) during 915 MHz continuous microwave processing: (a) unblanched red bell pepper cubes in 0% NaCl cover solution, (b) unblanched cubes in 1% NaCl cover solution, and (c) blanched, 1% NaCl equilibrated cubes in 0% NaCl cover solution. Error bars represent 1 standard deviation (n = 2). Refer to Figure 2 for locations of A, B, C, D, and E.

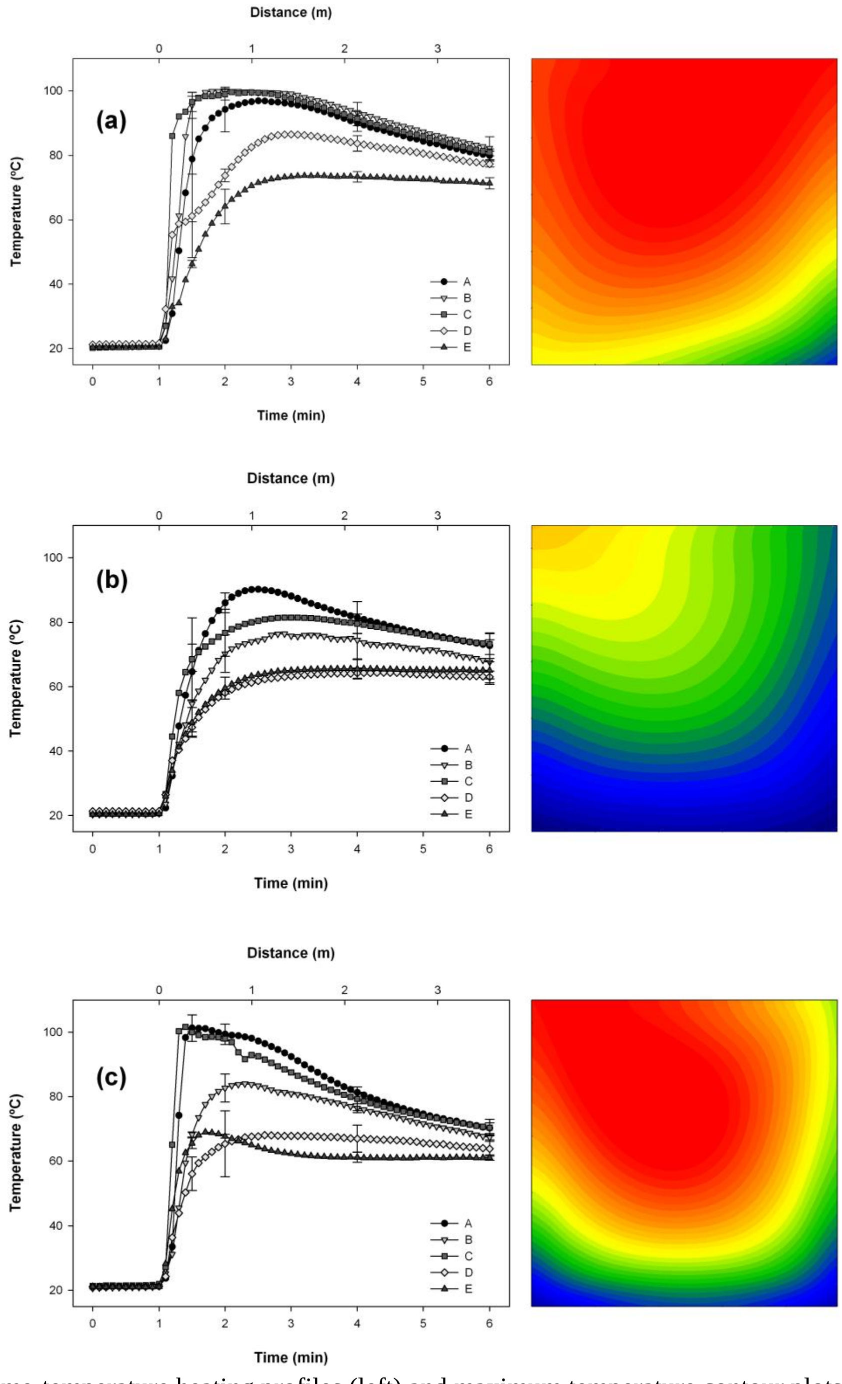

Figure 6. Time-temperature heating profiles (left) and maximum temperature contour plots (right) during 915 MHz continuous microwave processing: (a) unblanched broccoli in 0% NaCl cover solution, (b) unblanched broccoli in 1% NaCl cover solution, and (c) blanched, 1% NaCl equilibrated broccoli in 0% NaCl cover solution. Error bars represent 1 standard deviation (n = 2). Refer to Figure 2 for locations of A, B, C, D, and E.

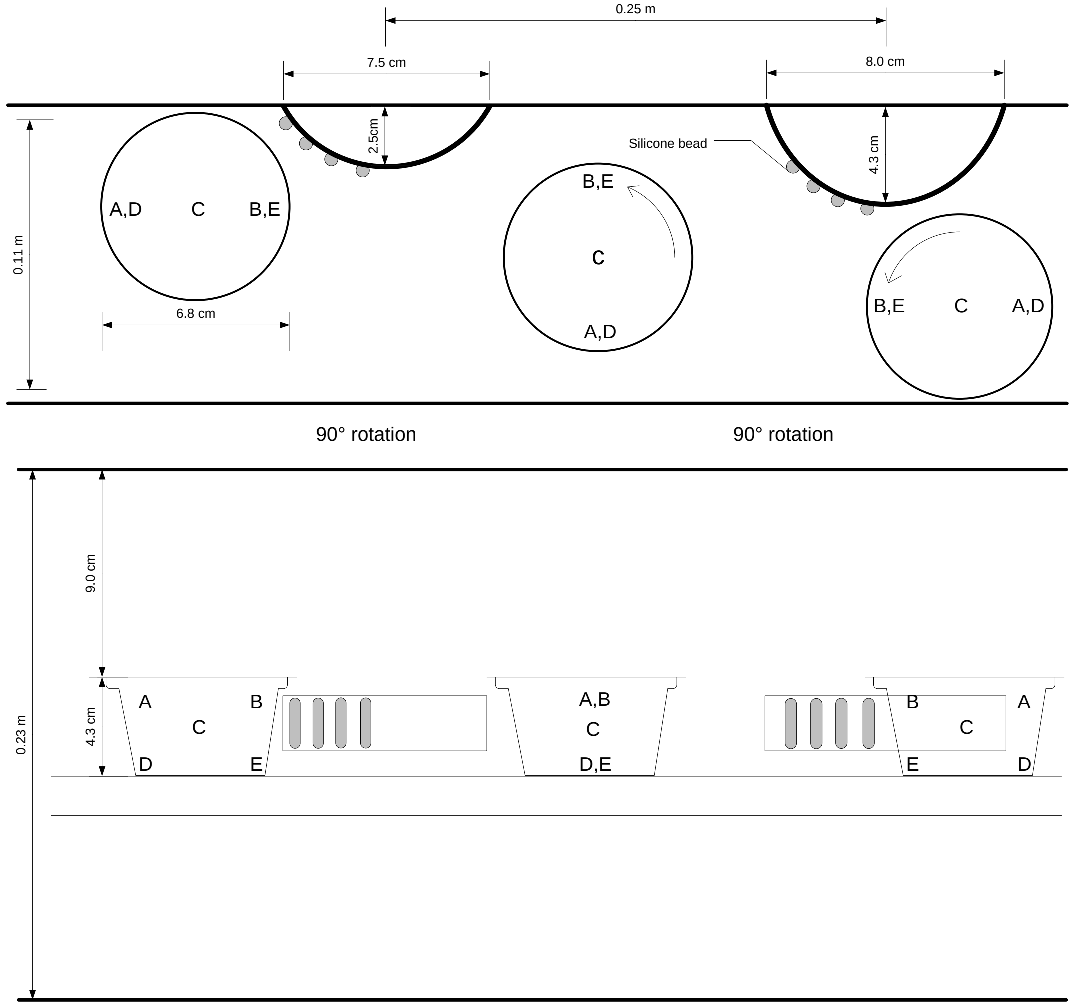

Figure 7. Schematic of two-stage rotation apparatus: top view (top) and side view (bottom).

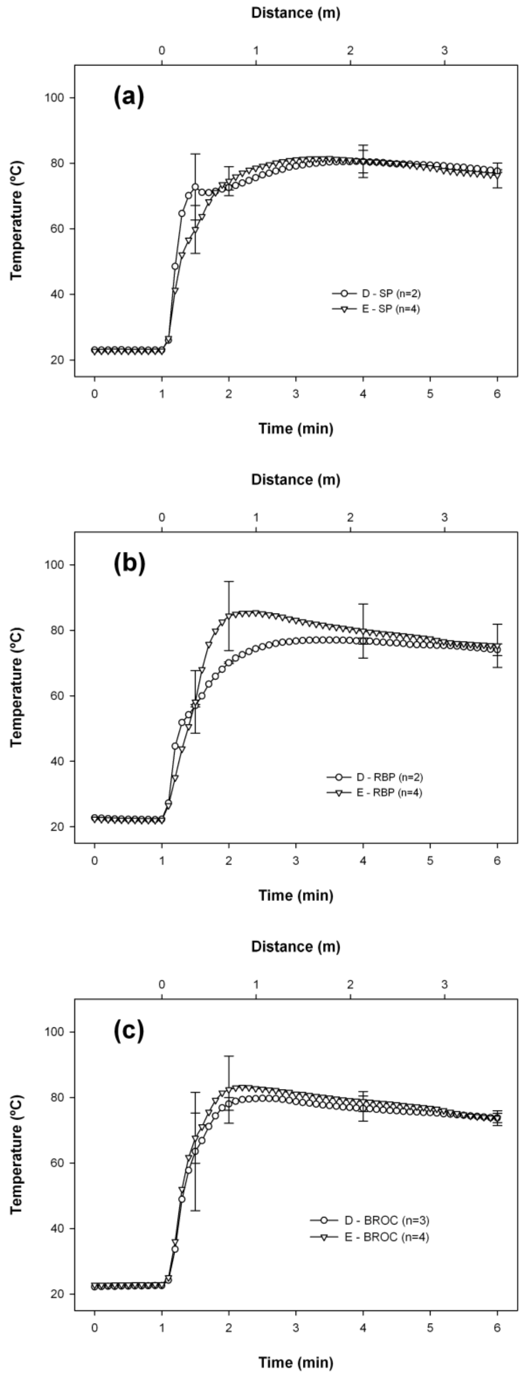

Figure 8. Time-temperature heating profiles of bottom locations (D and E) and the effect of rotation during 915 MHz continuous microwave processing of blanched, 1% NaCl equilibrated vegetables in 0% NaCl cover solution at 3.5 kW: (a) sweetpotato, (b) red bell pepper, and (c) broccoli. Error bars represent 1 standard deviation of at least two replicates. Refer to Figure 2 for locations of D and E.

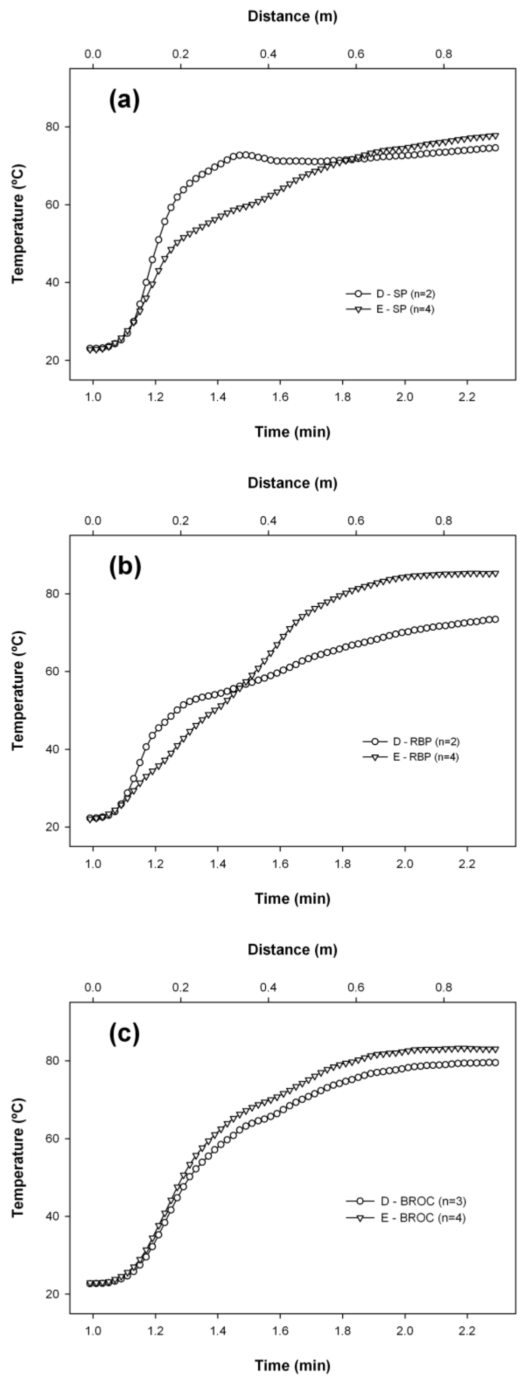

Figure 9. Detailed time-temperature heating profiles of bottom locations (D and E) during 915 MHz continuous microwave processing of blanched, 1% NaCl equilibrated vegetables in 0% NaCl cover solution at 3.5 kW: (a) sweetpotato, (b) red bell pepper, and (c) broccoli. Rotation occurs between 1.2 and 1.5 minutes, reversing the initial locations of D and E as shown in Figure 2.

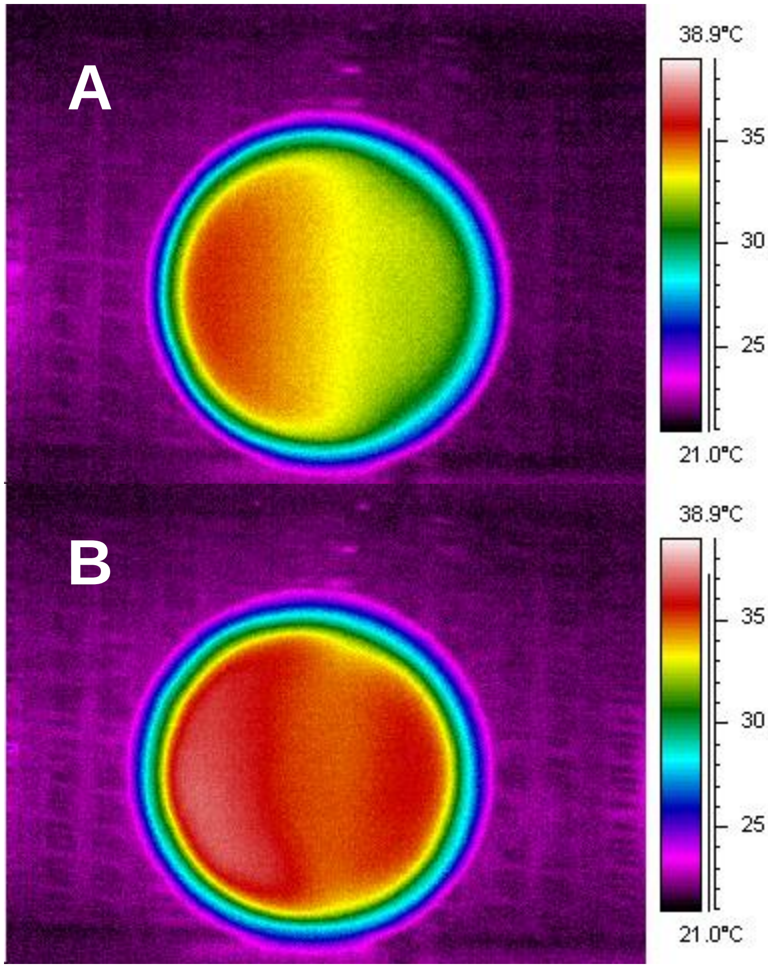

Figure 10. Infrared images of food simulant without (A) and with (B) rotation during 915 MHz continuous microwave processing. Microwaves move from left to right.

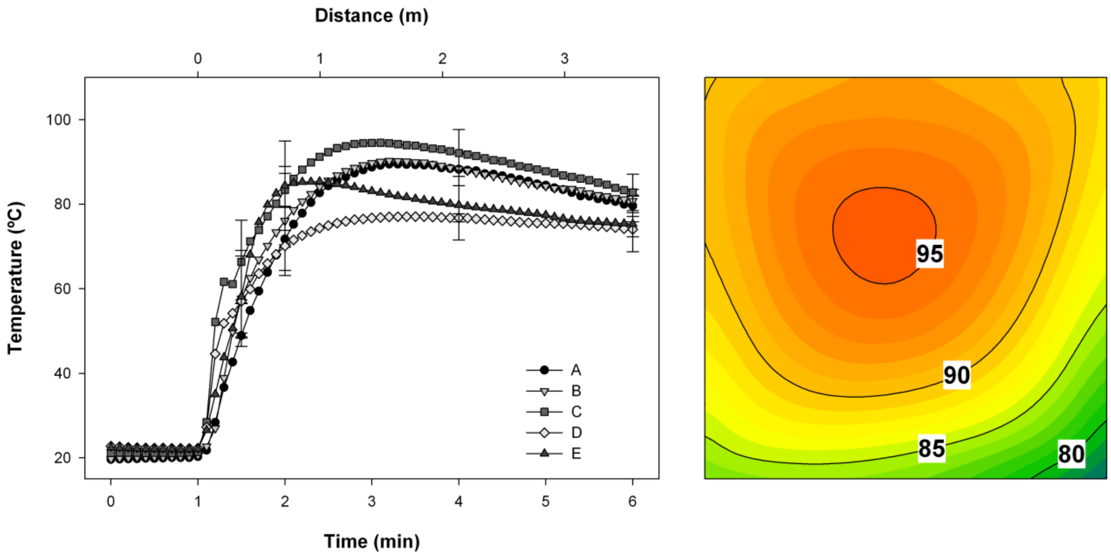

Figure 11. Time-temperature heating profile (left) and contour plot (right) of pre-equilibrated red bell pepper to 1% NaCl in 0% NaCl cover solution. Error bars represent 1 standard deviation of at least 2 replicates. Refer to Figure 2 for locations of A, B, C, D, and E.

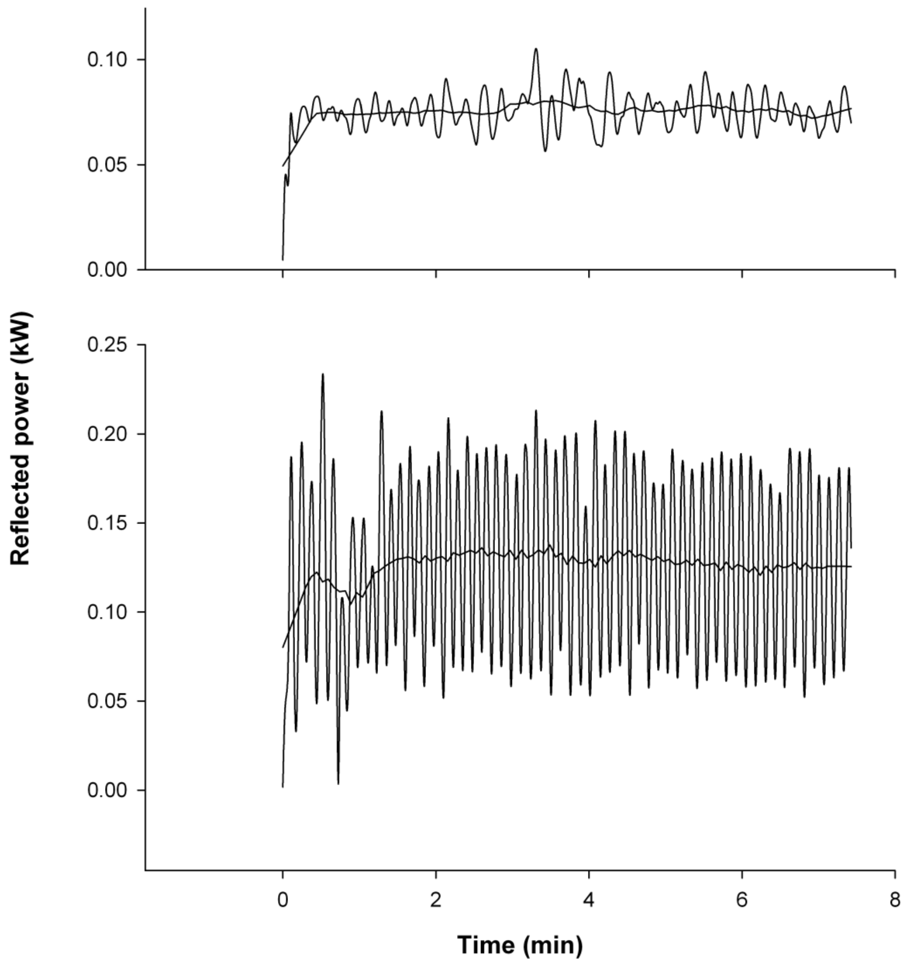

Figure 12. Reflected power during 4 kW processing with adjacent cups (top) and 3.5 kW processing with spaced cups and 180° rotation (bottom). Smoothed data is also shown.

Chapter 4

Quality Evaluation of Packaged Acidified Vegetables Subjected to Continuous Microwave Pasteurization

4.1 Abstract

The application of microwave processing technology for pasteurization of acidified vegetables presents an opportunity to improve product quality, reduce water and energy usage, and explore the development of novel, acidified food products. The current study evaluated the use of 915 MHz continuous microwave processing with a rotation apparatus to produce shelf-stable, acidified vegetable packs. Broccoli florets, and 1.2 cm cubes of broccoli stems, red bell pepper, and sweetpotato were pre-equilibrated to 1% NaCl and 0.38% (w/v) citric acid, and then separately placed in 110 mL cups with a 0.5% citric acid solution. Unsealed packages were placed on a conveyor belt and run through a 915 MHz microwave cavity operating at 3.5 kW (residence time = 4 min). After processing, cups were sealed with a lidding film, and held in insulating molds for 30 min. Infrared thermocouples, fiber optic temperature sensors, and infrared imaging were used to monitor product temperatures. Microbial stability and changes in color and texture were measured over a 60-day storage period at 30ºC. Good retention of color and texture of acidified vegetable pieces was observed after microwave pasteurization. Over storage, textural properties significantly degraded for all vegetables, but the brilliant color of red bell pepper and sweetpotato was relatively retained. Chemical indicators of microbial spoilage were not detected at the end of storage. This is the first report of a successful continuous microwave pasteurization process for packaged acidified vegetables.

4.2 Introduction

The common goals of the food industry and many other manufacturing operations include developing strategies and processes to: reduce water usage, generate less waste, utilize waste streams, and reduce energy usage (Khan and Hanjra, 2009; Dieu, 2009). Microwave processing technology provides opportunities to reduce water usage and improve efficiencies of thermal processes due to its rapid, volumetric heating caused by the conversion of electromagnetic energy into heat, as opposed to heat transfer by convection and conduction. Utilization of microwave processing technology for the thermal processing of foods has increased in recent years due to technological advancements and proven improvements in product quality.

However, before new thermal processes can be adapted and accepted, they must first be proven capable to produce a microbiologically safe product. For high acid ($pH < 4.6$), shelf-stable foods such as acidified vegetables, this means implementing a pasteurization process to kill all vegetative pathogenic microorganisms and spoilage microorganisms. Standard pasteurization processes for acidified vegetables involve heating to 74ºC and holding at this temperature for 15 min (Etchells and Jones, 1942). Once a safe, shelf-stable product has been produced, secondary quality attributes such as color and texture must be evaluated, as these are major determinants of consumer acceptability.

Pasteurization of acidified vegetables through the use of microwave energy has received little attention. A study by Lau and Tang (2002) used 915 MHz microwaves to pasteurize 1.8 kg glass bottles of pickled asparagus in a batch process. The authors used a combination of hot-fill and water bath heating to bring the product temperature to 80°C before applying microwave energy to reach their target of 88°C for 10 s. The application of microwaves to pickled asparagus was shown to reduce the heating time by half, and improve the textural properties compared to the traditional pasteurization method (Lau and Tang, 2002). Currently, there is no report on the application of continuous microwave heating for pasteurization of acidified vegetables.

With regards to product quality, previous studies have examined the effects of blanching (Tijskens et al., 2001; Goncalves et al., 2009) and cooking methods (Lin and Chang, 2005) on the texture and color of broccoli, but not of acidified and pasteurized broccoli. Methods to limit softening of acidified red bell pepper have been studied (Papageorge et al., 2003; McFeeters et al., 2004), and improved firmness of a sweetpotato French fry-type product through tissue acidification was shown by Walter et al. (1992). However, no previous study has examined the effects of acidification and microwave pasteurization on texture and color in packaged acidified vegetables such as broccoli, red bell pepper and sweetpotato. To this end, the current study seeks to illustrate changes in color and texture of acidified vegetables before and after microwave processing.

The goal of this study was to produce shelf-stable acidified vegetable packs using 915 MHz continuous microwave processing. The specific objectives of this study were: (1) to evaluate the thermal treatment of microwave pasteurization through temperature monitoring, (2) to assure the absence of microbial spoilage, and (3) to assess changes in color and texture of the products.

4.3 Materials and Methods

Vegetable preparation

Two lots of broccoli and red bell pepper (cultivars unknown) were purchased from two local supermarkets in Raleigh, NC. Sweetpotatoes (cv. Covington) were grown in Clinton, NC and samples were taken from two batches. Broccoli florets were prepared by cutting into pieces of 3 ± 1cm in length, and 2 ± 1cm in width. Broccoli stems, red bell peppers, and sweetpotatoes were diced into 1.2 cm cubes.

The vegetables were blanched prior to acidification to facilitate acid and salt penetration into the material. The blanching treatment involved submersion of the vegetables in 95ºC water for 30 seconds, followed by immediate cooling in an ice-water bath for 2 minutes. Each lot was then transferred to a 3.79 L glass jar, and a 2% w/v NaCl, 0.75% w/v citric acid soaking solution was added to the vegetables at a 50:50 ratio for red bell pepper and sweet potato cubes, and 33:67 ratio for broccoli florets. The blanched vegetables were allowed to equilibrate in the cover solution for 24 hours at 20 ± 2ºC. After 24 hours, the cover solution was drained from the vegetables. Forty-five-gram samples of sweetpotato and red bell pepper, and 30-g samples of broccoli were individually placed in 110 mL cups. Immediately prior to microwave processing, pre-measured volumes of 0.5% w/v citric acid were added to the cups containing vegetables, which brought the net weight of each cup to 90-g. Cups were not sealed prior to microwave processing.

Microwave processing

Vegetable packs were processed using a 915 MHz, 5-kW continuous conveyor-type microwave system (Industrial Microwave Systems, Morrisville, NC). The system was outfitted with a two-stage rotation apparatus to rotate the vegetable packs 180º during heating, as described in Chapter 3. The microwave system was set at 3.5 kW, the conveyor belt speed was 0.711m/min, and residence time in the microwave cavity was 4.7 min. Vegetable packs were spaced 4 cm apart, and were placed along the left wall of the conveyor to ensure rotation of the cups during processing. To minimize the use of vegetable material, a food simulant comprised of 0.5% carboxymethylcellulose and 0.5% NaCl (CMC) was placed in cups that preceded and followed the lot of vegetable packs. Prior to startup, the microwave applicator was filled with packs containing CMC to provide a load for energy absorption. Upon system startup, cups of CMC were continuously fed onto the conveyor until conditions in the microwave applicator had equilibrated. At this point, one lot of 45 vegetable packs containing all three vegetables was processed. Individual vegetable packs were placed on the belt in the following repeating order: sweetpotato, red bell pepper, and broccoli (e.g. an individual red bell pepper pack was adjacent to a sweetpotato and a broccoli pack on either side).

As each vegetable pack exited the microwave cavity, it was immediately sealed with a lidding film comprised of PET and CPP (Cello-Pack Corporation, Buffalo, NY) using a table-top pre-cut lid sealing machine (Quality Cup Packaging Machinery, Corp., Menomenie, WI). Upon sealing, each pack was placed in an insulating mold fabricated from polyurethane foam sealant (Dow Chemical Company, Wilmington, IL), inverted and held for 30 minutes. All packs were then held at 20ºC for 2 days until placed in a controlled atmosphere chamber at 30º C and 99% relative humidity for 2 months until final quality evaluation.

Fiber optic temperature sensor measurements

Vegetable and brine temperatures were continuously monitored during and after microwave processing in different cup locations by inserting precalibrated fiber optic temperature sensors (FOT-L/ 10M, Fiso Technologies, Inc., Quebec, Canada) through the walls of the polypropylene cup. The fiber optic temperature sensors were connected to a 4-channel fiber optic signal conditioner (Model UMI 4, Fiso Technologies, Quebec, Canada) controlled by FISOCommander software (FISO Technologies, Quebec, Canada), and measured the temperature in 0.6 s intervals. Upon exit of the microwave cavity, the vegetable pack with the sensors was placed in an insulating polyurethane mold and held for 30 min to monitor the heat treatment delivered after processing. Reported data are the average of eight replicate measurements for each vegetable.

Infrared thermocouple temperature measurements

Surface temperatures of the product in the microwave applicator were measured by 16 infrared thermocouples (Model OS36-T, OMEGA Engineering, Inc., Stamford, CT) spaced throughout the microwave. The data were collected from five infrared thermocouples located nearest the operator-side wall of the microwave tunnel at incremental distances from the start of the microwave cavity.

Infrared imaging

Infrared images of the cup surfaces were recorded at the end of the conveyor belt by a Thermovision Alert N infrared camera (FLIR Systems AB, Danderyd, Sweden) as a measure of cup-to-cup temperature uniformity. The infrared camera was controlled remotely by Thermovision Remote Software (FLIR Systems AB, Danderyd, Sweden) installed on a laptop computer. Infrared images were analyzed using Thermovision Researcher 2000 software (FLIR Systems AB, Danderyd, Sweden). Average surface temperatures of the cups were analyzed using the circle tool.

Microbial stability

The efficiency of thermal treatment applied through the continuous microwave pasteurization process was evaluated by monitoring the indicators of microbial spoilage over 60 days of storage at 30°C. Each vegetable pack was evaluated weekly for visual signs of spoilage such as turbidity, mold growth, or gas production. In addition, metabolic products indicative of bacterial and yeast growth such as lactic acid and ethanol, respectively, were measured at 2 and 60 days after microwave processing using high-performance liquid chromatography (HPLC). Two days after microwave processing, 1.5 mL samples of the cover solution were drawn from six randomly selected vegetable packs in each lot (two of each vegetable type), and frozen at -20°C in microcentrifuge tubes until further analysis. The same sampling procedure was used after 60-day storage. Samples were prepared for HPLC analysis by thawing and centrifuging at 16,053 x *g* for 10 min (Marathon 16 km, Fisher Scientific, Pittsburgh, PA). For HPLC analysis, 1:2 and 1:10 dilutions were prepared by pipetting 500μL and 100μL of sample into 500μL and 900μL volumes of 0.03 N sulfuric acid diluent, respectively. Samples were randomized and run on a 30 cm HPX-87H column (Bio-Rad Laboratories, Hercules, CA, USA), which was heated to 65°C, and eluted with 0.03 N sulfuric acid at a flow rate of 0.9 mL/min (Olsen and Perez-Diaz, 2009). A UV6000 LP detector (Thermo Separation Products, Inc., San Jose, CA, USA) was used to analyze malic acid, succinic acid, lactic acid, acetic acid, propionic acid, and butyric acid. Glucose, fructose, and ethanol were quantified by a Waters model 410 refractive index detector (Waters, Milford, MA, USA).

Color measurements

The colors broccoli florets and stems, sweetpotato, and red bell pepper were measured using a Minolta CR-300 Chroma Meter (Konica Minolta, Inc., Ramsey, NJ) with D65 light source. The instrument was calibrated with a white plate, and measurements were taken using the CIE L*a*b* system. The color of vegetables was measured after each processing step: dicing and cutting of the raw vegetable, blanching, 24 hr equilibration, 2 days post-processing, and after 2 months of storage. Five samples from each lot were measured at each sampling point, meaning that each reported datum is the average of 10 measurements. Hue angle (H°) (eqn. 1-3), chroma (C*) (eqn. 4), and total color difference (ΔE) (eqn. 5) were calculated using the following equations:

$$\text{H}° = \tan^{-1}(b^*/a^*) \qquad \text{when } a^* > 0 \text{ and } b^* \geq 0 \qquad (1)$$
$$\text{H}° = 180° + \tan^{-1}(b^*/a^*) \qquad \text{when } a^* < 0 \qquad (2)$$
$$\text{H}° = 360° + \tan^{-1}(b^*/a^*) \qquad \text{when } a^* > 0 \text{ and } b^* < 0 \qquad (3)$$

$$\text{C}^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad (4)$$

$$\Delta\text{E} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (5)$$

Texture measurements

Texture of the vegetable cubes was measured using a TA-XT2 texture analyzer (Texture Technology Corp., Scarsdale, NY) with a TA-42 knife probe with 45º chisel blade and slotted plate. A 50-kg load cell was used for all texture measurements. The pretest speed was 3.00 mm/s, the test speed was 2.50 mm/s, and the post-test speed was 10.00 mm/s. For each measurement, six cubes were placed over the slot of the guillotine holder, and the knife probe cut all the way through the vegetable material and advanced through the slotted plate. Red bell pepper pieces were placed skin side down. For each lot of vegetables, five replicate measurements were taken at each time point. Each datum is the mean of 10 measurements, and a bulk measurement 60 cubes. Post-processing, five samples were randomly selected from each lot.

Statistical Analysis

Significant differences in color and texture over the course of processing and storage were determined at the 0.05 significance level using oneway ANOVA and the Tukey-Kramer HSD method for mean comparisons using JMP 7 (SAS Institute Inc., Cary, NC) for each vegetable type.

4.4 Results and Discussion

Process validation and evaluation systems

Two independent trials were conducted to test the effectiveness of continuous microwave pasteurization of acidified vegetables. Processing temperatures were measured through multiple approaches. Infrared thermocouples placed in the microwave applicator recorded surface temperatures, fiber optic temperature sensors inserted into vegetable pieces recorded time-temperature heating profiles, and an infrared camera recorded thermal images at the exit of the microwave. Figure 1 shows the surface temperatures recorded along the length of the microwave applicator in real time. The surface temperatures of the packs were substantially lower than the measured temperatures of the vegetable pieces. This may be due to the emissivity of the product surface, as well as any condensate that may have formed on the infrared thermocouple lens during processing. The condensate hypothesis is supported by the sharp initial peak in temperature at all distances, followed by a decrease in temperature measurements. The same phenomenon was found by Boldor et al. (2005), who used the same microwave system for the drying of peanuts. The surface temperatures of the peanut bed were found to be substantially lower than the measured internal temperature of peanuts. Boldor et al. attributed the temperature difference between surface and internal temperatures to the difference in dielectric properties between the shell and peanut, and evaporative cooling of the peanut shell. However, the trends in temperature throughout the microwave applicator were consistent with time-temperature heating profiles obtained through fiber optic temperature sensor measurements.

Continuous time-temperature heating profiles showed that pasteurization temperatures (>74°C) were reached due to a 180° cup rotation apparatus (Figure 2). Figure 2 shows the heating of the hottest (C) and coldest (D and E) locations measured during processing of sweetpotato. Previous work showed that temperatures reached at locations A and B fell between the hottest and coldest temperatures (Chapter 3). However, most of the microwave energy was absorbed in the first meter of the microwave cavity (Figure 2). After this point, no additional microwave energy was available to further heat the product. Decreases in temperature were noted after the first meter in the upper half of the vegetable packs due to evaporative cooling since the packs were not yet sealed, and open to the atmosphere. Boldor et al. (2005) found similar results. Heating was shown to be very rapid during the first meter in the microwave applicator, but was then followed by a decrease in both internal and surface temperatures. This finding was especially pronounced for peanuts with higher moisture contents (21 to 33% moisture). As it relates to the current issue of pasteurization, this cooling effect presents a process inefficiency, and a need for temperature verification at the exit of the microwave cavity.

Upon exit of packs from the microwave tunnel, thermal images of the cups were captured using an infrared camera. Thermal images were analyzed, and the average surface temperatures of each cup during processing, starting with cups of CMC at the start of processing, are shown in Figure 3. Cups during the start up phase did not receive the full residence time in the microwave applicator, explaining the rise in surface temperatures leading to a plateau. The next phase, labeled “CMC”, represents the stage at which all cups from that point forward received the full thermal treatment. Interestingly, surface temperatures of the vegetable packs were 5ºC higher than CMC cups. Average cup-to-cup surface temperatures for runs 1 and 2 were within 5ºC, indicating a reproducible process. While infrared images cannot be used as a temperature validation tool, it does provide a qualitative measure of cup-to-cup heating uniformity.

Post-process thermocouple measurements

A 30 min holding period was implemented after microwave processing in order to deliver a defined thermal treatment to the sealed vegetable packs. Figure 4 shows the average of eight vegetable pack temperatures for sweetpotato, red bell pepper, and broccoli during the first 15 min hold of the hold period. Upon exit of the microwave cavity, temperatures were at least 75ºC, but did not retain this temperature. Even in an insulating mold, the temperatures of the vegetable packs decreased to 60ºC for sweetpotato and broccoli, and to 55ºC for red bell pepper within 15 min (Figure 4). Since vegetable packs were not sealed during microwave processing, the remaining heat in the pack is responsible for killing any pathogens or spoilage microorganisms on the lidding film, similar to a hot-fill process. While the hold time conditions employed in this study were less stringent than industrial practices, the product was still stored for 60 days and evaluated for microbial stability.

Microbial stability

Vegetable packs were examined for signs of microbial spoilage over a 60 day storage period at 30°C. To confirm the absence of spoilage, samples of cover solution were collected at the beginning and end of the storage period. These samples were then tested for the presence of metabolites of microbial growth such as organic acids and ethanol. A chemical detection method was chosen over a microbiological enumeration method due to its simplicity. Detecting microbial growth during storage would have required frequent enumeration due to the unpredictable cell growth behavior. The chemical method is advantageous in that it does not require live cells at the time of sampling, and so can be used at the end of storage to measure metabolic products as evidence of spoilage (Loureiro and Malfeito-Ferreira, 2004).

In addition to the chemical analysis, each pack was visually inspected on a weekly basis for turbidity, gas production, and mold growth. Visual inspections did not reveal any signs of spoilage, so the chemical analysis sought to confirm the absence of spoilage. If spoilage were to occur, lactic acid and/or ethanol would be present due to the growth of lactic acid bacteria and/or yeasts, respectively. As Table 1 shows, lactic acid and ethanol were not detected in any vegetable pack at 0 or 60 days of storage. Interestingly, small amounts (~1mM) of acetic acid were detected in all vegetables after storage. It is hypothesized that acetic acid may have arisen from pectin deacetylation caused by hydrolysis at low pH. The results in Table 1 suggested that malic acid was naturally present in broccoli and sweetpotato, but not red bell pepper. The apparent absence of malic acid in red bell pepper may have been due to the maturity stage of the peppers. The amount of malic acid has been shown to significantly decrease during ripening of bell peppers from green to red (Luning et al., 1994). Furthermore, since the samples of cover solution were diluted by a factor of 10, any malic acid present may have been below the detection limit. The presence of, and increase in succinic acid seen in red bell pepper could not be explained. The increases in glucose and fructose concentrations over the storage period could have been due to leaching of sugars into the cover solution, as well as starch and sucrose hydrolysis. These findings, coupled with no visual evidence of spoilage, proved that the microwave pasteurization process was effective in eliminating spoilage of acidified vegetable packs.

Color

Vegetable color was evaluated after each unit operation and 60 day storage period. The color of broccoli florets was found to change the most. After blanching, the color of broccoli was visually observed to be a bright green color. This change was noted by the decrease in *a** denoting an increased green color component, as well as the significant increase in hue angle (Table 2). The brightening of the green color after blanching is due to the elimination of intracellular air and ingress of blanch water and cellular fluids as a result of cell disruption (Tijskens et al., 2001a). Lightness decreased after blanching, and then remained unchanged throughout the study. The addition of acid during the equilibration process was found to have a profound effect on green color. The green component (a*) and hue angle significantly decreased, and produced an olive-green color. The addition of citric acid lowered the pH sufficiently to induce and accelerate pheophytinization (Tijskens et al., 2001b). Pheophytinization is a process wherein two H^+ ions displace Mg^{++} from the porphyrin ring of chlorophyll, and convert chlorophyll (green) into pheophytin (olive green). This acid effect was most detrimental to broccoli color, as microwave processing and extended storage did not produce further changes in any measured color component (Table 2).

The processing of red bell pepper also resulted in color changes, although not as drastic as was seen for broccoli. Compared to the raw material, blanching and equilibration significantly increased L* and b* values (Table 2). The increases in lightness (L*) and yellowness (b*) were likely due to a combination of leaching of carotenoids into the blanch water and soaking brine thereby changing the pigment composition in the tissue, and carotene isomerization by acid and heat treatments (Chandler and Schwartz, 1988; Melendez-Martinez et al., 2007). Hue angle did not change significantly ($p < 0.05$) throughout processing and storage; however, chroma decreased over the 60-day storage period. It is important to note that microwave processing did not produce any significant color change when the color values were compared before (equilibrated) and after processing (post-process) (Table 2). A comparison of the equilibrated and 60-day storage samples showed a significant decrease of a*, indicating a slight loss of the red color component. Despite these measured changes in color, informal visual observations found the final color to be acceptable after the 60-day storage period.

Sweetpotato color was stable over the course of processing, and only slightly degraded over the 60-day storage period. Blanching was found to only decrease L*, which resulted in a deeper orange color. This decrease in lightness is thought to be a result of the release of inter- and intracellular air, as well as the decompartmentalization of pigments in the cell (Purcell et al., 1969) and carotene isomerization (Chandler and Schwartz, 1988). Equilibration and microwave processing did not significantly affect any of the color parameters (Table 2). It was only after the 60-day storage period that color degraded. This was observed by significant decreases in L*, a*, b*, and chroma. Decreases in a* and b* were indicative of losses of red and yellow color components. Hue was more or less unchanged throughout the course of this study. However, chroma was significantly lower after processing. This loss of color intensity may have been caused by the oxidation of carotenes since the packaging material used was not impervious to oxygen (Minguez-Mosquera and Hornero-Mendez, 1994). However, despite the instrumentally measured degradation of sweetpotato color during storage, sweetpotato packs still maintained a vibrant orange color after storage.

Texture

Textural properties of the vegetable cubes were measured by a cut test. This type of test was used in order to quantify the force and the amount of work required to shear through the entire sample. Additionally, this method enabled the measurement of representative samples in a timely manner, since six cubes could be measured at one time, and cleanup time between samples was reduced compared to a Kramer Shear test. Figure 5 shows typical texture profiles for sweetpotato, red bell pepper, and broccoli. The first peak is representative of the force required to fracture the vegetable cubes, and can be considered as the hardness of the vegetable. The second peak indicates the force required to cut through the vegetable cubes, as the knife probe passes through the guillotine holder. The total area under the curve represents the total amount of work contributed by compression, puncture, shear, and extrusion forces.

Instrumental texture measurements were taken after each unit operation and 60-day storage at 30° C. Figure 6 shows the peak fracture forces of each vegetable over the course of processing. Blanching significantly reduced the fracture force (Figure 6) and total work (Figure 7) required to cut through the sweetpotato cubes. The dramatic decrease in peak force was likely related to the change in tissue structure near the surface of the cubes caused by blanching. Changes in cellular adhesion and loss of turgor pressure due to cell rupture may have been responsible for the decreased fracture force after blanching.

Interestingly, an increase in the fracture force was noted for sweetpotato after a 24-hr equilibration period in the soaking solution comprised of 0.75% w/v citric acid and 2% w/v NaCl (0.34M) (Figure 6). Examination of the total work (Figure 7) showed the same trend, although to a lesser extent. These results were consistent with the findings of Walter et al. (1992). Walter et al. (1992) found that sweetpotato tissue firmness increased as hydrogen ion concentration increased when sweetpotato strips were vacuum-infiltrated with various acidulants, including citric acid. The authors were able to demonstrate that tissue acidification decreased starch hydrolysis through inactivation of α- and β-amylase systems and reduced the amount of water-soluble pectin. However, the exact mechanism responsible for increased firmness was not determined. Since starch can play a role in cell structure, and pectin present in the middle lamella is important in cellular adhesion, maintenance of these components may contribute to firmness retention. Furthermore, increasing the ionic strength by addition of 0.3M NaCl was found to decrease firmness of the acidified tissue, but the mechanism could not be explained (Walter et al., 1992). Despite the observed increase in firmness after tissue acidification, firmness was not retained when subjected to further heat treatment.

The largest texture degradation in sweetpotato occurred over the 60-day storage period. Both the fracture peak force and total work significantly decreased by 85% from post-process to 60-day storage sampling times. The addition of NaCl and citric acid may have contributed to tissue softening. While no calcium was added to any of the products to increase firmness, the ability of endogenous Ca^{++} to crosslink pectin polymers may have been impeded by the high concentration of Na^{+} competing for carboxylic acids as shown by Vu et al. (2006). Vu et al. (2006) also showed that the addition of known chelating agents such as EDTA, ascorbic acid, and citric acid to the brine increased the degree of tissue softening in carrots by binding Ca^{++} and weakening the pectin network. Nevertheless, despite the observed reduction in firmness, sweetpotato cubes still maintained their shape and were not easily deformed, and required a force of 20.9 N to fracture six cubes (3.5 N per cube).

Textural properties of red bell pepper also changed significantly over the course of processing and storage. Compared to the raw tissue, the fracture force of red bell pepper tissue increased after 24-hr equilibration in the cover solution, but significantly decreased after microwave processing and 60-day storage (Figure 6). Total work decreased after each processing step for red bell pepper (Figure 7); a trend contrary to the measured fracture forces. The increase in fracture force after blanching and equilibration indicated that the tissue became more deformable, whereas the simultaneous decrease in total work indicated tissue softening. Two days after microwave processing (post-process) the fracture force and total work decreased by 48 and 51%, respectively, until the peppers were extremely soft (total work = 2.9 N s) after the 60-day storage period.

Softening of acidified red bell peppers is a well-known problem. The work of Papageorge et al. (2003) and McFeeters et al. (2004) sought to identify factors and methods to improve texture retention of acidified red bell peppers. The authors identified many factors such as genetic variability, growing conditions, blanching conditions, pH, oxygen, and calcium ion concentration which may significantly influence texture. In the current study, the final pH of red bell pepper was 3.12. Papageorge et al. (2003) suggested that at a pH < 3.4, softening is the result of nonenzymatic degradation of cell wall components, but note other studies which suggest tissue softening is not based on hydrolysis of pectic substances at low pH in cucumbers (McFeeters et al., 1990; Krall et al., 1998). In addition, peppers in the current study were packaged in the presence of oxygen. While the mechanism is unknown, oxygen has been shown to accelerate the softening of acidified red bell peppers (McFeeters et al., 2004), and likely contributed to the softening observed in this study.

Broccoli was the third vegetable examined in this study. Firmness of broccoli decreased as the degree of processing increased. Blanching reduced the fracture force (Figure 6), but no significant change was observed in the total work (Figure 7). The 24-hr equilibration period did not change the textural properties of broccoli, although the fracture force significantly decreased by 50% two days after microwave processing compared to force measured at the equilibrated stage. Over the course of storage, the fracture force and total work decreased by 71 and 77%, respectively. These results were similar to those of sweetpotato and red bell pepper.

Not to be overlooked is the effect of microwave processing on the textural properties of acidified vegetables. With the exception of sweetpotato, significant decreases in fracture force and total work were observed for red bell pepper and broccoli two days after processing. From these results, it was clear that thermal processing reduced vegetable firmness. Unfortunately, no comparison to vegetables pasteurized using the traditional water bath technique (15 minute hold time at 74°C) was made, and so any potential quality improvement conferred by microwave technology could not be quantified. However, previous studies that have looked at the effects of blanching and pasteurization on firmness retention of acidified peppers also observed similar reductions in firmness (Fleming et al., 1993; Papageorge et al., 2003). These studies suggested that the addition of calcium ions has been most effective in maintaining firmness, more so than low temperature blanching methods. Further studies must be done to improve the textural properties of acidified broccoli, red bell pepper, and sweetpotato.

4.5 Conclusion

The work demonstrated the applicability of 915 MHz continuous microwave processing as a pasteurization method for packaged, acidified vegetables. However, due to equipment and material limitations, vegetable packs were sealed after microwave processing, and then held to deliver a defined thermal treatment. Infrared thermocouples, fiber optic temperature sensors, and infrared imaging were used to assess the applied thermal treatment. A 60-day storage study showed no signs of microbial spoilage, indicating an adequate thermal process. However, texture degradation over storage was a major issue for broccoli and red bell pepper. Broccoli color degraded due to pheophytinization, but red bell pepper and sweetpotato retained much of the brilliant red and orange color during thermal processing and after storage. Further work must be done to enable cup sealing prior to microwave processing, and pretreatments evaluated to improve the textural properties of acidified vegetables.

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Table 1. Changes in acid, sugar, and ethanol concentrations in the cover solutions of pasteurized vegetable packs over a 60 day storage period at 30°C.

	Broccoli		Red bell pepper		Sweetpotato	
Analyte[a]	0 day	60 day	0 day	60 day	0 day	60 day
Malic acid	0.61	0.54	--	--	4.67	4.99
Succinic acid	--	--	5.30	7.01*	--	--
Lactic acid	--	--	--	--	--	--
Acetic acid	--	1.2**	--	0.90**	--	1.12**
Propionic acid	--	--	--	--	--	--
Butyric acid	--	--	--	--	--	--
Glucose	3.98	4.81	23.83	30.41**	21.15	44.30**
Fructose	3.88	4.74	25.84	32.95**	12.80	37.39**
Ethanol	--	--	--	--	--	--

[a]All analyte concentrations are in mM; '--' denotes analyte was below detection level

* Denotes a significant difference ($p < 0.05$) from initial time ($n = 4$)

** Denotes a significant difference ($p < 0.01$) from initial time ($n = 4$)

Table 2. Color values of raw and acidified vegetables after each unit operation and 60 day storage at 30°C[a].

Vegetable	Treatment	L*		a*		b*		Hue (º)		Chroma		ΔE	ΔE
Broccoli floret	Raw	52.87	a	-10.18	a	17.20	ab	120.08	b	20.02	ab	Ref[b]	
	Blanched	40.99	b	-16.13	b	19.40	a	130.42	a	25.28	a	13.46	
	Equilibrated	43.63	b	0.04	c	17.88	ab	89.62	d	17.89	bc	13.79	Ref
	Post-process	39.28	b	-0.48	c	17.45	ab	91.48	cd	17.46	bc	16.70	4.41
	Storage	40.38	b	-1.13	c	13.38	b	94.78	c	13.44	c	15.89	5.68
Broccoli stem	Raw	68.43	a	-9.38	a	21.92	a	113.14	a	23.84	a	Ref	
	Blanched	53.62	b	-10.23	a	20.98	a	115.94	a	23.52	a	14.87	
	Equilibrated	56.89	b	-3.06	b	10.86	b	106.04	ab	11.30	b	17.19	Ref
	Post-process	57.81	b	-2.70	b	8.45	b	110.16	bc	8.93	b	18.41	2.60
	Storage	54.10	b	-2.16	b	9.75	b	102.73	c	10.00	b	20.14	3.14
Red bell pepper	Raw	37.64	a	16.61	ab	15.71	bc	43.10	a	23.13	ab	Ref	
	Blanched	41.44	b	16.28	ab	17.42	abc	46.84	a	23.88	ab	4.17	
	Equilibrated	39.04	ab	18.48	a	20.17	a	47.26	a	27.42	a	5.03	Ref
	Post-process	36.08	a	16.62	ab	18.31	ab	47.77	a	24.77	a	3.03	3.96
	Storage	35.87	a	13.25	b	14.22	c	47.25	a	19.56	b	4.09	8.54
Sweet-potato	Raw	63.99	a	22.30	a	33.52	a	56.77	ab	40.42	a	Ref	
	Blanched	51.22	c	20.30	a	31.74	a	57.37	ab	37.68	a	13.05	
	Equilibrated	53.05	b	22.02	a	33.36	a	56.54	b	39.97	a	10.94	Ref
	Post-process	52.99	b	19.37	a	31.51	a	58.46	ab	36.99	a	11.56	3.24
	Storage	50.50	c	16.41	b	28.08	b	59.70	a	33.53	b	15.70	8.12

[a] For each vegetable, different letters within a column denote significant differences ($p < 0.05$) between treatments (*n* = 10)

[b] 'Ref' denotes the reference value for ΔE calculations

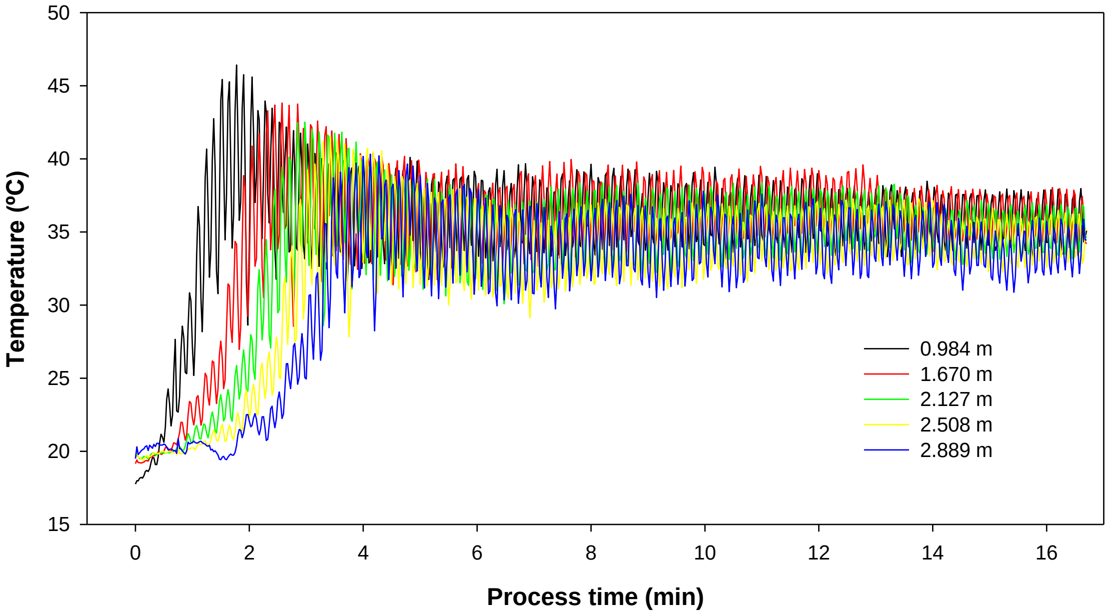

Figure 1. Infrared thermocouple temperature measurements at fixed points along the length of the microwave tunnel during continuous microwave processing of acidified vegetable packs at 3.5 kW.

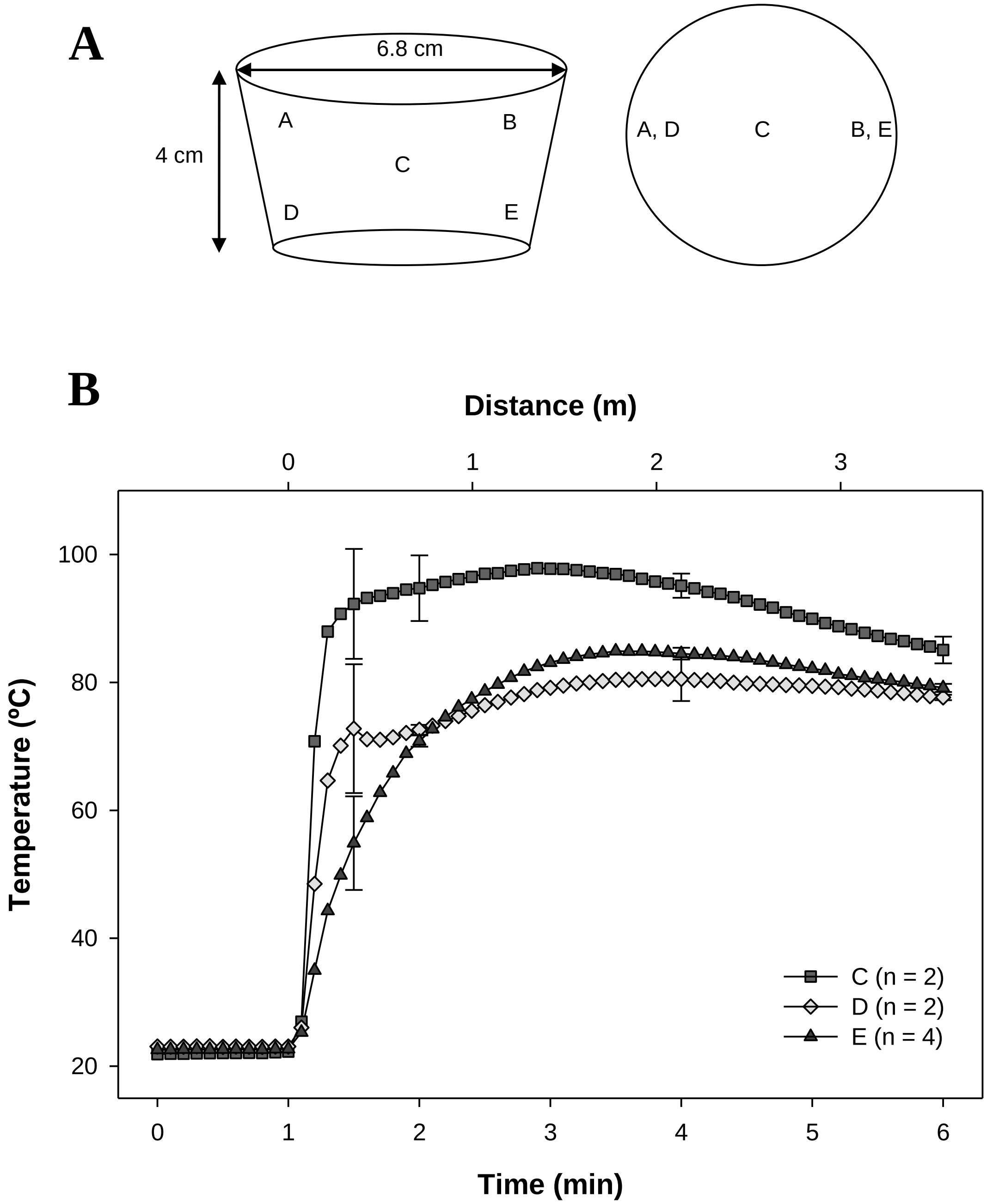

Figure 2. (A) Fiber optic temperature sensor locations: side view (left) and top view (right). (B) Time-temperature heating profile of pre-equilibrated sweetpotato to 1% NaCl in 0% NaCl cover solution. Product enters the microwave field at 0 m and exits at 3.3 m. Rotation occurs between 0.2 and 0.4 m (1.2 and 1.5 minutes), reversing the initial locations of D and E. Error bars represent 1 standard deviation of at least 2 replicates.

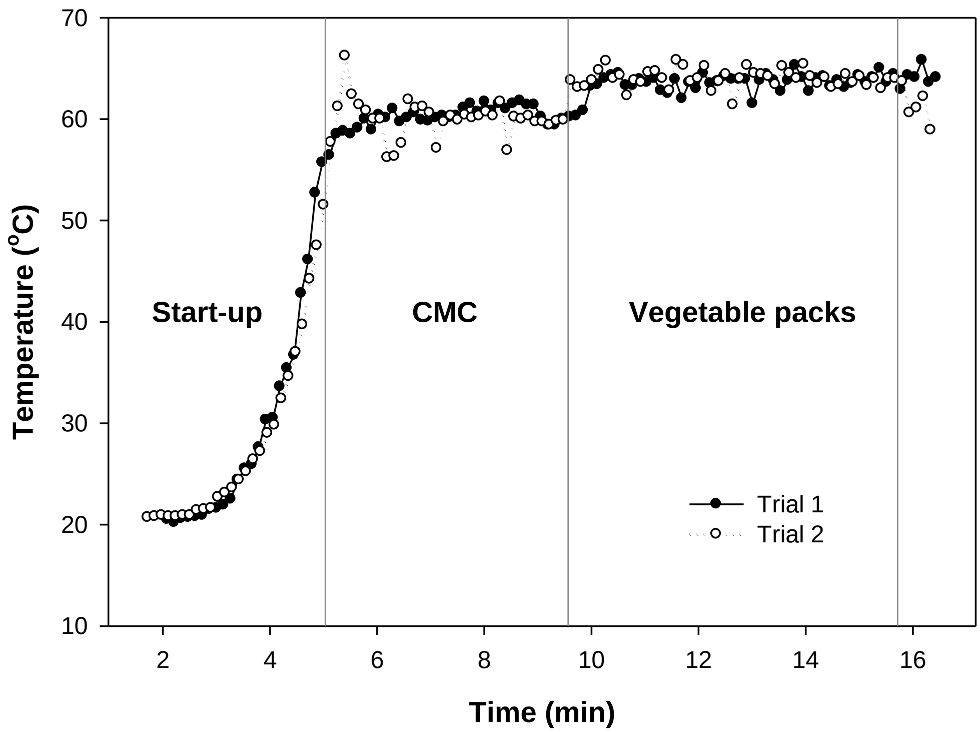

Figure 3. Average surface temperatures of vegetable packs after 915 MHz continuous microwave processing at 3.5 kW and 180° cup rotation as measured by infrared imaging.

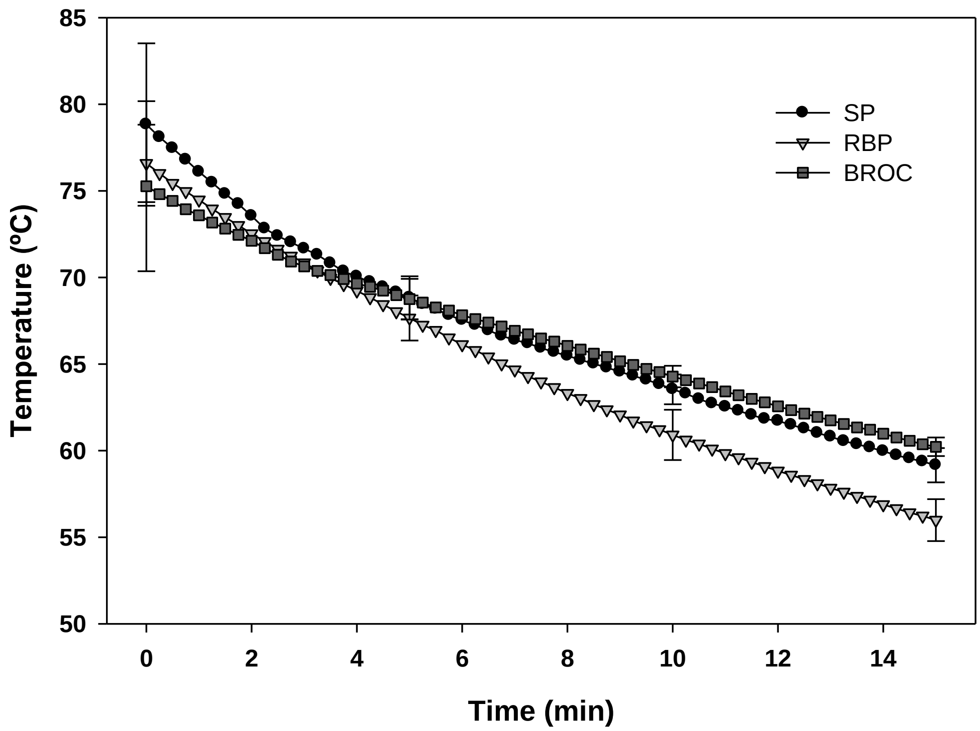

Figure 4. Mean temperature and standard deviation of sweetpotato (SP), red bell pepper (RBP), and broccoli (BROC) packs during a 15 min hold period in an insulating mold after microwave processing (*n* = 8 for each vegetable).

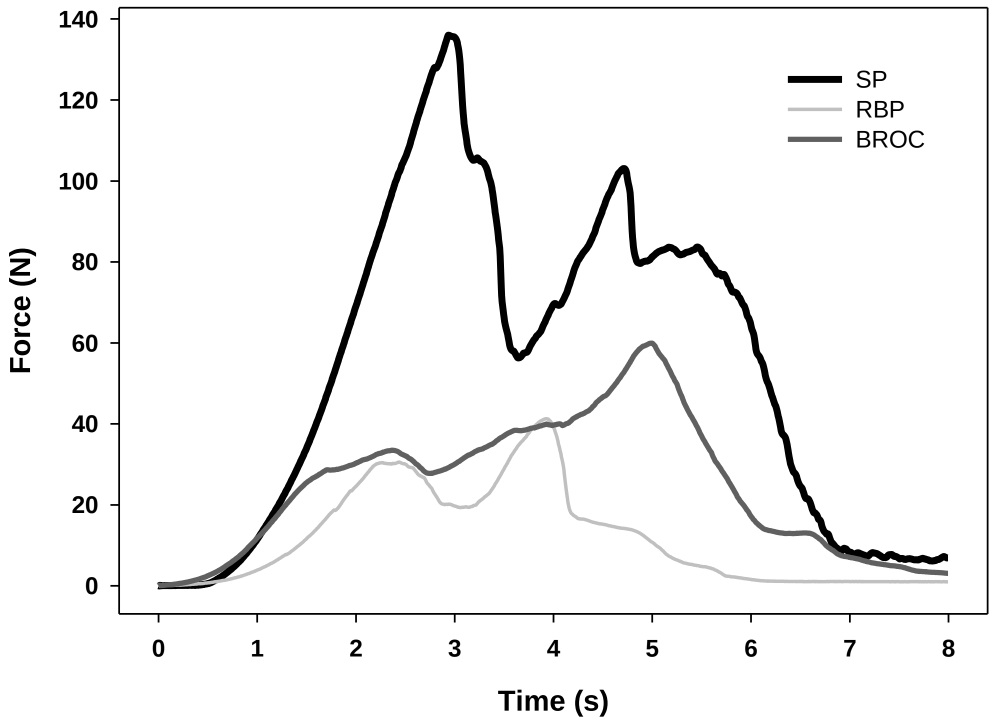

Figure 5. Typical texture profiles of sweetpotato, red bell pepper, and broccoli obtained from the cut test (above profiles are of vegetables 2 days after microwave processing).

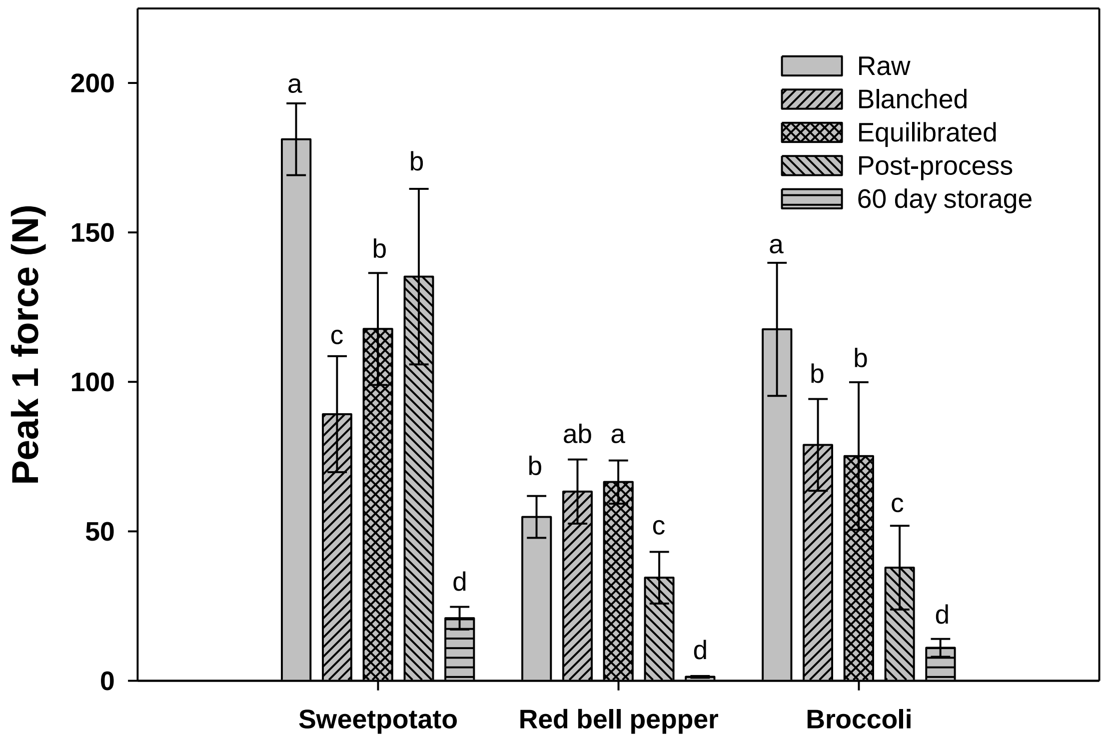

Figure 6. Peak forces obtained from the knife-cut test of sweetpotato, red bell pepper, and broccoli cubes after each unit operation and 60 day storage at 30°C. Different letters within each vegetable denote significant differences ($p < 0.05$); error bars represent one standard deviation (n = 10).

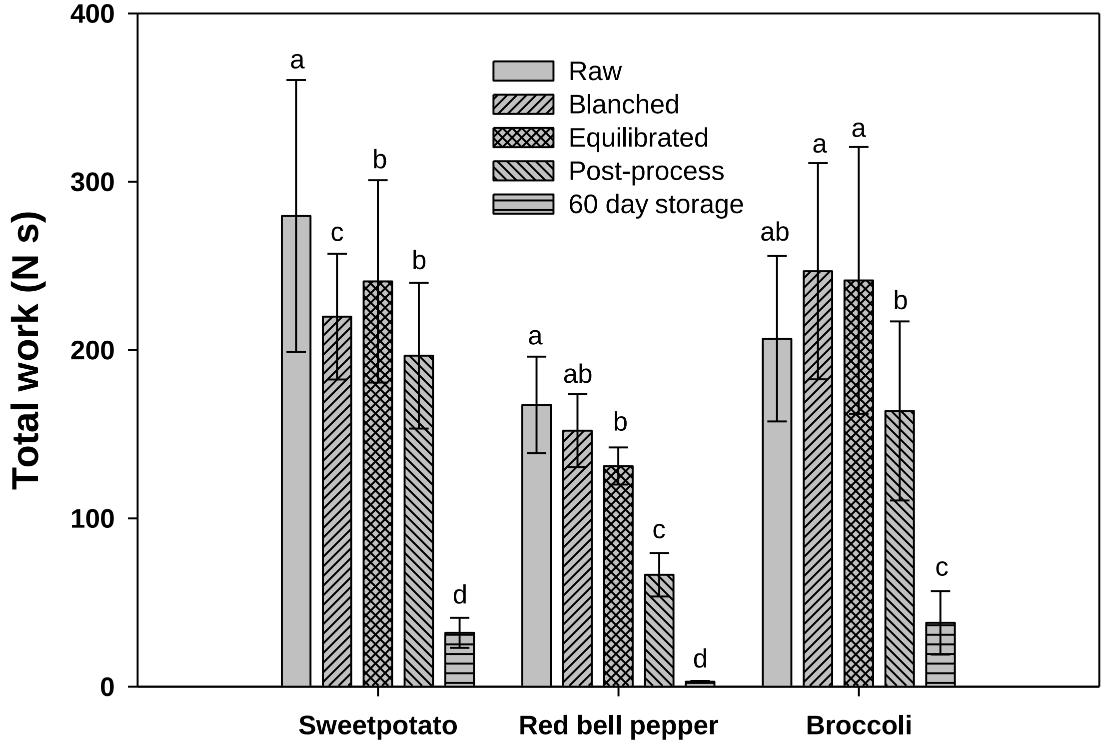

Figure 7. Total work required cut through sweetpotato, red bell pepper, and broccoli cubes after each unit operation and 60 day storage at 30°C. Different letters within each vegetable denote significant differences ($p < 0.05$); error bars represent one standard deviation ($n = 10$).

APPENDICES

Appendix A. Dielectric properties of broccoli at 915 MHz.

Treatment	°C	ε′ ± SD	ε″ ± SD	tan δ ± SD	Dp ± SD (cm)
Broccoli	25	67.87 ± 0.02	15.76 ± 0.39	0.23 ± 0.01	2.75 ± 0.07
0 hr	40	66.94 ± 0.07	16.10 ± 0.22	0.24 ± 0.00	2.67 ± 0.03
	55	64.60 ± 1.34	17.63 ± 0.64	0.27 ± 0.02	2.40 ± 0.11
	70	61.30 ± 1.16	20.28 ± 0.61	0.33 ± 0.02	2.04 ± 0.08
	85	58.12 ± 0.43	23.79 ± 0.18	0.41 ± 0.00	1.71 ± 0.01
	100	52.75 ± 1.92	26.57 ± 1.78	0.50 ± 0.02	1.47 ± 0.07
Broccoli	25	68.67 ± 4.30	28.44 ± 3.49	0.41 ± 0.03	1.56 ± 0.14
Blanched, equilibrated 4 hr	40	68.07 ± 4.10	29.40 ± 3.61	0.43 ± 0.03	1.50 ± 0.14
1% NaCl, 1.5% citric acid	55	66.01 ± 3.37	33.87 ± 4.84	0.51 ± 0.05	1.30 ± 0.15
	70	62.51 ± 2.61	43.00 ± 7.36	0.69 ± 0.09	1.02 ± 0.14
	85	59.86 ± 2.34	51.77 ± 9.41	0.86 ± 0.12	0.85 ± 0.12
	100	57.19 ± 2.34	61.65 ± 10.31	1.08 ± 0.14	0.72 ± 0.09
Broccoli	25	66.34 ± 5.01	26.66 ± 2.57	0.40 ± 0.01	1.63 ± 0.09
Blanched, equilibrated 24 hr	40	65.54 ± 5.19	28.08 ± 2.31	0.43 ± 0.00	1.54 ± 0.07
1% NaCl, 1.5% citric acid	55	63.29 ± 5.06	32.93 ± 2.34	0.52 ± 0.00	1.30 ± 0.04
	70	60.16 ± 4.99	40.94 ± 1.73	0.68 ± 0.03	1.04 ± 0.00
	85	57.53 ± 4.05	50.08 ± 1.97	0.87 ± 0.03	0.85 ± 0.01
	100	55.09 ± 2.93	60.52 ± 2.38	1.10 ± 0.02	0.71 ± 0.01
Broccoli	25	69.26 ± 6.65	37.49 ± 3.62	0.54 ± 0.00	1.20 ± 0.06
Blanched, equilibrated 4 hr	40	68.90 ± 6.39	38.51 ± 4.54	0.56 ± 0.01	1.17 ± 0.08
2% NaCl, 1.5% citric acid	55	67.66 ± 5.53	42.17 ± 6.52	0.62 ± 0.05	1.07 ± 0.12
	70	65.24 ± 4.51	49.82 ± 7.75	0.76 ± 0.07	0.91 ± 0.10
	85	62.86 ± 4.11	58.97 ± 7.66	0.94 ± 0.06	0.77 ± 0.07
	100	58.56 ± 2.41	80.98 ± 13.98	1.38 ± 0.18	0.58 ± 0.07
Broccoli	25	67.70 ± 1.41	38.36 ± 6.02	0.57 ± 0.08	1.17 ± 0.16
Blanched, equilibrated 24 hr	40	64.98 ± 2.81	43.46 ± 4.04	0.67 ± 0.03	1.02 ± 0.07
2% NaCl, 1.5% citric acid	55	62.07 ± 3.42	52.02 ± 5.10	0.84 ± 0.04	0.85 ± 0.06
	70	59.56 ± 3.36	62.83 ± 7.16	1.05 ± 0.06	0.71 ± 0.05
	85	56.92 ± 3.89	73.81 ± 10.62	1.29 ± 0.10	0.62 ± 0.06
	100	52.82 ± 6.57	81.87 ± 20.43	1.54 ± 0.20	0.56 ± 0.09
Broccoli	25	71.23 ± 1.80	38.12 ± 1.21	0.54 ± 0.00	1.19 ± 0.02
Blanched, equilibrated 4 hr	40	70.37 ± 1.36	40.18 ± 2.29	0.57 ± 0.02	1.13 ± 0.05
2% NaCl, 2% citric acid	55	67.83 ± 0.22	47.05 ± 6.29	0.69 ± 0.10	0.97 ± 0.12
	70	64.30 ± 0.44	57.99 ± 3.83	0.90 ± 0.05	0.78 ± 0.04
	85	61.40 ± 0.15	68.70 ± 5.09	1.12 ± 0.08	0.67 ± 0.04
	100	57.95 ± 0.13	83.63 ± 7.34	1.44 ± 0.13	0.56 ± 0.04
Broccoli	25	66.52 ± 1.06	34.77 ± 0.85	0.52 ± 0.00	1.26 ± 0.02
Blanched, equilibrated 24 hr	40	65.61 ± 1.34	37.28 ± 0.23	0.57 ± 0.01	1.18 ± 0.00
2% NaCl, 2% citric acid	55	64.02 ± 1.70	41.65 ± 0.12	0.65 ± 0.02	1.05 ± 0.01
	70	61.37 ± 0.92	51.62 ± 1.55	0.84 ± 0.01	0.85 ± 0.02
	85	58.04 ± 0.88	65.36 ± 1.07	1.13 ± 0.00	0.68 ± 0.01
	100	55.38 ± 0.92	78.90 ± 0.45	1.42 ± 0.03	0.58 ± 0.01

Appendix B. Dielectric properties of red bell pepper at 915 MHz.

Treatment	°C	ε′± SD			ε″± SD			tan δ± SD			Dp ± SD (cm)		
Red bell pepper	25	75.98	±	0.51	13.05	±	0.4856	0.17	±	0.01	3.50	±	0.14
0 hr	40	73.42	±	1.67	13.57	±	0.7715	0.18	±	0.01	3.32	±	0.22
	55	69.78	±	1.63	14.88	±	0.973	0.21	±	0.02	2.95	±	0.22
	70	66.27	±	1.40	16.85	±	1.1666	0.25	±	0.02	2.55	±	0.20
	85	62.65	±	1.28	19.29	±	1.3662	0.31	±	0.03	2.17	±	0.17
	100	59.02	±	1.24	21.93	±	1.4425	0.37	±	0.03	1.86	±	0.14
Red bell pepper	25	77.61	±	2.44	19.00	±	0.6046	0.25	±	0.02	2.44	±	0.11
Unblanched, equilibrated 4 hr	40	75.87	±	1.77	20.10	±	0.4288	0.27	±	0.01	2.28	±	0.07
1% NaCl, 0.5% citric acid	55	72.58	±	1.88	22.56	±	0.9123	0.31	±	0.02	2.00	±	0.10
	70	68.15	±	1.10	26.71	±	0.6187	0.39	±	0.02	1.64	±	0.05
	85	63.76	±	0.50	32.20	±	0.2776	0.50	±	0.00	1.33	±	0.01
	100	59.58	±	0.77	38.49	±	0.2505	0.65	±	0.00	1.10	±	0.00
Red bell pepper	25	69.56	±	9.40	17.82	±	2.627	0.26	±	0.00	2.47	±	0.20
Unblanched, equilibrated 24 hr	40	68.17	±	7.97	19.14	±	3.8483	0.28	±	0.02	2.30	±	0.33
1% NaCl, 0.5% citric acid	55	65.27	±	6.88	22.25	±	4.9898	0.34	±	0.04	1.96	±	0.33
	70	61.97	±	5.81	26.46	±	6.2586	0.42	±	0.06	1.62	±	0.30
	85	58.64	±	5.37	31.45	±	6.7242	0.53	±	0.07	1.34	±	0.22
	100	55.74	±	4.45	36.44	±	7.8423	0.65	±	0.09	1.14	±	0.19
Red bell pepper	25	75.36	±	2.37	24.12	±	0.8181	0.32	±	0.00	1.90	±	0.03
Unblanched, equilibrated 4 hr	40	73.82	±	1.71	25.31	±	2.1864	0.34	±	0.02	1.80	±	0.13
2% NaCl, 0.5% citric acid	55	70.74	±	0.40	28.82	±	3.103	0.41	±	0.04	1.56	±	0.16
	70	67.17	±	1.85	34.78	±	7.4049	0.52	±	0.12	1.30	±	0.28
	85	64.51	±	1.10	39.78	±	6.9022	0.62	±	0.12	1.12	±	0.19
	100	59.48	±	0.27	51.52	±	7.0401	0.87	±	0.11	0.85	±	0.10
Red bell pepper	25	66.36	±	13.22	23.47	±	8.1145	0.35	±	0.05	1.92	±	0.47
Unblanched, equilibrated 24 hr	40	64.77	±	11.97	26.20	±	10.673	0.40	±	0.09	1.74	±	0.55
2% NaCl, 0.5% citric acid	55	62.32	±	10.69	30.82	±	14.268	0.48	±	0.15	1.50	±	0.56
	70	59.96	±	9.41	36.35	±	17.788	0.59	±	0.20	1.28	±	0.51
	85	57.67	±	8.00	42.47	±	20.998	0.72	±	0.26	1.10	±	0.44
	100	55.00	±	6.65	52.69	±	20.044	0.94	±	0.25	0.85	±	0.25
Red bell pepper	25	75.26	±	0.58	30.98	±	0.3136	0.41	±	0.01	1.49	±	0.02
Unblanched, equilibrated 4 hr	40	74.93	±	0.71	31.42	±	0.3414	0.42	±	0.01	1.47	±	0.02
2% NaCl, 2% citric acid	55	72.50	±	1.78	35.52	±	2.1432	0.49	±	0.04	1.29	±	0.09
	70	68.92	±	2.26	42.12	±	3.0259	0.61	±	0.06	1.07	±	0.09
	85	65.32	±	2.20	50.30	±	3.5935	0.77	±	0.08	0.89	±	0.07
	100	60.46	±	1.37	64.30	±	4.652	1.06	±	0.10	0.70	±	0.05
Red bell pepper	25	74.13	±	1.02	34.05	±	4.035	0.46	±	0.06	1.36	±	0.16
Unblanched, equilibrated 24 hr	40	73.76	±	0.95	34.70	±	4.3036	0.47	±	0.06	1.34	±	0.17
2% NaCl, 2% citric acid	55	71.38	±	0.19	39.29	±	3.1907	0.55	±	0.04	1.16	±	0.09
	70	67.40	±	0.11	48.01	±	5.297	0.71	±	0.08	0.95	±	0.09
	85	63.38	±	0.54	58.85	±	8.4991	0.93	±	0.14	0.78	±	0.10
	100	59.24	±	0.36	72.85	±	7.4304	1.23	±	0.13	0.63	±	0.05

Appendix C. Dielectric properties of sweetpotato at 915 MHz.

Treatment	°C	ε′± SD	ε″± SD	tan δ± SD	Dp ± SD (cm)
Sweetpotato	25	70.08 ± 0.96	21.88 ± 0.60	0.31 ± 0.00	2.02 ± 0.04
0 hr	40	69.36 ± 0.77	22.60 ± 0.80	0.33 ± 0.01	1.95 ± 0.06
	55	66.63 ± 1.08	25.63 ± 0.47	0.38 ± 0.00	1.69 ± 0.02
	70	63.70 ± 0.97	29.55 ± 0.68	0.46 ± 0.00	1.45 ± 0.02
	85	60.64 ± 0.91	34.19 ± 0.86	0.56 ± 0.01	1.23 ± 0.02
	100	56.93 ± 0.42	40.79 ± 2.23	0.72 ± 0.03	1.02 ± 0.05
Sweetpotato	25	70.28 ± 1.56	26.11 ± 0.39	0.37 ± 0.00	1.70 ± 0.01
Blanched, equilibrated 4 hr	40	69.03 ± 0.77	27.69 ± 1.54	0.40 ± 0.02	1.60 ± 0.08
1% NaCl, 1.0% citric acid	55	66.57 ± 0.09	31.66 ± 2.36	0.48 ± 0.03	1.38 ± 0.10
	70	63.27 ± 0.29	38.19 ± 1.62	0.60 ± 0.02	1.13 ± 0.04
	85	60.11 ± 0.07	45.28 ± 1.71	0.75 ± 0.03	0.95 ± 0.03
	100	56.86 ± 0.28	53.34 ± 1.15	0.94 ± 0.02	0.80 ± 0.02
Sweetpotato	25	70.51 ± 2.51	26.49 ± 1.25	0.38 ± 0.00	1.68 ± 0.05
Blanched, equilibrated 24 hr	40	69.48 ± 1.88	27.90 ± 2.45	0.40 ± 0.02	1.59 ± 0.12
1% NaCl, 1.0% citric acid	55	66.23 ± 1.71	32.98 ± 3.65	0.50 ± 0.04	1.33 ± 0.12
	70	63.48 ± 2.35	38.98 ± 2.11	0.61 ± 0.01	1.11 ± 0.04
	85	60.68 ± 2.17	45.70 ± 3.23	0.75 ± 0.03	0.95 ± 0.05
	100	57.44 ± 2.13	53.59 ± 4.01	0.93 ± 0.04	0.80 ± 0.04
Sweetpotato	25	69.28 ± 3.14	39.69 ± 0.52	0.57 ± 0.02	1.14 ± 0.01
Blanched, equilibrated 4 hr	40	68.96 ± 2.49	40.96 ± 0.14	0.59 ± 0.02	1.10 ± 0.02
2% NaCl, 1.0% citric acid	55	67.42 ± 2.27	46.12 ± 0.55	0.68 ± 0.03	0.98 ± 0.02
	70	63.88 ± 2.27	58.50 ± 1.36	0.92 ± 0.05	0.77 ± 0.03
	85	60.50 ± 2.15	72.19 ± 2.08	1.19 ± 0.08	0.64 ± 0.02
	100	57.85 ± 1.49	85.99 ± 3.43	1.49 ± 0.10	0.55 ± 0.02
Sweetpotato	25	71.28 ± 2.65	41.63 ± 3.70	0.58 ± 0.03	1.10 ± 0.07
Blanched, equilibrated 24 hr	40	70.67 ± 2.97	43.45 ± 4.88	0.61 ± 0.04	1.06 ± 0.09
2% NaCl, 1.0% citric acid	55	68.42 ± 2.03	49.69 ± 7.95	0.72 ± 0.09	0.93 ± 0.12
	70	65.30 ± 0.96	59.40 ± 11.33	0.91 ± 0.16	0.78 ± 0.13
	85	62.46 ± 0.52	69.98 ± 12.73	1.12 ± 0.19	0.67 ± 0.10
	100	58.94 ± 0.74	85.16 ± 11.39	1.44 ± 0.18	0.56 ± 0.06
Sweetpotato	25	68.85 ± 2.22	35.91 ± 3.06	0.52 ± 0.03	1.25 ± 0.08
Blanched, equilibrated 4 hr	40	68.01 ± 2.40	37.81 ± 2.03	0.56 ± 0.01	1.18 ± 0.04
2% NaCl, 2% citric acid	55	66.42 ± 2.74	42.70 ± 0.65	0.64 ± 0.02	1.04 ± 0.00
	70	64.60 ± 3.27	48.94 ± 1.40	0.76 ± 0.06	0.91 ± 0.04
	85	62.22 ± 3.60	57.77 ± 3.63	0.93 ± 0.11	0.78 ± 0.06
	100	58.52 ± 2.77	75.02 ± 0.40	1.28 ± 0.07	0.61 ± 0.01
Sweetpotato	25	71.77 ± 1.59	38.45 ± 1.62	0.54 ± 0.03	1.19 ± 0.06
Blanched, equilibrated 24 hr	40	70.73 ± 0.85	41.11 ± 0.47	0.58 ± 0.00	1.11 ± 0.01
2% NaCl, 2% citric acid	55	68.68 ± 1.06	47.78 ± 1.00	0.70 ± 0.03	0.95 ± 0.02
	70	66.06 ± 1.96	56.29 ± 3.71	0.85 ± 0.08	0.81 ± 0.06
	85	64.15 ± 2.22	63.42 ± 4.25	0.99 ± 0.10	0.72 ± 0.05
	100	59.69 ± 1.53	81.69 ± 1.40	1.37 ± 0.06	0.57 ± 0.01

Appendix D. Dielectric properties of broccoli at 2450 MHz.

Treatment	°C	ε′± SD			ε″± SD			tan δ± SD			Dp ± SD (cm)		
Broccoli	25	64.32	±	0.36	14.03	±	0.31	0.22	±	0.01	1.12	±	0.03
0 hr	40	63.62	±	0.15	13.39	±	0.27	0.21	±	0.00	1.17	±	0.02
	55	61.53	±	1.11	12.61	±	0.48	0.20	±	0.00	1.22	±	0.04
	70	58.45	±	0.99	12.33	±	0.15	0.21	±	0.00	1.22	±	0.00
	85	55.25	±	0.04	12.72	±	0.06	0.23	±	0.00	1.15	±	0.01
	100	49.68	±	1.14	12.95	±	0.46	0.26	±	0.00	1.07	±	0.03
Broccoli	25	65.40	±	4.40	18.81	±	1.33	0.29	±	0.00	0.85	±	0.03
Blanched, equilibrated 4 hr	40	64.76	±	4.42	18.80	±	1.40	0.29	±	0.00	0.84	±	0.03
1% NaCl, 1.5% citric acid	55	62.79	±	3.73	19.25	±	1.67	0.31	±	0.01	0.81	±	0.05
	70	59.59	±	3.24	21.26	±	2.50	0.36	±	0.02	0.72	±	0.06
	85	57.00	±	3.18	23.80	±	3.24	0.42	±	0.03	0.64	±	0.07
	100	54.37	±	3.37	26.92	±	3.62	0.49	±	0.04	0.55	±	0.06
Broccoli	25	63.43	±	4.75	17.61	±	1.47	0.28	±	0.00	0.89	±	0.04
Blanched, equilibrated 24 hr	40	62.70	±	4.92	17.52	±	1.47	0.28	±	0.00	0.89	±	0.04
1% NaCl, 1.5% citric acid	55	60.67	±	4.84	17.98	±	1.38	0.30	±	0.00	0.85	±	0.03
	70	57.71	±	4.78	19.75	±	1.11	0.34	±	0.01	0.76	±	0.01
	85	55.13	±	3.95	22.42	±	1.01	0.41	±	0.01	0.66	±	0.01
	100	52.72	±	2.88	25.74	±	1.02	0.49	±	0.01	0.57	±	0.01
Broccoli	25	65.75	±	6.93	22.39	±	2.64	0.34	±	0.00	0.72	±	0.05
Blanched, equilibrated 4 hr	40	65.46	±	6.65	22.51	±	2.62	0.34	±	0.01	0.71	±	0.05
2% NaCl, 1.5% citric acid	55	64.35	±	5.97	23.00	±	2.84	0.36	±	0.01	0.69	±	0.05
	70	62.10	±	5.21	24.59	±	3.04	0.40	±	0.02	0.64	±	0.05
	85	59.67	±	5.17	27.13	±	2.95	0.45	±	0.01	0.57	±	0.04
	100	55.16	±	4.14	34.32	±	4.98	0.62	±	0.04	0.44	±	0.05
Broccoli	25	63.93	±	1.58	22.57	±	1.89	0.35	±	0.02	0.70	±	0.05
Blanched, equilibrated 24 hr	40	61.47	±	2.63	23.04	±	1.93	0.37	±	0.02	0.68	±	0.04
2% NaCl, 1.5% citric acid	55	58.50	±	3.14	24.95	±	2.33	0.43	±	0.02	0.61	±	0.04
	70	55.77	±	2.92	28.17	±	2.98	0.50	±	0.03	0.53	±	0.04
	85	52.73	±	3.36	31.75	±	4.26	0.60	±	0.04	0.47	±	0.05
	100	48.32	±	5.93	34.28	±	8.04	0.70	±	0.08	0.42	±	0.07
Broccoli	25	67.75	±	1.95	22.39	±	0.77	0.33	±	0.00	0.73	±	0.01
Blanched, equilibrated 4 hr	40	66.98	±	1.53	22.62	±	0.87	0.34	±	0.01	0.72	±	0.02
2% NaCl, 2% citric acid	55	64.73	±	0.19	23.87	±	1.66	0.37	±	0.02	0.67	±	0.04
	70	61.47	±	0.77	26.62	±	1.28	0.43	±	0.02	0.59	±	0.02
	85	58.72	±	0.59	29.88	±	1.72	0.51	±	0.02	0.52	±	0.03
	100	55.39	±	0.43	34.73	±	2.46	0.63	±	0.04	0.44	±	0.03
Broccoli	25	62.95	±	0.81	20.91	±	0.33	0.33	±	0.00	0.75	±	0.01
Blanched, equilibrated 24 hr	40	62.22	±	1.01	21.22	±	0.17	0.34	±	0.00	0.73	±	0.00
2% NaCl, 2% citric acid	55	60.75	±	1.37	21.87	±	0.33	0.36	±	0.00	0.71	±	0.00
	70	58.14	±	0.59	24.44	±	0.57	0.42	±	0.01	0.62	±	0.01
	85	54.72	±	0.45	28.58	±	0.44	0.52	±	0.00	0.52	±	0.01
	100	51.91	±	0.41	33.09	±	0.06	0.64	±	0.01	0.44	±	0.00

Appendix E. Dielectric properties of red bell pepper at 2450 MHz.

Treatment	°C	ε′± SD			ε″± SD			tan δ± SD			Dp ± SD (cm)		
Red bell pepper	25	73.07	±	0.80	14.41	±	0.75	0.20	±	0.01	1.16	±	0.07
0 hr	40	71.08	±	1.55	12.57	±	0.07	0.18	±	0.00	1.31	±	0.01
	55	67.88	±	1.50	11.23	±	0.13	0.17	±	0.01	1.44	±	0.03
	70	64.61	±	1.29	10.74	±	0.31	0.17	±	0.01	1.46	±	0.06
	85	61.22	±	1.19	10.82	±	0.42	0.18	±	0.01	1.42	±	0.07
	100	57.80	±	1.16	11.25	±	0.47	0.19	±	0.01	1.32	±	0.07
Red bell pepper	25	74.68	±	2.14	16.68	±	0.65	0.22	±	0.00	1.02	±	0.03
Unblanched, equilibrated 4 hr	40	73.37	±	1.57	15.68	±	0.27	0.21	±	0.00	1.07	±	0.01
1% NaCl, 0.5% citric acid	55	70.46	±	1.66	14.84	±	0.14	0.21	±	0.00	1.11	±	0.00
	70	66.38	±	0.93	14.85	±	0.04	0.22	±	0.00	1.08	±	0.01
	85	62.27	±	0.51	15.88	±	0.11	0.26	±	0.00	0.98	±	0.00
	100	58.44	±	0.84	17.51	±	0.10	0.30	±	0.00	0.86	±	0.00
Red bell pepper	25	66.92	±	9.38	14.41	±	2.16	0.22	±	0.00	1.12	±	0.09
Unblanched, equilibrated 24 hr	40	65.67	±	8.10	13.82	±	1.70	0.21	±	0.00	1.15	±	0.07
1% NaCl, 0.5% citric acid	55	63.04	±	7.04	13.48	±	1.87	0.21	±	0.01	1.16	±	0.10
	70	59.90	±	6.03	13.97	±	2.18	0.23	±	0.01	1.10	±	0.12
	85	56.70	±	5.66	15.05	±	2.37	0.26	±	0.02	0.99	±	0.11
	100	53.84	±	4.86	16.44	±	2.74	0.30	±	0.02	0.89	±	0.11
Red bell pepper	25	72.18	±	2.12	18.25	±	0.84	0.25	±	0.00	0.91	±	0.03
Unblanched, equilibrated 4 hr	40	70.72	±	1.92	17.53	±	0.85	0.25	±	0.01	0.94	±	0.03
2% NaCl, 0.5% citric acid	55	68.10	±	0.73	17.19	±	0.90	0.25	±	0.01	0.94	±	0.04
	70	64.81	±	1.44	18.15	±	2.06	0.28	±	0.04	0.88	±	0.11
	85	62.43	±	0.74	19.10	±	2.22	0.31	±	0.04	0.82	±	0.10
	100	57.61	±	0.58	22.41	±	2.61	0.39	±	0.04	0.68	±	0.07
Red bell pepper	25	62.88	±	13.55	16.41	±	4.58	0.26	±	0.02	0.97	±	0.17
Unblanched, equilibrated 24 hr	40	61.55	±	12.47	16.18	±	4.64	0.26	±	0.02	0.98	±	0.18
2% NaCl, 0.5% citric acid	55	59.49	±	11.17	16.62	±	5.40	0.28	±	0.04	0.95	±	0.22
	70	57.24	±	10.04	17.74	±	6.53	0.30	±	0.06	0.88	±	0.25
	85	54.91	±	8.87	19.34	±	7.62	0.35	±	0.08	0.81	±	0.25
	100	51.85	±	8.30	22.47	±	7.32	0.43	±	0.07	0.66	±	0.16
Red bell pepper	25	72.05	±	0.56	20.43	±	0.23	0.28	±	0.01	0.82	±	0.01
Unblanched, equilibrated 4 hr	40	71.83	±	0.77	20.32	±	0.16	0.28	±	0.01	0.82	±	0.01
2% NaCl, 2% citric acid	55	69.70	±	1.70	20.39	±	0.32	0.29	±	0.01	0.81	±	0.02
	70	66.55	±	2.17	21.41	±	0.68	0.32	±	0.02	0.75	±	0.03
	85	63.23	±	2.11	23.41	±	1.02	0.37	±	0.03	0.67	±	0.04
	100	58.80	±	1.35	27.58	±	1.64	0.47	±	0.04	0.56	±	0.04
Red bell pepper	25	70.98	±	0.96	21.36	±	1.09	0.30	±	0.02	0.78	±	0.04
Unblanched, equilibrated 24 hr	40	70.64	±	0.92	21.31	±	1.24	0.30	±	0.02	0.78	±	0.05
2% NaCl, 2% citric acid	55	68.54	±	0.06	21.63	±	1.44	0.32	±	0.02	0.76	±	0.05
	70	64.94	±	0.10	23.37	±	2.09	0.36	±	0.03	0.69	±	0.06
	85	61.23	±	0.72	26.33	±	3.11	0.43	±	0.06	0.60	±	0.07
	100	57.35	±	0.69	30.73	±	2.80	0.54	±	0.06	0.50	±	0.05

Appendix F. Dielectric properties of sweetpotato at 2450 MHz.

Treatment	°C	ε′± SD			ε″± SD			tan δ± SD			Dp ± SD (cm)		
Sweetpotato	25	66.78	±	0.96	16.90	±	0.25	0.25	±	0.00	0.95	±	0.01
0 hr	40	66.26	±	0.83	16.56	±	0.20	0.25	±	0.00	0.97	±	0.01
	55	64.13	±	0.97	15.96	±	0.37	0.25	±	0.00	0.99	±	0.02
	70	61.52	±	0.96	16.22	±	0.31	0.26	±	0.00	0.95	±	0.01
	85	58.72	±	0.91	17.03	±	0.35	0.29	±	0.00	0.89	±	0.01
	100	55.27	±	0.52	18.79	±	0.73	0.34	±	0.01	0.78	±	0.03
Sweetpotato	25	66.75	±	1.40	18.34	±	0.64	0.27	±	0.00	0.88	±	0.02
Blanched, equilibrated 4 hr	40	65.78	±	0.67	18.03	±	0.47	0.27	±	0.00	0.88	±	0.02
1% NaCl, 1.0% citric acid	55	63.70	±	0.12	18.08	±	0.63	0.28	±	0.01	0.87	±	0.03
	70	60.74	±	0.21	19.17	±	0.62	0.32	±	0.01	0.80	±	0.02
	85	57.78	±	0.16	20.93	±	0.70	0.36	±	0.01	0.72	±	0.02
	100	54.68	±	0.41	23.27	±	0.58	0.43	±	0.01	0.63	±	0.02
Sweetpotato	25	67.22	±	2.85	18.62	±	0.51	0.28	±	0.00	0.87	±	0.01
Blanched, equilibrated 24 hr	40	66.46	±	2.20	18.36	±	0.44	0.28	±	0.00	0.87	±	0.01
1% NaCl, 1.0% citric acid	55	63.65	±	2.10	18.82	±	0.39	0.30	±	0.00	0.83	±	0.00
	70	61.24	±	2.55	19.54	±	0.71	0.32	±	0.00	0.79	±	0.01
	85	58.56	±	2.43	21.24	±	0.96	0.36	±	0.00	0.71	±	0.02
	100	55.46	±	2.52	23.60	±	1.33	0.43	±	0.00	0.63	±	0.02
Sweetpotato	25	64.92	±	1.54	22.80	±	0.06	0.35	±	0.01	0.70	±	0.01
Blanched, equilibrated 4 hr	40	64.70	±	0.94	23.01	±	0.24	0.36	±	0.01	0.69	±	0.01
2% NaCl, 1.0% citric acid	55	63.38	±	0.87	23.83	±	0.63	0.38	±	0.02	0.66	±	0.02
	70	60.63	±	1.74	26.31	±	1.91	0.43	±	0.04	0.59	±	0.05
	85	57.89	±	2.20	29.84	±	3.08	0.52	±	0.07	0.52	±	0.06
	100	55.08	±	1.24	34.84	±	3.00	0.63	±	0.07	0.44	±	0.04
Sweetpotato	25	68.08	±	2.93	23.76	±	1.41	0.35	±	0.01	0.69	±	0.03
Blanched, equilibrated 24 hr	40	67.63	±	3.21	24.07	±	1.73	0.36	±	0.01	0.68	±	0.03
2% NaCl, 1.0% citric acid	55	65.67	±	2.36	25.18	±	2.53	0.38	±	0.02	0.64	±	0.05
	70	62.84	±	1.38	27.57	±	3.69	0.44	±	0.05	0.58	±	0.07
	85	60.17	±	1.01	30.70	±	4.29	0.51	±	0.06	0.51	±	0.06
	100	56.78	±	1.15	35.58	±	4.04	0.63	±	0.06	0.43	±	0.04
Sweetpotato	25	64.59	±	1.80	22.27	±	1.03	0.34	±	0.01	0.71	±	0.02
Blanched, equilibrated 4 hr	40	63.93	±	1.95	22.32	±	0.89	0.35	±	0.00	0.71	±	0.02
2% NaCl, 2% citric acid	55	62.59	±	2.23	23.00	±	0.60	0.37	±	0.00	0.68	±	0.01
	70	60.89	±	2.70	24.35	±	0.00	0.40	±	0.02	0.64	±	0.01
	85	58.61	±	3.07	26.72	±	0.85	0.46	±	0.04	0.57	±	0.03
	100	54.95	±	2.16	32.14	±	0.03	0.59	±	0.02	0.47	±	0.01
Sweetpotato	25	67.75	±	1.33	23.73	±	0.21	0.35	±	0.01	0.69	±	0.01
Blanched, equilibrated 24 hr	40	66.94	±	0.78	23.84	±	0.11	0.36	±	0.01	0.68	±	0.01
2% NaCl, 2% citric acid	55	65.21	±	0.94	24.95	±	0.49	0.38	±	0.01	0.64	±	0.02
	70	62.95	±	1.68	26.81	±	1.14	0.43	±	0.03	0.59	±	0.03
	85	61.16	±	1.96	28.81	±	1.36	0.47	±	0.04	0.54	±	0.03
	100	56.88	±	1.20	34.54	±	0.58	0.61	±	0.02	0.44	±	0.01