ABSTRACT

CAUDILL, MORGAN FRANCES. Thermal Processing of Acidified Sweetpotato-Based Products Using a Modular 2450 MHz Continuous Flow Microwave System. (Under the direction of Dr. Van-Den Truong and Dr. Josip Simunovic).

Microwave technology is becoming more popular in the food industry; however, a system to process food products on a small scale for research and development purposes and for lower capacity processing has not been commercialized. As a potential solution to this problem, a modular 2450 MHz continuous flow system has been developed using household microwave ovens for pasteurization of acidified vegetable-fruit mixed purees. This study aimed to: 1) evaluate the effects of acidification on dielectric properties of sweetpotato-based products formulated for microwave pasteurization, 2) to evaluate the heating performance of a modular 2450 MHz continuous flow microwave system, 3) to determine the parameters required to reach pasteurization temperatures of pumpable food products, and 4) to assess nutrient retention in the processed products.

Acidified sweetpotato-fruit mixed purees were prepared and processed as a model product for this system. The high beta-carotene content of sweetpotato makes them a desirable ingredient for mixing with fruit purees to enhance the phytochemical profiles in various healthy food applications. Sweetpotato puree was mixed with lemon juice, citric acid, raspberry puree, and apple puree. These mixtures had a pH range of 3.79 to 3.97. Dielectric properties of the sweetpotato-based mixtures were measured at a frequency of 2450 MHz over a temperature range of 20-105°C using an open ended coaxial probe connected to a network analyzer. The sweetpotato mixtures had moisture contents of 82-87% which did not affect the measured dielectric properties. Each mixture showed the expected trend in which the dielectric constant decreased linearly as temperature increased. The measured dielectric

constant was consistent with the calculated values obtained using mixture equations. The results provided basic information on dielectric properties of acidified foods that would be useful in designing small and large scale microwave processes to pasteurize acidified sweetpotato products with high phytonutrient retention.

The modular microwave system in this study consisted of four stacks of microwaves with four 2450 MHz household microwave units of 1200 W power each. Sweetpotato puree mixed with blueberry puree, apple puree, and lemon juice were processed with the modular microwave system at a flow rate of 1.0 ± 0.1 L/min through a Teflon pipe that was located in the center of the microwave stacks. It was determined that the modular system used in this study was capable of rapidly increasing the product temperature from room temperature (~20°C) to a target temperature of 85°C. The modular system required a relatively small production area, low capital investment, and used less product than what is needed for the large microwave system. However, manual maintenance of the system was required to maintain the target temperature. This modular system had a similarly low nutrient degradation when compared to the large microwave system. Processing with this system resulted in a 20-27% decrease in antioxidant activity, a 10% reduction in anthocyanins, and an 8-14% decrease in beta-carotene content. The color change in the products after processing was also minimal. Therefore, this modular system has potential to be a cheaper, more efficient pasteurization method suitable for R&D and small scale processing of acidified fruit and vegetable products while maintaining high product quality.

Thermal Processing of Acidified Sweetpotato-Based Products Using a Modular 2450 MHz Continuous Flow Microwave System

by
Morgan Frances Caudill

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Food Science

Raleigh, North Carolina

2017

APPROVED BY:

Dr. Gabriel Keith Harris	Dr. Mary Ann Lila
Dr. Van-Den Truong Committee Co-chair	Dr. Josip Simunovic Committee Co-chair

DEDICATION

To those that bring love to my life.

BIOGRAPHY

Morgan Caudill is from a small family operated beef farm in rural North Carolina where she managed the day to day operations during high school. Morgan was able to increase the farm's hay production nearly tenfold by performing experiments on drought resistant grass varieties with plots in the field. Morgan also was involved with the operation and maintenance of the farm equipment. These activities largely contributed to Morgan's interest in science and engineering.

After graduating as salutatorian from East Montgomery High school, Morgan began a bachelor's degree in Bioprocessing science at NC State University. She became an active member and leader within the food science club as the dinner committee chair for three years and as a member of the executive board for two years. Morgan participated in two undergraduate research projects; one analyzed the effect of cooling on the nutrient content of apple puree and the other looked at the optimization of alcohol production using a new strain of yeast for brewing. Academically, Morgan excelled at her classes with a final GPA of 3.81 and was particularly interested in mathematics; earning A's in Calculus 1, 2, and 3. Morgan graduated with her bachelor's in 3.5 years and began working as a biological science aid in the USDA-ARS unit in Schaub hall during the last summer of her undergraduate career.

After graduating summa cum laude Morgan began her Master's degree in Food Science under the direction of Dr. Truong and Dr. Simunovic. She worked to determine the effects of a modular microwave processing system on nutritional fruit purees. Morgan plans to continue her education and pursue a doctoral degree in Food Science at NC State.

ACKNOWLEDGMENTS

Many thanks to Dr. Truong for the many hours spent providing advice and for patiently editing my posters, papers, and thesis. You have been a phenomenal mentor and are deeply appreciated. It has been a pleasure to be part of your lab. I will always consider myself a member of the sweetpotato lab family.

Thank you so very much to Rong Renolds for her help and friendship throughout my time in the sweetpotato lab.

Dr. Simunovic your guidance and advice during my Master’s has been greatly appreciated. Your curiosity and excitement about research is contagious and has made me a better scientist.

This project would not have been possible without Mike Bumgardner’s help in the pilot plant. His assistance setting up and operating the microwave system was invaluable.

I’ve been very grateful for the support and guidance that Dr. Keith Harris and Dr. Mary Ann Lila have so graciously provide as members of my advisory committee.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 3

CHAPTER 4

CHAPTER 1: Introduction

Food processing innovations play a critical role in improving food utilization. Microwave technology has been one processing method that has successfully produced puree of exceptional nutritional quality (Steed et al., 2008). Conventional heat processing of purees can be challenging because heat transfer via conduction and convection can be slow for viscous products resulting in poor product quality. Microwave processing, on the other hand, has the potential to rapidly raise the product temperature by volumetric heating (Thostenson & Chou, 1999). Thus, microwave heating is able to process product more quickly than conventional heating and produce superior products from both a quality and nutritional standpoint.

With the increasing popularity of nutritional foods in recent years, the food industry has focused on developing food products with high antioxidant capacity, anthocyanin content, and overall increased nutritional values (Sloan, 2016). A simple mixture of fruit and vegetable purees such as blueberry and sweetpotato would be one such product. Orange fleshed sweetpotatoes contain high amounts of beta-carotene which makes sweetpotato puree a healthy starting material (Padmaja, 2009; Truong and Avula, 2010).

Due to these consumer trends and the nutritional benefits of microwave heating, this technology has increased in popularity within the food industry. Continuous flow microwave technology operated at 915 MHz has been developed and implemented for commercial processing and aseptic packaging of various foods (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). The current 915 MHz systems are more suitable for large scale settings and require considerable capital investment. The main goal of this study was to implement a microwave system which is more suitable for research and development and for lower capacity processing. A modular microwave system utilizing household microwaves has been developed and initially evaluated for processing of fruit purees (Truong, 2014). The microwaves were arranged in stacks and product was pumped through a Teflon pipe passing through the center of the stacks. This system could prove useful in the development of new product by microwave processing and hot-fill packaging. The specific objectives of this study were as follows: 1) to evaluate the effects of acidification on dielectric properties of sweetpotato-based products formulated for microwave pasteurization, 2) to evaluate the heating performance of a modular 2450 MHz continuous flow microwave system, 3) to determine the parameters required to reach pasteurization temperatures of pumpable food products, and 4) to assess nutrient retention in the processed products.

REFERENCES

Coronel, P., Truong, V.-D., Simunovic, J., Sandeep, K. P., & Cartwright, G. D. (2005). Aseptic Processing of Sweetpotato Purees Using a Continuous Flow Microwave System. *Journal of Food Engineering and Physical Properties*, 531-536.

Padmaja, G. (2009). Uses and Nutritional Data of Sweetpotato. In G. Loebenstein, & G. Thottappilly, *The Sweetpotato* (pp. 189-234). Springer Science and Business Media.

Sloan, A. E. (2016). Top 10 Functional Food Trends. *Journal of Food Technology*, 24-45.

Steed, L., Truong, V., Simunovic, J., Sandeep, K., Kumar, P., Cartwright, G., et al. (2008). Continuous Flow Microwave-Assisted Processing and Aseptic Packaging of Purple-Fleshed Sweetpotato Purees. *Journal of food Science*, 455-462.

Thostenson, E., & Chou, T.-W. (1999). Microwave processing: fundamentals and applications. *Composites Part A: Applied Science and Manufacturing*, 1055-1071.

Truong, A. N. (2014). Nutrient Retention in Continuous Flow Microwave Processing of Fruit Purees Containing Particulates. MS Thesis, North Carolina State University.

Truong VD, Avula RY. 2010. *Sweet potato purees and powders for functional food ingredients*. In: Ray RC, Tomlins KI, editors. Sweet potato: Post harvest aspects in food, feed and industry. New York: Nova Science Publishers, Inc., 117-161.

CHAPTER 2: Literature Review

2.1 Acidification

2.1.1 Potential Benefits of Acidified Foods

Heat processing treatments often cause a significant reduction of nutrients in food products. One way to reduce the nutrient loss in processed foods is to decrease the intensity of the heat treatment. Lower temperatures and reduced processing time can be achieved by acidifying the food product. Thus, the destruction of heat sensitive nutrients can be reduced, which allows acidified food products to maintain a high phytonutrient profile. In order to acidify a food product, natural ingredients are incorporated, such as fruit purees. This is an opportune way to increase both acidity and nutrient content of a food product. Fruits such as raspberries and strawberries have exceptionally high antioxidant contents (Halvorsen et al., 2001). Therefore, these ingredients could further increase the phytochemical content of a sweetpotato-based product. Orange-fleshed sweetpotatoes are known as rich source of beta-carotene and the purple-fleshed sweetpotatoes are high in polyphenolics especially anthocyanins (Truong et al. 2011).

2.1.2 Processing Requirements of Acidified Foods

High acid foods are defined as having a pH at or below 4.6 as outlined by Title 21 CFR part 114 (US Food and Drug Administration). Processing low acid food (pH > 4.6) requires a sterilization temperature of at least 121°C (U.S. Department of Health and Human Services, 2010). The process must also include a hold time in which the temperature remains at least 121°C for a certain period of time depending on the type of food. In contrast, high acid foods require less processing time and/or lower processing temperatures during pasteurization in order to achieve safe log reductions of potentially harmful microorganisms.

Research has been done to investigate the appropriate times and temperatures to reach a five log reduction of various microorganisms which is necessary to produce a safe product (Breidt, Kay, Osborne, Ingham, & Arritt, 2014). For sweetpotato puree, work has been done to analyze the effect of acidification on microbial growth during storage. It was shown that sweetpotato purees acidified to a pH of 4.2 and refrigerated at 4°C had no growth of *L. monocytogenes* when acidified using citric acid and reduced growth when acidified with hydrochloric acid (Perez-Diaz, Truong, Webber, & McFeeters, 2008).

2.1.3 Safety of Acidified Foods

Spores are typically the most difficult organisms to neutralize during processing of food products. Therefore, foods in which spores are a concern require extensive heat treatments. Products acidified to a pH of 4.6 or less are considered to be safe with regard to pathogenic spores such as *C. botulinum*. At this pH, there is concern that an acid resistant vegetative organism such as *E. coli* O157:H7 may still be a safety risk. Vegetative cells do not require as considerable a heat treatment as spore forming pathogens. For this reason, acidified foods are able to undergo less heat processing while maintaining product safety. For products with a pH above 3.3, an appropriate heat treatment is necessary to control *E. coli* O157:H7 (Breidt, Sandeep, & Arritt, 2010). At a pH range of 4.6 to 3.3, pathogenic spores are not a concern, but a heat treatment must ensure at least a 5 log reduction of vegetative *E. coli* O157:H7 cells.

2.1.4 Hot Fill Packaging

Hot fill packaging refers to the process of packaging a hot product directly into the container (Berk, 2009). The heat and acid combination will achieve microbial kill on the interior of the package. The product must be filled into the container, sealed, and inverted for a set amount of time in order to ensure the entire package comes in contact with the hot product. This ensures that the entire interior of the package is heated to an appropriate temperature to reduce microbial growth within the package.

The hot fill process is predominately used for acidic products and, when heated to the correct temperature, produces shelf stable products. If non-acidic products with a pH greater than 4.6, as defined above, are packaged using a hot fill process, the product would require refrigeration and have a diminished shelf life (Lewis & Heppell, 2000) .

Some examples of hot filled products are acidic fruits, juices, and other beverage products such as Gatorade. These products should be heated to “about 77° to 99°C for about 30 to 60 sec, hot filled no lower than 77°C and often closer to 93°C, and held at this temperature for about 1 to 3 min including an inversion before cooling.” (Potter, 1973)

2.2 Microwave Processing

2.2.1 Microwave Heating

Microwaves heat through energy conversion in which electromagnetic energy is converted into heat (Thostenson & Chou, 1999).The electromagnetic energy causes dipoles within a product to move as the molecules follow the constantly changing direction of the electric field. This rapid movement of the molecules creates heat. However, the ability of the dipoles to move affects the ability of microwaves to produce heat (Tang, 2005). For example, at different phases (i.e., solid verses liquid), a molecule can move more or less freely within the material. Therefore, moisture content, temperature, frequency, composition, etc. contribute to the ability of a product to absorb and heat using microwaves (Nelson & Datta, 2001).

One of the major challenges in the field of microwave heating is runaway heating. Runaway heating is often associated with the thawing of different food products in which liquid water molecules absorb microwave energy more readily than frozen water molecules (Virtanen, Goedeken, & Tong, 1997). This causes hot spots to form within the product and promotes non-uniform heating. A possible solution to this issue is to use microwaves in conjunction with circulated air and to control the microwave energy used on the product (Virtanen, Goedeken, & Tong, 1997).

The heating of particles in a continuous flow system is another area that has had difficulty using microwave energy. Through the use of packaged bio-indicators, the ability of a continuous flow microwave system has been shown to achieve necessary microbial inactivation of purees with a uniform consistency (Brinley, et al., 2007). However, when particles such as vegetable chunks are included in a product, there are concerns that all particles may not be adequately heated. For example, to find the coldest point in the product, it would be necessary to determine which particle moved through the system most quickly and was also least effective in conducting heat. Work has been done to mimic a worst-case scenario particle to validate a continuous flow microwave system for the use of processing a pumpable fluid product with particles (Steed, 2011)

2.2.2 2450 MHz Household Microwave Oven

Household microwaves became widely available in the 1960s and quickly became a standard kitchen appliance which led to the development of many microwaveable foods. The way in which microwaves heat was studied extensively in order to both optimize the microwave's design and to determine the optimal product geometry to absorb microwave energy. While microwaves were very successful as household appliances, they were only marginally successful in industry, largely due to the non-uniform heating profile. Microwaves do not provide uniform heating for a number of reasons such as the variable magnetic and electric fields, product composition, and other factors. This causes products to be at risk of having hot and cold spots in which a portion of the product may not be fully cooked. For instance, it was discovered that for a cylindrical object, the hot spot was at the center of the product while for a square slab, the hot spots were at the corners (Vadivambal & Jayas, 2010). In order to design foods that can be heated more uniformly in microwave ovens, work has been done to create a model of microwave heating of food products in conventional microwaves with turntables (Chen, et al., 2016). Another potential source of nonuniform heating is the age of the microwave. Over time the frequency of the microwave could slowly change which affects how products heat (Luan, Wang, Tang, & Jain, 2016).

The design of household microwaves has become standardized. A transformer provides increased voltage to the capacitor in order to charge the capacitor. The capacitor is then able to provide a steady stream of energy to the cavity magnetron. The cavity magnetron directs electrons into metal cavities which creates oscillating waves. The wave guide then directs the microwaves into the cooking chamber. The metal cavities and wave guide do not absorb microwave energy and instead reflect the energy. This allows the microwaves to move into the cooking chamber which become contained within the chamber by the metal. A turntable or a stir fan is used to help more evenly heat the product as the microwaves enter the cooking chamber. This design allows for the heating of multiple different products. However, due to the wide variability of the microwaves produced by this method, the heating is extremely variable. This design is also difficult to implement in an industrial setting.

Microwaves operate at one of two frequencies: 915 MHz or 2450 MHz. Nearly all household microwaves operate at 2450 MHz while most industrial microwave systems operate at 915 MHz. A novel 2450 MHz stacked continuous flow microwave processing system was recently developed and evaluated for apple puree containing particulates (Truong, 2014). The frequency has a slight effect on the heating of a product which can be predicted by measuring the dielectric properties of the product (Tong, Lentz, & Rossen, 1994). For example, microwaves operating at 915 MHz are more likely to heat using ionic interactions rather than dipolar interaction (Tong, Lentz, & Rossen, 1994).

2.2.3 915 MHz Industrial Microwave Heating

As previously mentioned, microwaves do not heat uniformly. However, this can be mitigated by the oven design (i.e., via an applicator) so the microwave energy can be focused on the product (Coronel, Simunovic, & Sandeep, 2003). In the case of commercial continuous flow applications, the microwave energy is focused on a Teflon tube through which the product is pumped. Teflon is a material that is transparent to microwave energy. This allows the microwaves to pass through the tube and heat the product. By measuring the dielectric properties of the product, the penetration depth of the microwave energy can be calculated. The penetration depth helps to determine the optimal diameter of the Teflon tube so that the majority of the microwave energy is absorbed by the product (Zhu, Kuznetsov, & Sandeep, 2007). A tube that is too large could potentially contain hot and cold spots where microwaves do not reach certain parts of the product. In contrast, a tube with a diameter that is too small would result in microwaves passing through the tube without affecting the molecules in the product. This would prevent the molecules from becoming excited and generating heat. However, the types of products that can be heated by the system may be slightly limited because the penetration depth calculations assume that a material is uniform and without large particles. Furthermore, many of the current commercial microwave systems are operated using 915 MHz, are costly to build, and require a high amount of energy to operate.

One of the industrial microwaves that has been successfully utilized to process different purees provides two periods of microwave heating to the product. The product is heated in a short section of Teflon pipe, passes through a static mixer, and is then heated once more with microwaves (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). This method reduces non-uniform heating within the pipe because the product is mixed between microwave treatments. Mathematical modeling has been done to further investigate the heating profile of a product within a pipe while being heated with microwave energy. The location and diameter of the pipe within the microwave cavity and the shape of the microwave cavity was studied in order to better understand how to construct the microwave system (Zhu, Kuznetsov, & Sandeep, 2007).

2.2.4 Dielectric Properties

Dielectric properties are important in the interaction between the product being processed and electromagnetic energy. The dielectric constant, ε', represents the ability of microwaves to penetrate a product while the loss factor, ε", represents a material's ability to convert microwaves into heat. The loss tangent is a ratio of these two terms and "indicates the ability of a product to absorb microwave energy." (Zhu, Kuznetsov, & Sandeep, 2007) However, dielectric properties are "specific only for a given frequency and state of material." (Venkatesh & Raghavan, 2004) Thus, the product's dielectric properties may change depending on temperature, moisture content, frequency, ionic content, viscosity, and other factors (Brinely et al. 2008; Koskiniemi et al. 2013). In order to estimate how a product will respond to microwave energy, it is important to determine the dielectric properties of that product at the temperature range of interest.

2.2.5 Mixture Equations

Equations used to predict the dielectric properties of mixtures based on the components have been researched in polymers and for agriculture commodities (Nelson & Trabelsi, 2012; Nelson, 1992). The complex refractive index equation (CRIME) was found to be reliable. CRIME uses the volume of the components being added to the mixture and their measured dielectric properties in order to predict the dielectric properties of the mixture.

Because the dielectric properties of a material help to determine how it will heat, it is important to know the dielectric properties of the product. The use of a mixture equation could help to reduce the number of measurements needed for various formulations if the dielectric properties of the components are already known. However, very little research has been done on the reliability of mixture equations. It is also necessary to use dielectric properties of the components measured at the same frequency and temperature as what the product will be processed. Because the dielectric properties are only valid under specific conditions, the functionality of the values found in literature is limited.

2.2.6 Microwave Processing of Purees and Other Food Products

A variety of homogenous, pumpable food products have been successfully processed using continuous flow microwave processing. These products include tomato paste, sweetpotato puree, apple sauce, broths, carrot puree, and pea puree. (Zhu, Kuznetsov, & Sandeep, 2007; Kumar et al., 2008). The use of microwave technology with sweetpotato puree has been especially successful and is being commercialized. Sweetpotato puree is extremely viscous and therefore heats very slowly by conventional means such as retorting or with a tube and tube heat exchanger (Steed et al., 2008). The use of microwaves significantly decreased the heating time due to the ability of sweetpotatoes to absorb microwave energy.

Microwaves have also been in other industrial processing such as the drying of fruit and vegetable products. Wojdylo et al (2014) found that vacuum-microwave drying was a viable method for drying cherries and retaining a high nutrient content in the cherries. When used for drying, microwaves have again shown the need for shorter processing times and greater nutrient retention. When used on carrot slices, the color, nutritional value, and textural properties of microwaved dried carrot slices were improved when compared to air dried carrot slices (Lin, Durance, & Scaman, 1998). Microwave drying has also been used in the production of palm oil and has been shown to produce oil of better quality than conventional methods (Law, Liew, Chang, Chan, & Leo, 2016). Although there are limitations for the use of microwaves in drying, the combination of microwave drying with other drying methods may mitigate these limitations (Zhang, Tang, Mujumdar, & Wang, 2006).

Microwaves are most commonly associated with the heating of frozen dinners or other household food items. Much research has been done to investigate the use of microwaves with these meals to optimize the heating profile of the food by altering the placement of the food in the tray, the shape of the tray, etc. (Vadivambal & Jayas, 2010)

2.2.7 Benefits of Microwave Heating

Conventional heating relies on conduction of heat from the outside of the product into the inside of the product. Thus, in order to ensure that the core reaches a safe temperature, the outside of the product may be overcooked or the size and shape of a product may be limited (Fryer & Robbins, 2005). This process can result in a large decrease in heat sensitive nutrients due to the amount of processing necessary to correctly heat the core of a product. For instance, antioxidants which are thought to have many health benefits are typically unstable and can be damaged by extensive heat processing (Nicoli, Anese, & Parpinel, 1999). The quality of the product is another attribute that can be negatively affected by overheating which can cause undesirable changes in color, flavor, texture and other sensory attributes. In contrast, microwave heating has the potential to transfer energy throughout the product simultaneously. This volumetric heating reduces the amount of time necessary to process a product because the core is heated at the same rate as the outer edges. Thus, microwave heating is able to process product more quickly than conventional heating and produce superior products from both a quality and nutritional standpoint.

2.3 Phytochemicals of Sweetpotatoes and Ingredients

2.3.1 Nutrient Food Trends

Nutraceutical is a term that does not have a regulatory definition but it is commonly believed to refer to functional foods that provide health benefits such as aiding in the prevention of chronic diseases (Kalra, 2003). Many fruits and vegetables are considered to be nutraceuticals especially berries such as blueberries and raspberries (Hollingsworth, 2001). A significant amount of research is focused on understanding the possible effect of the phytonutrient compounds on human health (Szliszka & Krol, 2015). This information is desired by companies to allow them to make health claims associated with these different food ingredients and food products.

With the increasing popularity of nutritional and functional foods in recent years, the food industry has focused on developing food products with high antioxidant capacity, rich in anthocyanins and proteins. Products that have been shown to be beneficial to the heart, immune system, and blood pressure, are some of the most consumed functional foods (Sloan, 2016). Reports have indicated that consumers are trending towards all natural products with easily understood and recognized ingredients. An important finding was that “Half of consumers would be more likely to buy a beverage if it were antioxidant-rich” (Sloan, 2016). Therefore, food companies are attempting to produce products with labels that denote nutritional benefits. A simple mixture of fruit and vegetable purees such as blueberry and sweetpotato would be one such product.

2.3.2 Nutrients Commonly Found in Sweetpotato and Ingredients

Sweetpotato puree is a nutritious product. Orange-fleshed sweetpotatoes contain high amounts of β-carotene which can be converted to vitamin A by metabolic pathways within the body (Olson & Hayaishi, 1965; Berni, Chitchumroonchokchai, Canniatti-Brazaca, Moura, & Failla, 2015). Therefore, orange-fleshed sweetpotatoes have been proposed as a possible solution to vitamin A deficiencies in developing countries (Low, Walker, & Hijmans, 2001; Lowa, Mwanga, Andrade, Carey, & Ball, 2017). Other benefits of sweetpotatoes include dietary fiber and rich mineral concentrations of calcium, magnesium, potassium, and zinc (Suda, Toshimoto, & Yamakawa, 1999). Sweetpotatoes also contain favorable amounts of thiamin, riboflavin, and pantothenic acid (Padmaja, 2009).

Fruit purees are combined with products because of their ability to acidify the product as well as impart nutritional benefits. Blueberries are considered to be very healthy due to their exceptionally high polyphenol content and have been linked to a decrease in cardiovascular risk (Basu, et al., 2010). An indication of how rich blueberries are in polyphenols is the fact that, of the six anthocyanidins commonly found in nature, blueberries contain five of them (Elks et al., 2013). It has also been shown that certain anthocyanins may influence the hypoglycemic activity in mice (Grace, et al., 2009). Blueberries have been found to have many components such as phenolic acids, anthocyanins, and flavan-3-ols that exhibit anticancer properties (Kraft, et al., 2005). However, blueberries themselves have been shown to be useful in the prevention or control of many diseases for reasons that are not fully known. Blueberries have been associated with having beneficial effects on areas such as cognitive function, cancer, and as an antidiabetic (Stull, Cash, Johnson, Champagne, & Cefalu, 2010).

Another fruit puree used to acidify the product was apple sauce. Apples were chosen as an ingredient for several reasons. They are one of the most widely consumed fruits in the United States (Foundation, 2015). They also have a high nutritional content; however, the nutritional content can vary among different apple varieties and even among the different parts of the same apple. For example, depending on the amount of sunlight, growing conditions, the anthocyanin content located in the skin of some apples could change. However, what is more relevant to human health is the fact that apples exhibit high antioxidant capacity when tested via *in vitro* studies. This is typically considered to be more indicative of how antioxidants will be absorbed in the human body. Anthocyanins are considered to be beneficial for chronic diseases such as cardiovascular disease, asthma, and diabetes. Other advantages of apples are their possible ability to reduce cognitive decline due to aging and to boost gastrointestinal health. (Espley & Martens, 2013)

Lemon juice proved to be the most effective acidifying agent. Lemons also impart some health benefits. They are known to be extremely high in vitamin C of 40 mg/100 ml as compared to oranges which have a vitamin C content of approximately 20 mg/100ml (Magwaza, Mditshwa, Tesfay, & Opara, 2017). Vitamin C is a compound that the human body cannot make, but also cannot live without. A deficiency in vitamin C can lead to the development of scurvy which can be a deadly disease (Akikusa, Garrick, & Nash, 2003).

Vitamin C is also a powerful antioxidant which is known to have many health benefits (Padayatty, et al., 2003). The citric acid in lemons has also been examined as a potential nutritional therapy to help inhibit urinary crystallization (kidney stones) in at risk patients (Penniston, Nakada, Holmes, & Assimos, 2008).

2.3.3 Nutrient Retention and Quality of Purees

The thermal processing and storage of fruit purees has a significant effect on nutrient retention. It has been shown that both thermal treatments and storage results in significant decreases of anthocyanins in fruit smoothies (Patras, Bruton, O'Donnell, & Tiwari, 2010). Work has been done comparing the effect of different heat treatments on blueberries. Brownmiller, Howard and Prior (2008) reported a 28-59% reduction in total monomeric anthocyanins due to thermal processing of the blueberries. Heat treatments also have an effect on the color of fruit based products. For example, the overall color of pineapple puree was found to be very sensitive to heat treatments (Chutintrasri & Noomhorm, 2007).

Thermal processing may also increase the extractability and bioavailability of some nutrients. For example, it has been suggested that a gentle thermal process resulted in an increase of β-carotene which was thought to be due to improved extractability (Padmaja, 2009). The type of processing also affects the nutrient content of purees. Microwave processing has shown to have a greater nutrient retention in sweetpotatoes than conventional processing such as canning or baking (Chandler & Schwartz, 1988). In dried cherries, it has been shown that microwave dried cherries have higher nutrient contents than cherries dried using conventional methods (Wojdylo, Figiel, Lech, Nowicka, & Oszmianski, 2014).

Microwave heating has also been shown to be a more beneficial method of heating in tomato puree (Arjmandi, et al., 2016). One of the reasons for the higher nutrient retention in these products is that microwave processing reduces the amount of heat treatment received by the product.

2.4 Analysis of Antioxidant Activity and Phytochemicals

2.4.1 Antioxidant Activity

Antioxidants are compounds believed to be capable of scavenging free radicals. Free radicals are formed when an electron is left without a pair and is therefore, unstable and reactive. The formation of unstable radicals often occurs when a covalent bond is broken. The free radicals can lead to a chain reaction which results in oxidative damage to cell membranes. Antioxidants react with the free electrons and stabilize the charge to prevent the subsequent chain reaction. (Krasovskaya, 2012)

There are many methods available to analyze the antioxidant activity of food products. The 2,2-Diphenyl-1-picrylthydrazyl (DPPH) method has been used when analyzing the antioxidant content of purple sweetpotato puree (Steed & Truong, 2008). DPPH is a radical that reacts with antioxidants. In its radical form, the absorbance of DPPH is read at 515 nm. The absorbance will decrease as antioxidants react with and decrease the amount of radical DPPH present in a solution (Brand-Williams, Cuvelier, & Berset, 1995). This method can be used on a wide variety of food products. However, different solutions may require different amounts of time to react with DPPH and thus the reaction must be allowed sufficient time to be completed.

2.4.2 Total Phenolics

In its simplest form, a phenol is a compound comprised of a hydroxyl group bonded to an aromatic hydrocarbon ring. Phenols act as antioxidants and thus are associated with many health benefits (Velioglu, Mazza, Gao, & Oomah, 1998). The antioxidant activity of phenolics is largely due to the oxygen radical scavenging potential of the compound which have both a lower electron reduction potential and are less reactive (Ainsworth & Gillespie, 2007). Due to these properties, phenolics are able to stabilize the radicals and prevent further oxidative reactions.

The common procedure used to determine the phenolic content is the Folin-Ciocalteu (F-C) method, which may also be known as the gallic acid equivalence method. The acid in the F-C reagent reacts with reducing compounds such as phenols. The electrons are transferred from the phenol to the acid while in an alkaline medium. This results in a blue color that can be measured via spectroscopy at 760 nm (Singleton & Rossi, 1965). Because the compounds are more reactive in basic solutions, the extracts are performed using acidic solutions to prevent oxidation until the samples are ready to be tested. A major issue with this method is that it is only an approximation of the total phenolics because the acid in the F-C reagent is able to react with other compounds (Ainsworth & Gillespie, 2007). Thus, this method measures the total oxidative potential of the sample and not just the phenolic content.

2.4.3 Anthocyanins

Anthocyanins are a class of flavonoids that are linked to a variety of positive health effects due to their oxygen radical scavenging ability. It has been estimated that almost 180-

215 mg of anthocyanins are consumed per day in the United States (Wang, Cao, & Prior, 1997). However, the absorption of these compounds into the body of humans is not well known.

The pH-differential method has been successfully used to measure the total anthocyanins of purple-fleshed sweetpotato samples (Truong, et al., 2010). Anthocyanins are measured at an absorbance of 530nm. The pH of the samples must be altered in order to account for the degradation of anthocyanins into melanoidins (Giusti & Wrolstad, 2001). Therefore, samples are subjected to two pH values: 1.0 and 4.5. At a pH of 4.5, anthocyanins form a colorless compound which serves as a blank. The absorbance of the blank is subtracted from the absorbance read at a pH of 1.0. Samples are also read at an absorbance of 700 nm at both pH values to correct for haze.

Anthocyanins have many different structures based on differing sugar substitutes such as glucose, rhamnose, xylose, galactose, arabinose, and fructose (Wang, Cao, & Prior, 1997). Therefore, in order to calculate the monomeric anthocyanin content from absorbance, the molecular weight and the molar absorptivity of the pigment being analyzed must be known. Cyanidin-3-glucoside was used in this study and has a molecular weight of 449.2 and molar absorptivity of 26,900 (Giusti & Wrolstad, 2001).

2.4.4 β-Carotene

β-carotene in many fruits and vegetables is a well-known carotenoid which is a precursor to vitamin A. Sweetpotatoes have high in β-carotene content and are considered to be a healthy way to increase vitamin A consumption in developing countries. One study estimated that total β-carotene content in sweetpotato puree was 38 mg/100g (Grabowski, Truong, & Daubert, 2008). β-carotene consists of two beta rings on either end of a hydrocarbon chain. This structure causes the β-carotene molecule to be highly non-polar and thus a fat-soluble vitamin. The polarity is exploited in the extraction process in which a hexane/acetone mixture can be used to extract β-carotene from a predominately water based matrix such as puree.

β-carotene can be damaged by thermal processing in which the molecule is converted from an all-trans structure into cis isomers which have less bioavailability (Chandler & Schwartz, 1988). β-carotene can also be damaged via oxidation, thus exposure to oxygen and light should be limited when analyzing samples for β-carotene.

To extract β-carotene a mixture of hexane and acetone may be used in a 1:1 ratio (Chandler & Schwartz, 1988). As a nonpolar compound, β-carotene collects in the hexane which can be separated from the acetone using a seperatory funnel. The total beta carotene in the hexane may then be measured on a spectrophotometer at a wavelength of 450 nm. The β-carotene isomers can be identified via HPLC methods as described by Grabowski, Truong, and Daubert (2008).

Overall, research on microwave processing technology has resulted in a commercial microwave system operated at 915 MHz and aseptic packaging of various food products (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). However, the current 915 MHz systems are more suitable for large scale settings and require considerable capital investment.

On the other hand, limited information is available on the use of 2450 MHz microwave system for food processing operation (Truong, 2014). This system has the following potential advantages over other processing methods: it requires a small processing area, is a low capital investment, can be applied to a wide variety of products, requires a small batch size, has a flexible design, low operating costs, and low utility demands. These factors make this system an alternative to expensive processing systems that can be difficult to operate and install. This system needs to be further developed to demonstrate its applications in the development of new product by microwave processing.

REFERENCES

Ainsworth, E. A., & Gillespie, K. M. (2007). Estimation of total phenolic content and other oxidation substrates in plant tissues using Folin-Ciocalteu reagent. *Nature Protocols*, 875-877.

Akikusa, J., Garrick, D., & Nash, M. (2003). Scurvy: Forgotten but not gone. *Journal of Pediatrics and Child Health*, 75-77.

Arjmandi, M., Oton, M., Artes, F., Artes-Hernandez, F., Gomez, P. A., & Aguayo, E. (2016 Microwave flow and conventional heating effects on the physiochemical properties, bioactive compounds and enzymatic activity of tomato puree. *Journal of the Science of Food and Agriculture*, 984-990.

Basu, A., Du, M., Leyva, M. J., Sanchez, K., Bets, N. M., Wu, M., . . . Lyons, T. J. (2010). Blueberries Decrease Cardiovascular Risk Factors in Obese Men and Women with Metabolic Syndrome. *The Journal of Nutrition*, 1582-1587.

Berk, Z. (2009). *Food Process Engineering and Technology*. New York, NY, USA: Elsevier Inc. .

Berni, P., Chitchumroonchokchai, C., Canniatti-Brazaca, S. G., Moura, F. F., & Failla, M. L. (2015). Comparison of Content and In vitro Bioaccessibility of Provitamin A Carotenoids in Home Cooked and Commercially Processed Orange Fleshed Sweet Potato (Ipomea batatas Lam). *Plant Foods for Human Nutrition*, 1-8.

Brand-Williams, W., Cuvelier, M. E., & Berset, C. (1995). Use of a Free Radical Method to Evaluate Antioxidant Activity. *Lebensmittel-Wissenschaft & Technologie*, 25-30.

Breidt, F., Kay, K., Osborne, J., Ingham, B., & Arritt, F. (2014). Thermal Processing of Acidified Foods with pH 4.1 to pH 4.6. *Food Protection Trends*, 132-138.

Breidt, F., Sandeep, K., & Arritt, F. (2010). Use of Linear Models for Thermal Processing of Acidified Foods. *Food Protection Trends*, 268-272.

Brinely TA, Truong VD, Coronel P, Simunovic J, Sandeep KP. (2008). Dielectric Properties of Sweetpotato Purees at 915 MHz As Affected By Temperature and Chemical Composition. *International Journal of Food Properties*, 11:158-172.

Brinley, T., Dock, C., Truong, V.-D., Coronel, P., Kumar, P., Simunovic, J., . . . Jaykus, L.-A. (2007). Feasibility of Utilizing Bioindicators for Testing Microbial Inactivation in Sweetpotato Purees Processed with a Continuous-Flow Microwave System. *Journal of Food Science*, 235-242.

Brownmiller, C., Howard, L., & Prior, R. (2008). Processing and Storage Effects on Monomeric Anthocyanins, Percent Polymeric Color, and Antioxidant Capacity of Processed Blueberry Products. *Journal of Food Science*, 72-79.

Chandler, L. A., & Schwartz, S. J. (1988). Isomerization and Losses of trans-beta-Carotene in Sweet Potatoes as Affected by Processing Treatments. *Journal of Agriculture and Food Chemistry*, 129-133.

Chen, J., Pitchai, K., Birla, S., Joens, D., Negahban, M., & Sabbia, J. (2016). Modeling heat and mass transport during microwave heating of frozen food rotating on a turntable. *Journal of Food and Bioproducts Processing*, 116-127.

Chutintrasri, B., & Noomhorm, A. (2007). Color degradation kinetics of pineapple puree during thermal processing . *LWT - Food Science and Technology*, 300-306.

Coronel, P., Simunovic, J., & Sandeep, K. (2003). Temperature Profiles With Milk After Heating in a Continuous-flow Tubular Microwave System Operating at 915 MHz. *Journal of Food Science*, 1976-1981.

Coronel, P., Truong, V.-D., Simunovic, J., Sandeep, K. P., & Cartwright, G. D. (2005). Aseptic Processing of Sweetpotato Purees Using a Continuous Flow Microwave System. *Journal of Food Engineering and Physical Properties*, 531-536.

Elks, C. M., Francis, J., Stull, A. J., Cefalu, W. T., Shukitt-Hale, B., & Ingram, D. K. (2013). Overview of the Health Properties of Blueberries. In M. Skinner, & D. Hunter, *Bioactives in Fruit: Health Benefits and Functional Foods* (pp. 251-271). John Wiley & Sons.

Espley, R., & Martens, S. (2013). Health Properties of Apple and Pear. In M. Skinner, & D. Hunter, *Bioactives in Fruit: Health Benefits and Functional Foods* (pp. 81-100). John Wiley & Sons.

Foundation, P. (2015). 2015 Study on America's Consumption of Fruits and Vegetables. *State of the Plate*. Produce for Better Health Foundation.

Fryer, P. J., & Robbins, P. T. (2005). Heat transfer in food processing: ensuring product quality and safety. *Applied Thermal Engineering*, 2499-2510.

Giusti, M. M., & Wrolstad, R. E. (2001). Characterization and Measurement of Anthocyanins by UV-Visible Spectroscopy. *Food Analytical Chemistry*, F1.2.1-F1.2.13.

Grabowski, J., Truong, V.-D., & Daubert, C. (2008). Nutritional and rheological characterization of spray dried sweetpotato powder. *Journal of Food Science and Technology*, 206-216.

Grace, M. H., Ribnicky, D. M., Kuhn, P., Poulev, A., Logendra, S., Yousef, G. G., . . . Lila, M. A. (2009). Hypoglycemic activity of novel anthocyanin-rich formulation from lowbush blueberry, Vaccinium angustifolium Aiton. *Journal of Phytomedicine*, 406-415.

Halvorsen, B. L., Holte, K., Myhrstad, M. C., Barikmo, I., Hvattum, E., Remberg, S. F., . . . Blomhoff, R. (2001). A Systematic Screening of Total Antioxidants in Dietary Plants. *The Journal of Nutrition*, 461-471.

Hollingsworth, P. (2001). Growing Nutraceuticals. *Journal of Food Technology*, 22.

Kalra, E. K. (2003). Nutraceutical - Definition and Introduction. *Journal of American Association of Pharmaceutical Scientists*, 1-2.

Koskiniemi CB, Truong VD, McFeeters RF, Simunovic J. (2013). Effects of acid, salt and soaking time on the dielectric properties of acidified vegetables. *International Journal of Food Properties*, 16:917-927.

Koskiniemi CB, Truong VD, McFeeters RF, Simunovic J. (2013). Quality evaluation of packaged acidified vegetables subjected to continuous microwave pasteurization. *Lebensmittel-Wissenschaft Food Science and Technology*, 54:157-164.

Kraft, T. F., Schmidt, B. M., Yousef, G. G., Knight, C. T., Cuendet, M., Kang, Y.-H., . . . Lila, M. A. (2005). Chemopreventive Potential of Wild Lowbush Blueberry Fruits in Multiple Stages of Carcinogenesis. *Journal of Food Science*, 159-166.

Krasovskaya, V. (2012). Antioxidant Properties of Berries: Review of Human Studies and their Relevance in the Contex of the European Food Safety Authority. *thesis*, Hogeschool Van Amsterdam.

Kumar, P., Coronel, P., Truong, V., Simunovic, J., Swartzel, K., Sandeep, K., & Cartwright, G. (2008). Overcoming issues associated with the scale-up of a continuous flow microwave system for aseptic processing of vegetable purees. *Journal of Food Research International*, 454-461.

Law, M. C., Liew, E. L., Chang, S. L., Chan, Y. S., & Leo, C. P. (2016). Modelling microwave heating of discrete samples of oil palm kernels. *Journal of Applied Thermal Engineering*, 702-726.

Lewis, M., & Heppell, N. (2000). *Continuous Thermal Processing of Foods Pasteurization and UHT Sterilization*. Gaithersburg, Maryland: Aspen Publishers, Inc.

Lin, T. M., Durance, T. D., & Scaman, C. H. (1998). Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International*, 111-117.

Low, J., Walker, T., & Hijmans, R. (2001). The potential impact of orange-fleshed sweetpotatoes on vitamin A intake in Sub-Saharan Agrica. *Centro Internacional De La Papa*, (pp. 1-16). Nairobi, Kenya.

Lowa, J. W., Mwanga, R. O., Andrade, M., Carey, E., & Ball, A.-M. (2017). Tackling vitamin A deficiency with biofortified sweetpotato in sub-Saharan Africa. *Global Food Security*, 1-8.

Luan, D., Wang, Y., Tang, J., & Jain, D. (2016). Frequency Distribution in Domestic Microwave Ovens and Its Influence on Heating Pattern. *Journal of Food Science*.

Magwaza, L. S., Mditshwa, A., Tesfay, S. Z., & Opara, U. L. (2017). An overview of preharvest factors affecting vitamin C content of citrus fruit. *Journal of Scientia Horticulturae*, 12-21.

Nelson, S. (1992). Correlating Dielectric Properties of Solids and Particulate Samples Through Mixture Relationships. *Food and Process Engineering Inst. of ASAE*, 625-629.

Nelson, S. O., & Datta, A. K. (2001). Dielectric Properties of Food Materials and Electric Field Interactions. In A. K. Datta, *Handbook of Microwave Technology for Food Applications* (pp. 69-114). New York: Marcel Dekker, Inc.

Nelson, S. O., & Trabelsi, S. (2012). Factors Influencing the Dielectric Properties of Agricultural and Food Products. *Journal of Microwave Power and Electromagnetic Energy*, 93-107.

Nicoli, M., Anese, M., & Parpinel, M. (1999). Influence of processing on the antioxidant properties of fruit and vegetables. *Trends in Food Science & Technology*, 94-100.

Olson, J. A., & Hayaishi, O. (1965). The enzymatic cleavage of B-carotene into vitamin A by soluble enzymes of rat liver and intestine. *Proceedings of the National Academy of Sciences of the United States of America*, 1364-1370.

Padayatty, S. J., Katz, A., Wang, Y., Ech, P., Kwon, O., Lee, J.-H., . . . Levine, M. (2003). Vitamin C as an Antioxidant: Evaluation of Its Role in Disease Prevention. *Journal of the American College of Nutrition*, 18-35.

Padmaja, G. (2009). Uses and Nutritional Data of Sweetpotato. In G. Loebenstein, & G. Thottappilly, *The Sweetpotato* (pp. 189-234). Springer Science and Business Media.

Patras, A., Bruton, N. P., O'Donnell, C., & Tiwari, B. (2010). Effects of thermal processing on anthocyanin stability in foods; mechanisms and kinetics of degradation. *Trends in Food Science and Technology*, 3-11.

Penniston, K. L., Nakada, S. T., Holmes, R. P., & Assimos, D. G. (2008). Quantitative Assessment of Citric Acid in Lemon Juice, Lime Juice, and Commercially-Available Fruit Juice Products. *Journal of Endourology*, 567-570.

Perez-Diaz, I. M., Truong, V.-D., Webber, A., & McFeeters, R. F. (2008). Microbial Growth and the Effects of Mild Acidification and Preservatives in Refrigerated Sweet Potato Puree. *Journal of Food Protection*, 639-642.

Potter, N. N. (1973). Food Science. In N. N. Potter, *Norman N Potter* (pp. 183-184). Westport, Connecticut: The AVI Publishing Company, Inc.

Singleton, V., & Joseph A. Rossi, J. (1965). Colorimetry of Total Phenolics With Phosphomolybdic-Phosphotungstic Acid Reagents. *American Journal of Enology and Viticulture*, 144-158.

Sloan, A. E. (2016). Top 10 Functional Food Trends. *Journal of Food Technology*, 24-45.

Steed, Laurie Elaine. (2011). Development and Validation of Processes for Continuous Flow Microwave Processing of Foods Containing Sweetpotato Particulates. PhD Thesis, North Carolina State University.

Steed, L., & Truong, V.-D. (2008). Anthocyanin Content, Antioxidant Activity, and Selected Physical Properties of Flowable Purple-Fleshed Sweetpotato Purees. *Journal of Food Science*, 215-221.

Steed, L., Truong, V., Simunovic, J., Sandeep, K., Kumar, P., Cartwright, G., & Swartzel, K. (2008). Continuous Flow Microwave-Assisted Processing and Aseptic Packaging of Purple-Fleshed Sweetpotato Purees. *Journal of food Science*, 455-462.

Stull, A. J., Cash, K. C., Johnson, W. D., Champagne, C. M., & Cefalu, W. T. (2010). Bioactives in Bluberries Improve Insulin Sensitivity in Obese, Insulin-Resistant Men and Women. *The Journal of Nutrition*, 1764-1768.

Suda, I., Toshimoto, M., & Yamakawa, O. (1999). Sweetpotato Potentiality: Prevention for Life Style-Related Disease Induced by Recent Food Habits in Japan. *Food & Food Ingredients*, 59-68.

Szliszka, E., & Krol, W. (2015). Natural Polyphenols Target the Tumor Nerosis Factor-related Apoptosis-inducing Ligand (TRAIL) Signaling Pathway for cancer Chemoprevention. In R. R. Warson, *Foods and Dietary Supplements in the Prevention and Treatment of Disease in Older Adults* (pp. 119-134). Elsevier Inc.

Tang, J. (2005). Dielectric properties of food. In H. Schubert, & M. Regier, *The microwave processing of foods* (pp. 22-38). Woodhead Publishing Limited.

Thostenson, E., & Chou, T.-W. (1999). Microwave processing: fundamentals and applications. Composites Part A: *Applied Science and Manufacturing*, 1055-1071.

Tong, C. H., Lentz, R. R., & Rossen, J. L. (1994). Dielectric Properties of Pea Puree at 915 MHz and 2450 MHz as a Function of Temperature. *Journal of Food Science*, 121-123.

Truong, A. N. (2014). Nutrient Retention in Continuous Flow Microwave Processing of Fruit Purees Containing Particulates. MS Thesis, North Carolina State University.

Truong, V.-D., Deighton, N., Thompson, R. T., McFeeters, R. F., Dean, L. O., Pecota, K. V., & Yencho, G. C. (2010). Characterization of Anthocyanins and Anthocyanidins in Purple-Fleshed Sweetpotatoes by HPLC-DAD/ESI-MS/MS. *Journal of Agriculture and Food Chemistry*, 404-410.

Truong VD, Avula RY, Pecota K, Yencho CG. 2011. *Sweetpotatoes*. In: Sinha NK, editor. Handbook of vegetables & vegetable processing. New Jersey: Wiley-Blackwell. p 717-737.

U.S. Department of Health and Human Services. (2010). Processing Acidified Foods. In Guidance for Industry - Acidified Foods (pp. 26-31). Food and Drug Administration.

US Food and Drug Administration, (n.d.). Title 21, Part 114 Acidified Foods.

Vadivambal, R., & Jayas, D. (2010). Non-uniform Temperature Distribution During Microwave Heating of Food Materials -- *A Review. Food Bioprocessing Technology*, 161-171.

Velioglu, Y., Mazza, G., Gao, L., & Oomah, B. (1998). Antioxidant Activity and Total Phenolics in Selected Fruits, Vegetables, and Grain Products. *Journal of Agriculture and Food Chemistry*, 4113-4117.

Venkatesh, M., & Raghavan, G. (2004). An Overview of Microwave Processing and Dielectric Properties of Agri-food Materials. *Biosystems Engineering*, 1-18.

Virtanen, A., Goedeken, D., & Tong, C. (1997). Microwave Assisted thawing of Model Frozen Foods Using Feed-back Temperature Control and Surface Cooling. *Journal of Food Science*, 150-154.

Wang, H., Cao, G., & Prior, R. L. (1997). Oxygen Radical Absorbing Capacity of Anthocyanins. *Journal of Agriculture and Food Chemistry*, 304-309.

Wojdylo, A., Figiel, A., Lech, K., Nowicka, P., & Oszmianski, J. (2014). Effects of Convective and Vacuum-Microwve Drying on the Bioactive Compounds, Color, and Antioxidant Capacity of Sour Cherries. *Journal of Food and Bioprocessing Technology*, 829-841.

Zhang, M., Tang, J., Mujumdar, A., & Wang, S. (2006). Trends in microwave-related drying of fruits and vegetables. *Trends in Food Science and Technology*, 524-534.

Zhu, J., Kuznetsov, A., & Sandeep, K. (2007). Mathematical modeling of continuous flow microwave heating of liquids (effects of dielectric properties and design parameters). *International Journal of Thermal Sciences*, 328-341.

CHAPTER 3: Effects of Acidification on Dielectric Properties of Sweetpotato-Based Products Formulated for Microwave Processing

3.1 Abstract

Continuous flow microwave sterilization and aseptic packaging of low acid foods such as sweetpotato purees have been successfully developed and commercialized. The high beta-carotene content of sweetpotatoes makes them a desirable ingredient in the food industry. Sweetpotato puree can be blended with fruit juices/purees to enhance the phytonutrient profiles in various healthy food applications. To help preserve the phytonutrient profile of the food products, it is advantageous to optimize the heat treatment. Decreasing the pH of the products to an acidic pH of less than 4.6, requires a milder heat treatment resulting in reduced degradation of the nutrients. Dielectric properties are important characteristics to measure when attempting to predict interactions between materials and electromagnetic energy from microwaves. This study aimed to (1) measure the dielectric properties of acidified sweetpotato mixtures and (2) compare the measured dielectric constant (ε') values with those calculated using mixture equations.

Covington sweetpotatoes were peeled, cut into slices, steamed, and ground into puree. The puree was then blended with either lemon juice, citric acid, raspberry puree, or apple puree. These various mixtures had a pH range of 3.79 to 3.97. Dielectric properties of the sweetpotato-based mixtures were measured at a frequency of 2450 MHz over a temperature range of 20-105°C using an open ended coaxial probe connected to a network analyzer. The sweetpotato mixtures had moisture contents of 82-87% which did not affect the measured dielectric properties. Each mixture showed the expected trend in which the dielectric constant decreased linearly as temperature increased. The measured dielectric constants were consistent with the calculated values obtained using mixture equations. This study provided

basic information on dielectric properties of acidified foods that would be useful in designing small and large scale microwave processing installations to pasteurize acidified sweetpotato products with high phytonutrient retention.

3.2 Introduction

North Carolina is the largest sweetpotato producer in the country. Recent microwave technology developed and commercialized by NC State's Food, Bioprocessing, and Nutrition Science department has made it possible to convert less desirable sweetpotatoes (sub-standard sizes and shapes) to marketable puree. This microwave technology has helped farmers to utilize crop that otherwise would have been wasted, thus, increasing overall yield. The microwave process heats the puree more quickly than conventional methods such as canning. The milder heat treatment results in the improved retention of nutrients, color, flavor, and texture.

Microwave processed purees have been utilized as ingredients in several food commodities, such as baby foods and bakery products. In response to the growing trend towards more naturally healthy products, use of sweetpotatoes as an ingredient has increased. Sweetpotato purees have become more common in acidic foods such as smoothies and fruit beverages. Consumer trends are also moving toward "clean labeling" in which only a few simple ingredients are listed in the product. Therefore, it has become common to select acidifying ingredients based on their acidic properties as well as consumer trends. However, the process of acidifying sweetpotato purees followed by a pasteurization step is an area that requires more research.

Thermal processing of low acid foods (pH > 4.6) to achieve shelf stability at ambient temperatures requires a sterilization temperature of at least 121°C (U.S. Department of Health and Human Services, 2010). The process must also include a hold time in which the temperature remains at least 121°C for a certain amount of time depending on the type of food. High acid foods (pH < 4.6) require a lower sterilization temperature and hold time. Decreasing the pH of sweetpotato puree from its original pH of 5.75 to below 4.0 reduces the amount of time and energy required to process the puree. A better understanding of how acidified sweetpotato purees perform with microwave processing may increase the use of sweetpotato puree as an ingredient.

Dielectric properties represent a material's ability to absorb energy which is represented as heat (Zhu, Kuznetsov, & Sandeep, 2007). Therefore, dielectric properties are an essential part of microwave processing. Furthermore, dielectric properties are "specific only for a given frequency and state of a material" (Vebjatesg & Raghavan, 2004). Dielectric properties are also dependent on temperature, moisture, frequency, ionic content, viscosity, and other factors. The effect of pH is not believed to have a significant effect on dielectric properties (Ryynänen, 1995). However, by adding ingredients that change the pH, other properties such as moisture content, which have a large impact on dielectric properties, will be affected. The objectives of this study were to (1) measure the dielectric properties of acidified sweetpotato mixtures and (2) compare the measured dielectric constant (ε') values with those calculated using mixture equations.

3.3 Materials and Methods

3.3.1 Sweetpotato Puree Production

Covington sweetpotatoes were obtained from the Sweetpotato Breeding Program, North Carolina State University (NCSU). The roots were washed, hand peeled, and cut into 0.5 cm thick slices. The sweetpotato slices were then steamed in a thermoscrew cooker (Rietz Manufacturing Co., Santa Rosa, CA) at 100°C for about 40 to 45 min or until soft. The cooked slices were then pureed using a robot coupe (Robot Coupe Inc.; Jackson, MS). The sweetpotato puree was packed into plastic bags and stored in a 0°C freezer for future use.

3.3.2 Ingredients

Citric acid was selected as an acidifier due to its prevalent use in industry. A 0.15 M solution with a pH of 2.00 was used in this study. Lemon juice (ReaLemon 100% Lemon Juice) is an extremely effective acidifier with a pH of 2.52 and was used in every mixture except the citric acid mixture. Raspberry puree (obtained from Aseptia Inc.; Raleigh, NC) was selected due to the nutritional aspects such as high phenol, anthocyanin, and antioxidant content (Halvorsen, et al., 2002). Apple puree (obtained from Aseptia Inc.; Raleigh, NC) also adds nutritional value to the product but was selected primarily due to availability in North Carolina. Raspberry puree had an initial pH of 3.21 and the apple puree had an initial pH of 3.60.

3.3.3 Formulating Puree Mixtures

Lemon juice, apple puree, raspberry puree, and citric acid were used to create a more acidic products. These acidifying ingredients were added to sweetpotato puree to make four total mixtures. The acidifying ingredients were used to ensure the mixtures had a final pH of less than 4.0. Refer to Figure 3.1 for clarification of the experimental design.

The sweetpotato puree started with a pH of 5.75 and was decreased to a pH of 3.82 - 3.97 depending on the mixture. The lemon (SL) and citric acid (SC) mixtures had a sweetpotato puree content of 81.7% and 76.9%, respectively. The raspberry mixture (SR) contained 49.0% sweetpotato puree, 49.0% raspberry puree, and 2.0% lemon juice. The apple mixture (SA) contained 46.0% sweetpotato puree, 46.0% apple puree, and 8.0% lemon juice.

3.3.4 Moisture Content

Moisture content is a factor that significantly affects dielectric properties. Therefore, the moisture content of the original sweetpotato puree and of the samples was measured using a Thermo Scientific oven (Thermo Scientific Inc., Waltham MA, U.S.A.). Approximately 20 grams of each sample were placed in the oven at 105°C for approximately 17.5 hours. The moisture content of each treatment is shown in Table 3.1. The moisture content was measured for two replications of each ingredient and mixture.

3.3.5 Degree Brix

The degree brix is a commonly used test to determine product quality in agriculture. It is also a test used to estimate sugar content in a sample. A higher degree brix is correlated to a higher sugar content. The degree brix was measured using a pocket refractometer (model PAL-1, Atago Co., LTD, Tokyo, Japan). The measurements can be seen in Table 3.1.

3.3.6 Dielectric Properties

The dielectric properties of the samples were measured using an open-ended coaxial probe (Model HP 85070B, Agilent Technologies, Palo Alto, Calif., U.S.A.) and network analyzer (Model HP 8753C, Agilent Technologies) (Sipahioglu & Barringer, 2003). Approximately 120 ml of sample was used to measure the dielectric properties of the ingredients and mixtures. Measurements were taken every 10 degrees with a range of frequency from 300 MHz to 3,000 MHz but only the values measured at 2450 MHz were of interest in this study (Kumar, Coronel, Simunovic, Truong, & Sandeep, 2007). The frequency used to measure the dielectric properties was the same as the frequency used by household microwaves. The dielectric properties of two samples were measured for each ingredient and mixture.

3.3.7 Calculating Dielectric Constant

Various equations may be used to predict the resulting dielectric properties when two materials are mixed. However, the accuracy of these equations has not been examined. The weighted mean and equations 1-3 were used to predict the dielectric constant (ε) of the treatments in this study (Liu, Tang, & Mao, 2009). The variable v_1 represents the percent volume of the first ingredient and the variable v_2 represents the percent volume of the second ingredient. Similarly, ε_1 and ε_2 represent the measured dielectric constants of the first and second ingredient, respectively. If the mixture contained three ingredients, a third term was added to the equation.

Equation 1: Complex Refractive Index Mixture equation (CRIME):

$$\varepsilon^{\frac{1}{2}} = v_1(\varepsilon_1)^{\frac{1}{2}} + v_2(\varepsilon_2)^{\frac{1}{2}}$$

Equation 2: Landau and Lifshitz, Looyenga equation (LLLE):

$$\varepsilon^{\frac{1}{3}} = v_1(\varepsilon_1)^{\frac{1}{3}} + v_2(\varepsilon_2)^{\frac{1}{3}}$$

Equation 3: Lichtenecher equation (LE):

$$\ln \varepsilon = v_1 \ln \varepsilon_1 + v_2 \ln \varepsilon_2$$

3.3.8 Statistical Analysis

Two replications of each mixture were measured for moisture content, pH, and the dielectric constants. All data was reported as the mean of the two replications. Statistical analysis of the pH and moisture content was performed using XLSTAT Version 2017 (Addinsoft, New York, NY). A one-way analysis of variance (ANOVA) in conjunction with a Turkey's HSD test was used to determine statistical significance between the mixtures and ingredients at a confidence interval of 95%.

3.4 Results and Discussion

3.4.1 Product Properties

The moisture content of the sweetpotato puree was 81.29% which was a lower value than any of the mixtures and was similar to values found by Brinley et al. (2008). The SR mixture had a moisture content of 87.22% which was the highest moisture content for the mixtures. Table 3.1 shows the moisture content of the sweetpotato puree and the mixtures.

The sweetpotato puree had a pH of 5.75. The SR mixture had the lowest pH at 3.86. The SC mixture had the highest pH of the mixtures at a pH of 3.98 which was below the targeted pH of 4.0. The pH of the SC, SL, and SA mixtures did not have a statistically significant difference ($p<0.05$). The degree brix of the sweetpotato puree was the highest at 15.8. Of the mixtures, the SR mixture was the lowest degree brix at 12.6 and the SL mixture was the highest at 15.2. The pH and degree brix of each mixture can be seen in Table 3.1.

3.4.2 Measured Dielectric Constants

The measured dielectric constants of each mixture followed similar trends. As temperature increased, the dielectric constants decreased (Figure 3.2). At room temperature

(20°C), the dielectric constants ranged from 68 to 75 depending on the mixture. At 105°C, the dielectric constants of the mixtures ranged from 55 to 57. The dielectric constants of the SR mixture (Figure 3.2D) was most similar to the dielectric constants of its ingredients (raspberry and sweetpotato puree). The dielectric constants of the SC mixture (Figure 3.2A) had the most variability when compared to the dielectric constants of the citric acid solution and sweetpotato puree.

3.4.3 Calculated Dielectric Constants

The percent volume (*v*) and measured dielectric constants (ε') of the ingredients was used in the equations to determine the calculated dielectric constants of the mixtures. The calculated dielectric constants of the mixtures were very similar to the measured dielectric constants as shown in Figure 3.3. The calculated dielectric constants of the SR mixture found by each equation was nearly identical to the measured dielectric constants. The calculated dielectric constants for the SC, SL, and SA mixtures were slightly higher than the measured values. For each mixture, there was a larger amount of variability at lower temperatures between the calculated and measured dielectric constants. However, the variability between the calculated and measured dielectric constants decreased at higher temperatures for each mixture. The minimal variability between the calculated and measured dielectric constants for each mixture indicates that the equations were effective in predicting the dielectric constants of the mixtures.

3.4.4 Dielectric Constants Compared to Moisture Content

There was not a linear relationship between the dielectric constants and moisture contents of the mixtures. The correlation between moisture content and the dielectric constant is indicated by the R^2 values in Figure 3.4 and Figure 3.5. The low R^2 values indicated there was little to no correlation. The R^2 value at 20°C was 0.0002 and the R^2 value at 90°C was 0.0456. Sipahioglu and Barringer (2003) had some success relating the dielectric constant to the moisture and ash content of various vegetables but had the most difficulty with potato.

3.5 Conclusion

The measured dielectric constants showed the expected trends for each ingredient and mixture. As anticipated, the dielectric constants decreased as temperature increased. The calculated dielectric constants of the mixtures were reasonably accurate in this study. However, the measured dielectric properties of each ingredient and mixture in this study were very similar which may be why the equations so effectively predicted the dielectric constant of the mixtures. The dielectric constants of the mixtures in this study were not correlated to the moisture content at any temperature. Overall, this information could be useful in predicting how well acidified sweetpotato based products will heat in a modular microwave system operated at 2450 MHz.

REFERENCES

Brinley, T., Truong, V., Coronel, P., Simunovic, J., & Sandeep, K. (2008). Dielectric Properties of Sweet Potato Purees at 915 MHz as Affected by Temperature and Chemical Composition. *International Journal of Food Properties*, 158-172.

Halvorsen, B. L., Holte, K., Myhrstad, M. C., Barikmo, I., Hvattum, E., Remberg, S. F., . . . Blomhoff, R. (2002). A Systematic Screening of Total Antioxidants in Dietary Plants. *The Journal of Nutrition*, 461-471.

Kumar, P., Coronel, P., Simunovic, J., Truong, V., & Sandeep, K. (2007). Measurement of Dielectric Properties of Pumpable Food Materials Under Static and Continuous Flow Conditions. *Food Engineering and Physical Properties*.

Liu, Y., Tang, J., & Mao, Z. (2009). Analysis of bread dielectric properties using mixture equations. *Journal of Food Engineering*, 72-79.

Ryynänen, S. (1995). The Electromagnetic Properties of Food Materials: A Review of the Basic Principles. *Journal of Food Engineering*, 409-429.

Sipahioglu, O., & Barringer, S. (2003). Dielectric Properties of Vegetables and Fruits as a Function of Temperature, Ash, and Moisture Content. *Journal of Food Science*, 234-239.

U.S. Department of Health and Human Services. (2010). Processing Acidified Foods. In Guidance for Industry - Acidified Foods (pp. 26-31). Food and Drug Administration.

Vebjatesg, M., & Raghavan, G. (2004). An Overview of Microwave Processing and Dielectric Properties of Agri-food Materials. *Biosystems Engineering*, 1-18.

Zhu, J., Kuznetsov, A., & Sandeep, K. (2007). Mathematical modeling of continuous flow microwave heating of liquids (effects of dielectric properties and design parameters). *International Journal of Thermal Sciences*, 328-341.

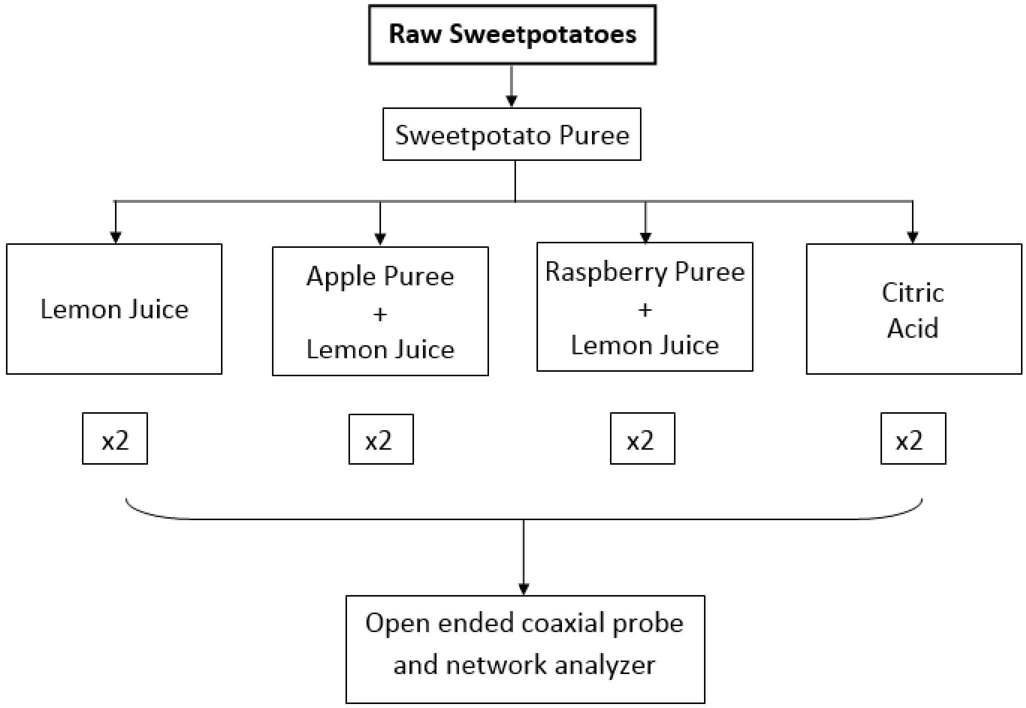

Figure 3.1: Flow Chart

Table 3.1: Moisture content, pH, and Degree Brix of the sweetpotato puree and mixtures

Sample	**% Moisture**	**pH**	**°Brix**
Sweetpotato Puree	81.29 ± 0.13[c]	5.75 ± 0.06[a]	15.8 ± 0.07
Citric Acid Mixture	86.59 ± 0.38[a]	3.98 ± 0.01[b]	14.8 ± ND
Lemon Mixture	84.95 ± 0.01[b]	3.96 ± 0.01[bc]	15.2 ± ND
Raspberry Mixture	87.22 ± 0.07[a]	3.88 ± 0.01[c]	12.6 ± ND
Apple Mixture	85.37 ± 0.02[b]	3.96 ± 0.01[bc]	14.7 ± ND

Different superscript letters within a column indicate a significant difference at $p<0.05$

Values for % moisture and pH are means of two replicates ± SEM

ND stands for no data

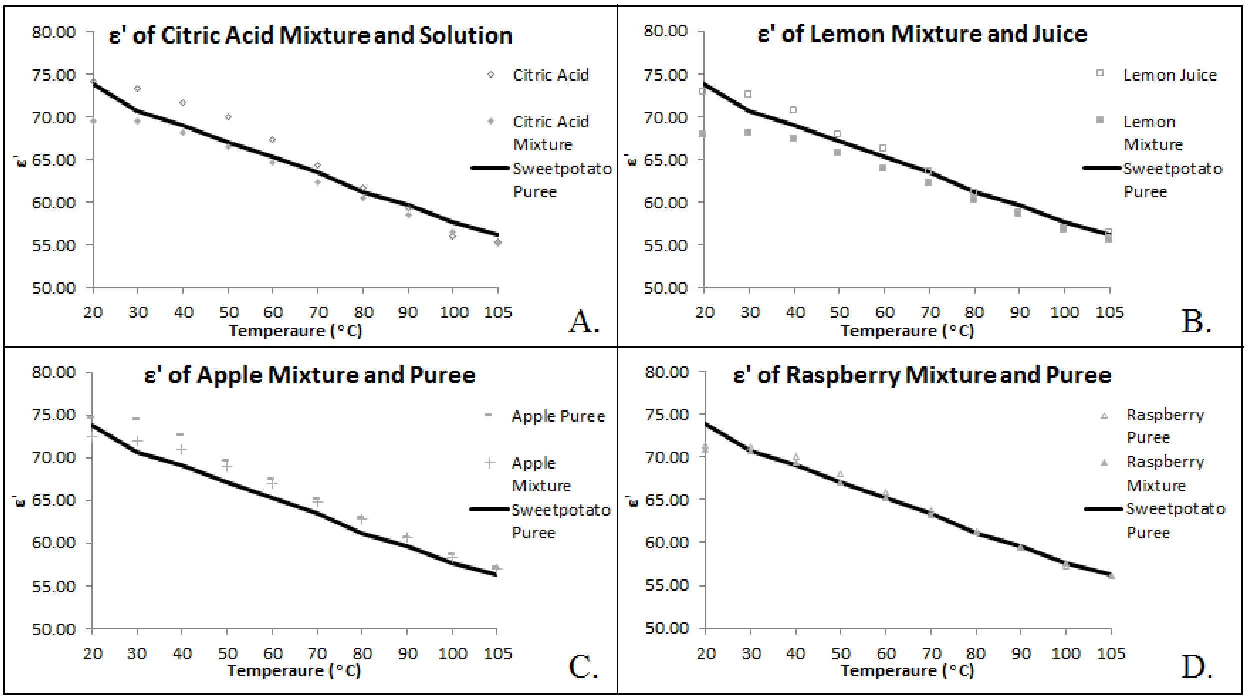

Figure 3.2: Measured dielectric constant of the mixtures and ingredients

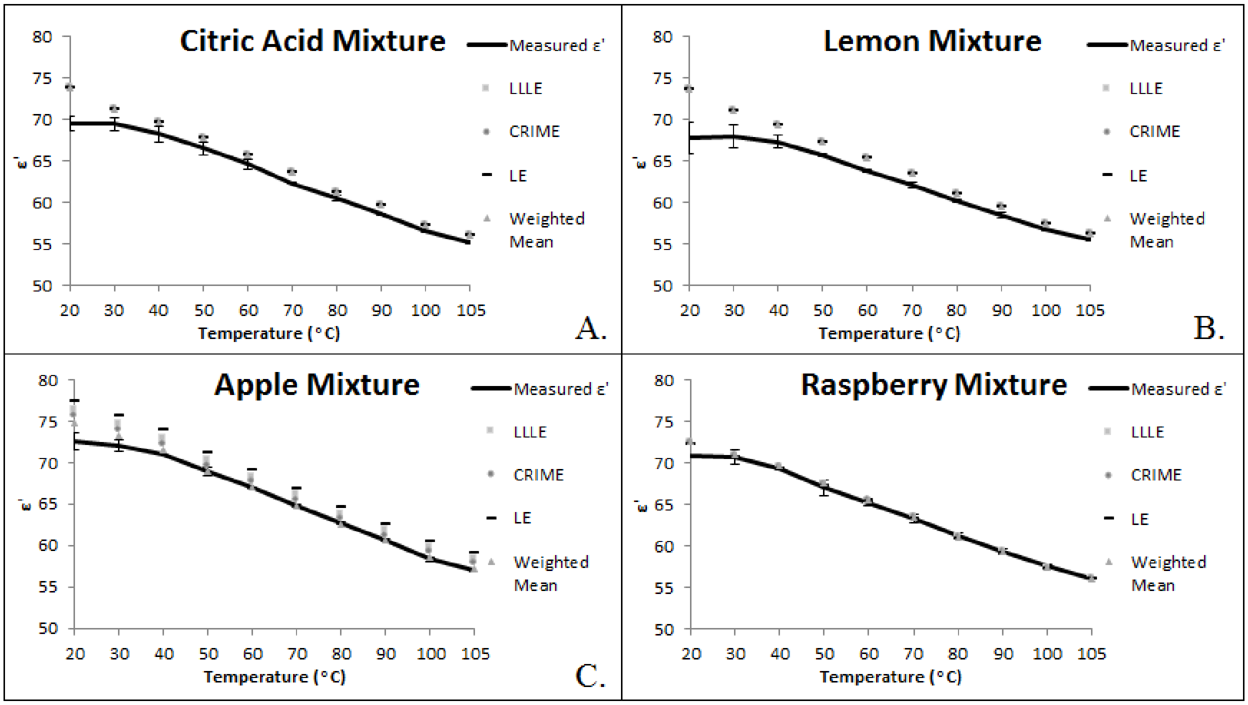

Figure 3.3: Calculated dielectric constant compared to the measured dielectric constant of each mixture

Landau and Lifshitz, Looyenga equation (LLLE)
Complex Refractive Index Mixture equation (CRIME)
Lichtenecher equation (LE)

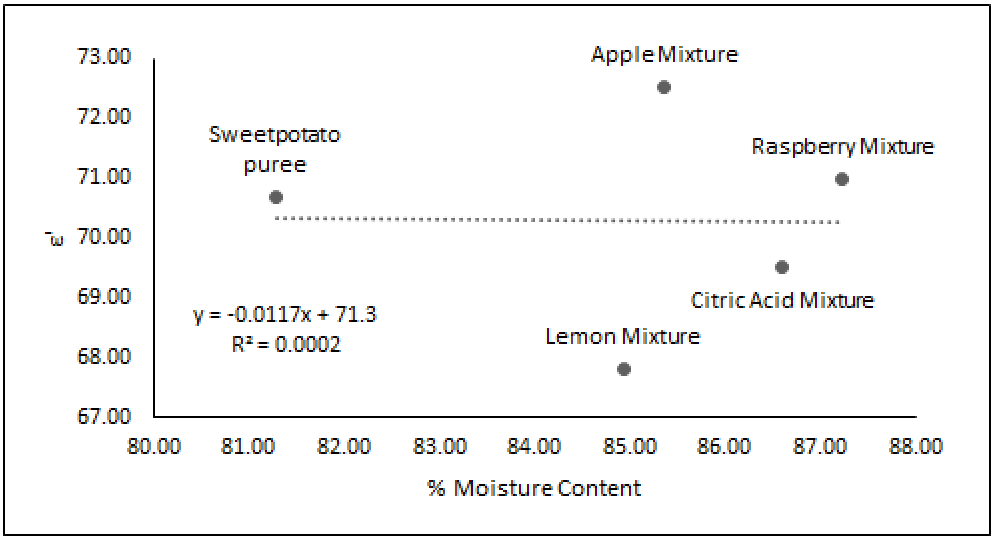

Figure 3.4: Dielectric constant (ε') at 20°C compared to % moisture content

Dotted line represents trendline between data points

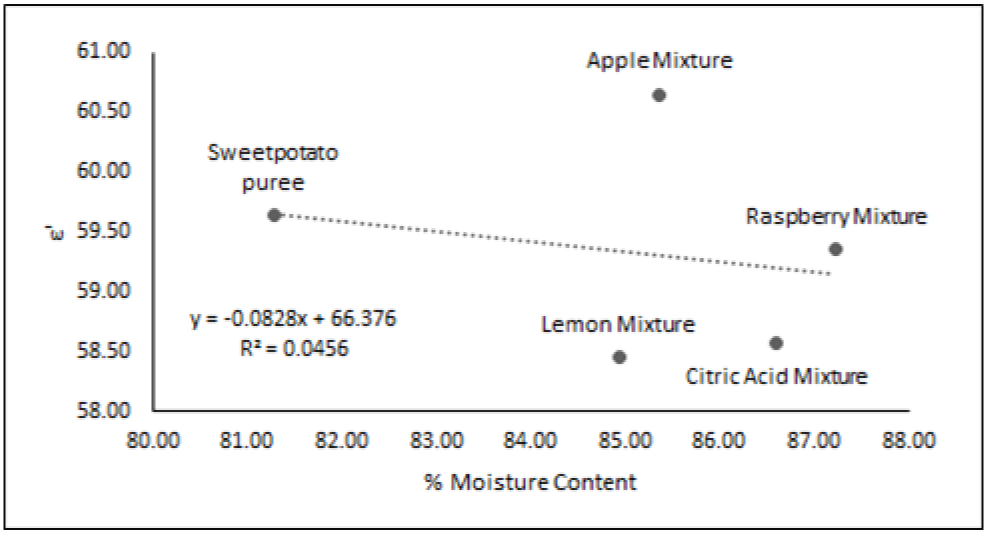

Figure 3.5: Dielectric constant (ε') at 90°C compared to % moisture content

Dotted line represents trendline between data points

CHAPTER 4: Thermal Processing and Nutrient Retention of Acidified Sweetpotato-Fruit Mixed Purees using a Modular 2450 MHz Continuous Flow Microwave System

4.1 Abstract

Continuous flow microwave technology operated at 915 MHz has been developed and implemented for commercial processing and aseptic packaging of various foods. However, the current 915 MHz systems are more suitable for large scale settings and require considerable capital investment. The goal of this study was to implement a microwave system which is more suitable for research and development (R&D) and for lower capacity processing. This study aimed to evaluate the heating performance of a modular 2450 MHz continuous flow microwave system, to determine the parameters required to reach pasteurization temperatures of sweetpotato-fruit mixed purees and to assess nutrient retention in the processed products. The current prototype utilized sixteen 2450 MHz microwave units of 1200 W power assembled into four modular stacks. A microwave-transparent tube conveyed the products through the center of the microwave units during thermal processing. Sweetpotato-fruit mixed purees (pH = 3.58 to 3.76) were processed at a flow rate of 1.0 ± 0.1 L/min. It was determined that the modular system used in this study was capable of heating the product from room temperature (~20°C) to 85°C required for pasteurization. Nutrient analysis indicated that there was minimal degradation of the phytochemicals in the purees after being processed with the microwave system. The antioxidant activity decreased 20-27%, anthocyanin level decreased by 10%, and beta-carotene content was decreased by 8-14%. Each of the processed purees became darker as indicated by slight decrease in L* value after being processed but had a low overall color change. This system has the potential to be a less expensive, more efficient pasteurization method suitable for R&D and small scale processing of acidified fruit and vegetable products while maintaining high product quality.

4.2 Introduction

Microwave technology has been a commonly used heating method in consumer homes since about the 1980's, when household microwaves became smaller and more affordable. It wasn't until more recently that microwave technology became more widely used in the food or pharmaceutical industry. Microwave heating is capable of heating products more quickly than conventional heating methods and therefore has a greater nutrient retention. A continuous flow microwave system operated at 915 MHz has been developed and successfully implemented in the production of fruit and vegetable purees, broths, and juices. (Steed, et al., 2008). This large system, with an operating flow rate of 5.7 L/min, requires a sizable capital investment which is a constraint for small companies interested in exploring microwave technology to experiment with potential products. Therefore, there is a need for a smaller, more cost effective system that can function in a pilot plant setting which is suitable for the purpose of R&D or small scale processing. In order to meet this need, a modular system was built utilizing household microwaves which traditionally operate at 2450 MHz (Truong, 2014). The difference in frequency, 915 MHz verses 2450 MHz, only has a slight effect on the heating of a product (Tong, Lentz, & Rossen, 1994). This modular system has a smaller production area foot print and is capable of processing products at low flow rates. The development of this type of system would allow companies to test new products while wasting less material, energy, and time.

Although commercialized systems are capable of reaching aseptic temperatures (>121°C) (Steed, et al., 2008), the modular system in this study was not constructed to surpass 100°C to prevent the occurrence of flashing (boiling of the product). The system can be used for pasteurization of various products . In order for these products to be shelf stable, it was necessary to acidify the products to a pH less than 4.6 (Bredt, Kay, Osborne, Ingham, & Arritt, 2014). There are many acidified products on the market including fruit beverages/juices, baby food, and jams. The ingredients used to acidify products in this research were apple sauce with a reported pH ranging from 3.1-3.6, blueberries with a pH of 3.1-3.3, and lemon juice with a pH of 2.0-2.6 (U.S. Food and Drug Administration, 2007). To achieve both the acidification and nutrient goals, the sweetpotato puree with high carotene levels was acidified with apple puree, blueberry puree, and/or lemon juice. Blueberries have been shown to contain exceptionally high amounts of anthocyanins, antioxidants, and phenols (Grace, et al., 2009). Apples and lemon both have high antioxidant activity and sweetpotatoes are rich in beta-carotene (Wojdylo, Osmianski, & Laskowski, 2008; Gonzalez-Molina, Moreno, & Garcia-Viguera, 2008; Teow et al., 2007). The addition of the apple puree, blueberry puree and or lemon juice to sweetpotato puree sufficiently decreased the pH of the sweetpotatoes to < 4.6.

A hot filler was used to package the processed product to better model a complete production line. This tested how well the system would operate as either a stand-alone processing line or as a tool for research and development. The products processed and packaged in this 2450 MHz microwave-hot filler system could be the finished products for retail markets or functional ingredients for fruit beverages, bakery products, and baby food.

The main purpose of this study was to develop a modular microwave system that would be useful for producing samples for R&D purposes but could also be used by small scale processors to produce commercial products. To determine whether the modular microwave system accomplish this, the effect of the heating imparted by the microwave system on nutritional sweetpotato-fruit mixed purees was examined. Temperature measurements were also gathered in order to analyze the heating capabilities of the system.

4.3 Materials and Methods

4.3.1 Modular Microwave System

A total of 16 units of 1200 W household microwaves (Panasonic model NN-SA651S, Newark, NJ, U.S.A) were used in the construction of the modular system. The microwaves were organized into four stacks, or modules, containing four microwaves each. A 3 inch diameter hole was cut in the bottom and top of each microwave as shown in Figure 4.1. A Teflon pipe which is permeable to microwave energy was fitted through the hole in the microwaves. Aluminum foil was used to cover gaps around the Teflon pipe to prevent microwaves from leaking through the hole. Product was pumped through the Teflon pipe during processing. This allowed product to flow through each microwave and receive heat treatment throughout the system. A similar system was used to study the effects of microwave processing on fruit cocktails containing apple puree (Truong, 2014).

Insulated, flexible metal piping was used to connect the Teflon tube in each module of microwaves. This conveyed the product into the bottom of one module, out the top, and into the bottom of the next module. The flow path ensured the product in the pipe was devoid of air bubbles which could affect heating (Figure 4.2). Product was poured into a hopper of the system and moved through the modules using a pump (Baldor Model NEMA-4X-IP65, Fort Smith, AR, U.S.A.).

Sight glasses were placed directly after the pump and at the outlet of each module. This made it possible to monitor the product for flashing and to determine the amount of time necessary for the product to move from the inlet of the first module to the exit of the fourth module. Temperature measurements were recorded every second at the inlet and outlet of each module and at the outlet of the hot filler (Inline Filling Systems Model FDP, Venice, FL, U.S.A.). Type T thermocouples and triple point thermocouples were used to measure temperature (Windridge Sensors, LLC Model KS3-R15T, Holly Springs, NC, U.S.A.). The temperature at the outlet of the hot filler and the outlet of the fourth module was closely monitored to ensure the temperature remained constant. Samples were only collected while the product was above a temperature of 85°C at the outlet of the hot filler. If the temperature at the outlet of the fourth module became too high (about 100°C), two of the microwaves in module four were turned off until the temperature dropped to approximately 95°C.

To ensure the temperature at the outlet of the hot filler maintained the target temperature (85°C), it was necessary to wrap the nozzle of the hot filler with heat tape. The nozzle was the exit of the hot filler and facilitated product packaging. Once the temperature at the outlet of the hot filler was consistently above 85°C, samples were collected 120 ml in glass mason jars. The filled mason jars were turned upside down and allowed to rest for 3 minutes to ensure sterilization of the package. Samples were then stored in a -80°C freezer.

Before adding product to the system, water was pumped through the microwaves and used to test the flow rate. Once the flow rate was established, each product mixture was pumped through the modules until it reached the outlet of the system. The flow rate was measured for each product mixture to ensure they were pumped at 1 L/min. After setting the flow rate, the microwaves were manually turned on.

To clean the system, hot water was back-flushed through the microwave system until particles were no longer visible in the sight glasses; this typically required about 10 minutes. The system was cleaned between each batch of product.

4.3.2 Formulating Puree Mixtures

Sweetpotato puree was acquired from Yamco LLC (Snow Hill, N.C., U.S.A.). Frozen blueberry puree was donated by Jasper Wyman & Son (Milbridge, Maine, U.S.A.). Frozen apple puree was acquired from Emerling International Foods, Inc. (Buffalo, N.Y., U.S.A.). Lemon juice (ReaLemon, 100% lemon juice) was purchased at local grocery stores. Each ingredient was processed by the company supplying the ingredients prior to use in this study. The blueberry and apple purees were received as frozen ingredients and were kept frozen until use. The sweetpotato puree and lemon juice were shelf stable at room temperature, therefore they were stored at room temperature.

The mixtures were formulated by blending sweetpotato puree with blueberry puree or apple puree followed by addition of lemon juice to obtain a pH range of 3.4 to 4.0 (Figure 4.3). The pH of the sweetpotato puree ranged from 5.7 to 5.8. The sweetpotato-apple mixture (SA) consisted of 46% sweet potato puree, 46% apple puree, and 8% lemon juice with a pH of 3.70 ± 0.03. The sweetpotato-blueberry mixture (SB) consisted of 46.5% sweetpotato puree, 46.5% blueberry puree, and 7.0% lemon juice with a pH of 3.76 ± 0.17. The sweetpotato-lemon mixture (SL) consisted of 82% sweetpotato puree and 18% lemon juice with a pH of 3.58 ± 0.11. A Fisher scientific, accumet AE150 pH meter was used to measure pH.

The frozen ingredients (blueberry and apple purees) were allowed to thaw in a refrigerator at 4°C for 72 hours. After thawing, the puree mixtures were prepared for processing by collecting the weighed ingredients in five-gallon buckets where they were mixed thoroughly before being poured into the hopper. Samples were collected before and after processing and were immediately frozen for future nutrient analysis.

4.3.3 Analyses of Antioxidant Activity, Anthocyanins, Phenolics, and Carotenoids

Preparation of the extracts: Extractions for antioxidant, anthocyanin, and phenolic analysis were done using acidified methanol (7% acetic acid). Acidified methanol (25 ml) was added to 4.0 g of each sample, except blueberry puree and the SB mixture which only required 2.5 g. The blueberry puree and SB mixture required less sample due to the high nutrient content of blueberries. The samples were blended using a Tekmar tissuemizer (type SDT-1810, Tekmar Co., Cincimati, OH, USA) and allowed to rest for 30 minutes before being centrifuged at 9,000 rpm, 10°C for 10 min. The supernatant was collected for further analysis.

DPPH radical scavenging activity assay: The total antioxidant activity was measured using the 2-2-diphenyl-1-picrylhydrazyl (DPPH) method in which 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox) was used as a standard (Brand-Williams, Cuvelier, & Berset, 1995). Trolox and DPPH solutions were prepared immediately prior to use and sonicated to ensure the compounds were dissolved. A volume of 100 µL of sample extract or standard was added to 3.9 ml of DPPH solution and allowed to react for 3 hours (Teow, et al., 2007). Solutions were then measured on a spectrophotometer at 515 nm using 80% ethanol as a blank. All values for total antioxidant activity were reported as µM trolox equivalent per g fresh weight (fw) of sample.

Quantification of total anthocyanins and phenolics: The total monomeric anthocyanin content was measured using the pH differential method as described by Giusti and Wrolstad (2001). Sample extract was diluted at a ratio of 0.5 ml of sample to 2 ml of buffer. The two buffer solutions in the analysis used were potassium chloride at a pH of 1.0 and sodium acetate at a pH of 4.5. The sample extract and buffer were allowed to react for 15 min before being measured on a spectrophotometer (Cary WinUV Model 300, Palo Alto, Calif., U.S.A.) at 510 nm and 700 nm. The spectrophotometer was blanked using distilled water. The following equations were used to calculate the total monomeric anthocyanin content:

$$A = (A_{510} - A_{700})_{pH1.0} - (A_{510} - A_{700})_{pH4.5}$$

where A_{510} and A_{700} are the absorbance of the solutions measured at 510 nm and 700 nm respectively. The difference between the absorbance of the solutions measured at both wavelengths at a pH of 4.5 was subtracted from the difference between the absorbance of the solutions measured at both wavelengths at a pH of 1.0. This calculation yields the absorbance (A) of the sample for determining the total monomeric anthocyanin content:

$$Monomeric\ anthocyanins\ pigment\ (mg/L) = \frac{A \times MW \times DF \times 1000}{\varepsilon \times 1}$$

where the molecular weight (MW = 449.2 g/mol) and extinction coefficient (ε = 26900 $L \bullet mol^{-1} \bullet cm^{-1}$) of cyaniding-3-glucoside was used. The dilution factor (DF) is variable depending on the sample and the path length is standard at 1 cm. The formula is multiplied by 1000 to convert to mg/L.

The total phenolic content was measured using a modified Folin-Ciocalteau (F-C) method (Ainsworth & Gillespie, 2007). The standard curve was made using a 1 mM chlorogenic acid solution. Samples were diluted at a ratio of 0.25 ml of sample extract to 4 ml of distilled water. The F-C reagent was added to both the standard and samples, and the mixture was allowed to react for 3 minutes. A 1 N solution of sodium carbonate was then added to the standard and samples and allowed to react for 1 hour before being measured with a spectrophotometer at 725 nm. The spectrophotometer was blanked using a mixture of distilled water, F-C reagent, and sodium carbonate. The absorbance measurements from the standard curve were used to calculate the total phenolic content in the samples. This method has been used to measure total monomeric anthocyanins and total phenolic content of purple fleshed sweetpotatoes (Steed & Truong, 2008). All values for total phenolic content and total monomeric anthocyanin content were reported as mg standard per g fresh weight (fw) of sample.

Quantification of β-carotene: Extractions for β-carotene analysis were performed using a 50:50 mixture of acetone and hexane. The mixture was added to samples, vortexed and allowed to rest for 5 min before being centrifuged. The supernatant was collected and the extraction was repeated twice. A separatory flask was used to separate the acetone from the hexane layer. The hexane layer was collected and additional hexane was added to bring the total volume to 50 mL and the absorbance (A) at 450 nm was measured using a spectrophotometer. This method was modified from the procedure described by Chandler and Schwartz (1988). The total beta-carotene (C) was calculated by the following:

$$C = \frac{A \times DF \times MW}{\varepsilon \times 1}$$

where the molecular weight (MW = 536.9 g/mol) and extinction coefficient (ε = 139200 $L \cdot mol^{-1} \cdot cm^{-1}$) of beta-carotene was used. The dilution factor (DF) is variable depending on the sample and the path length is standard at 1 cm. All values for carotene content were reported as µg per g fresh weight (fw) of sample.

4.3.4 Measurement of Color Values

All samples were placed on covered, clear Petri dishes and the color values (L*, a*, and b*) were measured with a Hunter colorimeter (Hunter Associates Laboratory Inc., Reston, VA). Each sample was measured in three different positions. The L* value represents lightness with 0 being black and 100 being white. The a* value represents the greenness or redness of a material with a negative a* value being more green and a positive a* value being more red. The b* value represents the blueness or yellowness of a material with a negative b* value being more blue and a positive b* value being more yellow. The total color change between the unprocessed and processed mixtures is represented by ΔE (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). The calculation for ΔE is shown below:

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

The ΔL*, Δa*, and Δb* variables represent the change in color values between the processed and unprocessed samples.

4.3.5 Statistical Analysis

Two replications of each mixture were processed with the modular microwave system. Each batch was prepared immediately prior to processing, utilizing the same ingredients, and in the same ratio. The system was flushed with water between each batch for approximately 10 minutes. Batches to be processed were chosen at random and samples were taken immediately before and after processing. All data was reported as the mean of the two replications. Error bars represent the standard error of the means. Statistical analysis of the nutrient data was performed using XLSTAT Version 2017 (Addinsoft, New York, NY). A one-way analysis of variance (ANOVA) in conjunction with a Turkey's HSD test was used to determine statistical significance between the mixtures and ingredients at a confidence interval of 95%.

4.4 Results and Discussion

4.4.1 Microwave Processing

In thermal processing of foods, the target organism of the heat treatment is *Clostridium botulinum* spores. These spores are very heat resistant which require high temperatures for a certain processing times to inactivate. However, in this study, C. botulinum spores are not a concern because the products are below a pH of 4.6 which prevents the growth of these spores. Other spoilage organisms such as yeasts and molds are still of concern due to their ability to potentially increase the pH of the product to a level where C. botulinum can grow. Another concern for spoilage is the presence of degradation enzymes in the fruit purees. The heat treatment needed to inactivate degradation enzymes is more intense than what is necessary to destroy the molds and yeast (Nath & Ranganna, 1981). Thus, the main target of the heat treatment for fruit products below a pH of 4.6, is degradation of oxidative enzymes and acid tolerant organisms. In order to produce a safe, shelf stable product, the heat treatment was based on industry standards of heat treatments for products with a pH of less than 4.6 (McGlynn, 2003). These standards were designed to ensure the inactivation of enzymes and destruction of molds, yeasts, and other acid tolerant organisms.

The initial temperature of the SA, SB, and SL mixtures at the inlet of the microwave system was 11°C, 6°C, and 18°C respectively. These initial temperatures varied due to inherent differences in the thaw rates of apple and blueberry puree. To preserve the nutrient content of the ingredients, the frozen blueberry and apple puree were thawed by placing them in a 4°C refrigerator for 72 hours prior to preparation of the mixtures. The set amount of time for the ingredients to thaw combined with their different thawing rates resulted in slight differences in the initial temperature of the mixtures. Each of the mixtures reached room temperature in approximately 1 minute within the microwave system. At a flow rate of 1 ± 0.1 L/min the products moved through the system in approximately 7 minutes.

The minimum processing temperature for each mixture was maintained at 85°C. This temperature was chosen because it is the standard minimum processing temperature set by the food industry for products within a pH range of 3.5-4.0 (McGlynn, 2003). Although the product samples in this study were not collected at the outlet of the modular microwave system (the outlet of module 4), temperature readings were recorded at this point. These temperature readings are of interest because it may be desirable to collect product at this point for other research and development projects or small scale processing operations. As shown in Figure 4.4, at the outlet of the modular microwave system, the temperature of the SB mixture remained above 85°C after 4 minutes and increased to 90°C in 5 minutes. The SA mixture reached 85°C in 3 minutes and remained above this temperature for the remainder of processing. Although the SL mixture was able to reach 85°C in 4.5 minutes, there was an unexpected loss of power to multiple microwaves in the system at the 5.2 minute time point. This caused the temperature of the SL mixture to drop as low as 78°C. The temperature returned to 85°C by the 6 minute time point after the microwaves regained power.

Product samples in this study were collected at the outlet of the hot filler, therefore, the temperature at this point was also monitored and recorded (Figure 4.5). The temperature at the outlet of the hot filler was consistently lower than the temperature at the microwave outlet because of heat loss through the flowing pipe connecting the microwave system to the hot filler. At the outlet of the hot filler, the SB mixture reached 85°C at 6.7 minutes. However, at 8.3 minutes the temperature dropped below 85°C (no lower than 82°C) for a period of 30 seconds. This may have been due to the SB mixture reaching flashing temperatures at the outlet of the 4th module. Flashing is believed to have occurred because the measured temperature exceeded 100°C and boiling was observed in the sight glass at the outlet of module 4. The flashing caused air pockets in the piping that likely resulted in temperature fluctuations in the hot filler. The SA mixture reached 85°C in 6 minutes and remained above this temperature for the remainder of processing. The SL mixture reached 85°C in 5.9 minutes and dropped slightly to 84°C at the 7 minute time point but recovered within 10 seconds. The temperature drop measured at the outlet of the hot filler was not as extreme as that observed at the outlet of the 4th module. It was possible that the heat tape on the nozzle of the hot filler maintained a more stable temperature at this point. Samples were only collected when the temperature at the outlet of the hot filler was above 85°C.

The results showed that the modular microwave system was capable of both reaching the target temperature and maintaining that temperature at the outlet of the microwave system. In a conventional heating system, it has been estimated that, to safely process a product with a pH of 3.8 to 97°C, could take between 7 to 17 minutes (Nath & Ranganna, 1981), whereas microwave processing can provide more rapid heating. For example, each product took no more than 5 minutes to reach the target temperature at the outlet of the microwave system. This rapid come up time minimizes product waste and, therefore, cost. This is important because the system is intended to be used as an inexpensive method of testing the compatibility of a product with microwave heating. The modular microwave system and hot filler utilized a small amount of product; requiring a minimum batch size of 200 L which is suitable for processing at small scales.

4.4.2 Effect of Microwave Heating on Phytochemicals

Each ingredient used in this experiment was preprocessed by the supplier. However, for the purposes described in this paper, the term “processed” will refer to the heat treatment provided by the modular microwave system being studied and not to the processing conditions provided by the supplier. Similarly, the term “unprocessed” refers to mixtures that did not received heat treatment from the modular microwave system being studied.

The term, “blueberry puree” refers to a puree composed of only blueberries. Similarly, “apple puree” is composed of only apples and “lemon juice” is lemon juice only. The term “SB mixture” or “SA mixture” refers to the combination of blueberry puree or apple puree with sweetpotato puree and lemon juice. The term “SL mixture” refers to the combination of lemon juice with sweetpotato puree as described in the methodology.

Antioxidant Activity: As shown in Figure 4.6, the blueberry puree had the highest antioxidant activity at 201.41 µM trolox/g fw. The unprocessed SB mixture had approximately half as much antioxidant activity as the blueberry puree. This was expected after the blueberry puree was mixed with the sweetpotato puree which had lower antioxidant activity. There was a statistically significant difference between the unprocessed and processed mixtures in which each mixture had a lower antioxidant activity after being processed. The unprocessed and processed SB mixtures had an antioxidant content of 95.1 µM trolox/g fw and 69.3 µM trolox/g fw, respectively. The antioxidant activity of the SA mixture dropped from 47.0 µM trolox/g fw to 37.43 µM trolox/g fw. The unprocessed SL mixture had an antioxidant activity of 33.82 µM trolox/g fw while the processed mixture was 24.56 µM trolox/g fw. Overall the SB mixture lost the most antioxidant activity. The antioxidant activity results for blueberry puree was similar to values found in literature where blueberries were reported to have an antioxidant activity betwen 59-115 µM trolox/g (Flis, et al., 2012).

Total Phenolics: The total phenolic content of blueberries has been reported to vary depending on the variety, growing conditions, and location. Regardless of these factors, blueberries are known to have high phenolic contents, with reported values ranging from 261-911 mg/100 g FW with gallic acid as the standard. (Sellappan, Akoh, & Krewer, 2002)

In this study, blueberry puree had the highest phenolic content with 34.7 mg chlorogenic acid/g sample (Figure 4.7). As expected, after being mixed with the sweetpotato puree, the SB mixtures contained less total phenolics than the blueberry puree alone. However, the SB mixtures still had the second highest total phenolic content with 20.7 mg/g sample and 21.3 mg/g sample in the unprocessed and processed mixtures, respectively. There was no significant difference in total phenolic content between the unprocessed and processed SB mixtures ($p < 0.05$). The total phenolic content of the apple puree was 17.6 mg/g sample. The SA mixtures had less total phenolics than the apple puree with a total phenolic content of 12.3 mg/g sample and 13.6 mg/g sample in the unprocessed and processed mixtures, respectively. The SL mixtures had a total phenolic content of 7.7 mg/g sample in the unprocessed mixture and 8.7 mg/g sample in the processed mixtures. The total phenolic contents of the unprocessed and processed SL mixtures were not statistically different from the sweetpotato puree which had a total phenolic content of 7.6 mg/g sample and the lemon juice contained 6.7 mg/g sample. The total phenolic content of lemon juice and apple puree have been reported by various sources that used gallic acid as a standard (Gonzalez-Molina, Moreno, & Garcia-Viguera, 2009; Wolfe, Wu, & Liu, 2003).

The processed SA mixture had a higher total phenolic content than the unprocessed which was statistically significant ($p<0.05$). However, there was no statistically significant difference in total phenolic content between the unprocessed and processed SB and SL mixtures. Although it is common to see nutrient degradation due to heat processing, it has been shown that microwave can uniquely disrupt the food matrix and therefore facilitate the extractability of phenolics and other phytochemicals as described in the microwave assisted extraction technology (Pedroza, et al., 2015).

Anthocyanins: Blueberries have been shown to have high amounts of total anthocyanins with ranges of 12-197 mg/100 g fw (Sellappan, Akoh, & Krewer, 2002), 109-260 mg/100 g fw (Gao & Mazza, 1994) and 199.1-373.3 mg/100 g fw (Yousef, et al., 2013). In this study, blueberries were the only ingredient that contained a high amount of anthocyanins with a total monomeric anthocyanin content of 79.1 mg/100 g FW. The anthocyanin contents of the blueberries in the literature were measured from fresh berries, while the blueberry puree in this study had been pasteurized and stored by the supplier. Other common fruit used in fruit purees are strawberries which have been found to contain 20-39 mg/100 g fw, raspberries which have 19-49 mg/100 g fw, red grapes which have 30-750 mg/100 g, and cherries which have been found to contain up to 350-450 mg/100 g of anthocyanins (Szajdek & Borrowska, 2008; Horbowicz, Kosson, Grzesiuk, & Debski, 2008).

The SB mixture was also the only formulation in this study that contained high amounts of anthocyanins. The amount of anthocyanins in the SB mixtures was about half as much as the amount found in the blueberry puree. This was expected because the mixture contained a ratio of approximately half blueberry and half sweetpotato. The anthocyanin content of the unprocessed SB mixture was 40.0 mg/100 g fw and the content of the processed mixture was 35.9 mg/100 g fw. Because there was a statistically significant difference between the unprocessed and processed mixtures ($p < 0.05$), it indicated that processing with the microwave system resulted in a decrease of anthocyanin content in the SB mixture.

The other mixtures contained less than 1 mg/100 g fw of total monomeric anthocyanins. Figure 4.8 shows the total monomeric anthocyanin content of each ingredient and mixture. The anthocyanin content of the other ingredients and mixtures used in this study was very low. The anthocyanin content of the sweetpotato puree was only 1.5 mg/100 g fw while the apple and lemon juice were found to have none. Previous studies have found that orange-fleshed sweetpotato puree and apple flesh contain little to no anthocyanins; Teow et al (2007) reported 0.038 mg/g fw in raw sweet potatoes (Wolfe, Wu, & Liu, 2003).

Beta-carotene: Total beta-carotene contents of each ingredient and mixture are shown in Figure 4.9. The beta-carotene content of the lemon juice was below the level of detection. The beta-carotene content of the other ingredients was 52.9 µg/g fw, 5.9 µg/g fw, and 11.3 µg/g fw in the sweetpotato, apple, and blueberry purees, respectively. Previous studies have shown similar results in sweetpotatoes and blueberries. Sweetpotatoes had values ranging from 15-33 µg/g wet weight in boiled sweetpotatoes, 120 µg/g fw in raw sweetpotatoes, and raw blueberries contained 49 µg/100g (Failla, Thakkar, & Kim, 2009; Teow, et al., 2007; Marinova & Ribarova, 2007). The blueberry puree in this study had been pasteurized and stored by the manufacturer.

The SA mixture had a total beta-carotene content of 30.6 µg/g fw before processing and 28.6 µg/g fw sample after processing. The unprocessed SB mixture had a total beta-carotene content of 36.1 µg/g fw and the processed had 31.1 µg/g fw. The SL mixtures had a beta-carotene content of 69.4 µg/g fw and 63.6 µg/g fw in the unprocessed and processed samples, respectively. For each mixture, there was a statistically significant decrease in total beta-carotene after the mixtures were processed.

The unprocessed SB and SA mixtures contained about half as much total beta-carotene as the sweetpotato puree. However, the unprocessed SL mixture contained a higher amount of total beta-carotene than the sweetpotato puree. This occurrence could be due to the acidification of the puree by the lemon juice and the subsequent effect on the beta-carotene isomers. Previous study has shown that beta-carotene in acidified sweetpotato puree (pH= 3.6-3.8) was stabilized or even increased after being pasteurized (Thor et al. 2013). The content of total β-carotene isomers in sweetpotato puree was retained by 92% with continuous flow 915 MHz microwave heating (Truong et al. 2012). This indicated that microwave processing can result in good retention in beta-carotene contents of food products.

4.4.3 Color

L Value*: The L* value represents the lightness or darkness of a sample. Lemon juice was the lightest sample with an L* value of 58.14. Blueberry puree was the darkest with an L* value of 2.30 (Figure 4.10). For each mixture, the sample was darker after processing, indicated by a decrease in L* value. The L* values of the SA mixtures dropped from 58.14 to

54.72, the SB mixtures dropped from 19.55 to 12.50, and the SL mixtures dropped from 57.90 to 55.99. These decreases were statistically significant ($p < 0.05$).

a Value*: After processing, the SB mixture was more red which was indicated by an increase in a* value from 15.13 to 20.55 (Figure 4.11). There was not a statistically significant difference in a* value between the unprocessed and processed SA and SL mixtures. The apple puree and lemon juice had negative a* values while the sweetpotato puree and blueberry puree had positive a* values.

b Value*: The sweetpotato and apple purees had high, positive b* values while the blueberry puree and lemon juice had low, positive b* values. The SA and SL mixtures became more yellow after processing. There was not a statistically significant difference in b* value between the unprocessed and processed SB mixtures. Figure 4.12 shows the b* values for each ingredient and mixture.

Overall: The average L*, a* and b* values of the sweetpotato puree in this study were 54.6, 12.8, and 46.0, respectively. This is comparable to prior research with orange fleshed sweetpotato puree (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). The total color change (ΔE) for the SL mixture, SA mixture, and SB mixture was 3, 4, and 9, respectively. While this processing system did have a small effect on total color change, it was significantly less than other processing methods. Generally, a ΔE value of 1 is considered to be the threshold value necessary to perceive a color difference (Hill, Roger, &

Vorhagen, 1997). Previous studies have shown ΔE values as high as 20 with sweetpotato puree heated to 130°C (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). Koskiniemi et al (2013) reported ΔE values of 11.56 after blanching and microwaving sweetpotato cubes to 77°C.

4.5 Conclusion

The 2450 MHz modular microwave system was capable of heating the acidified sweetpotato-fruit puree mixtures and maintained the target temperature of 85°C for effective pasteurization and packaging. Therefore, this system may have good potential for cost effective, small scale processing operations and would also be suitable for research and development to determine how well a product would heat with microwave technology.

Similar to the large-scale 915 MHz microwave systems, the 2450 MHz modular microwave system could maintain a high nutrient retention in the processed products. Processing the acidified sweetpotato-fruit puree mixtures with the 2450 MHz modular microwave system resulted in a 20-27% decrease in antioxidant activity, a 10% reduction in anthocyanins, and an 8-14% decrease in total beta-carotene. Each of the processed mixtures was darker than the unprocessed mixtures. The processed SA and SL mixtures also became more yellow while the processed SB mixture became more red.

Work is still needed to improve the ease of use and consistency of the system. For example, to regulate the temperature, it was necessary to manually adjust the microwaves during processing, ideally this would be automated. Automation would likely allow for better control of the temperature fluctuations. However, this study has shown that this modular microwave system has potential applications in many areas. Overall the system could be used as a complete processing and packaging line with minimal effect on nutrient content or color of the product.

REFERENCES

Ainsworth, E. A., & Gillespie, K. M. (2007). Estimation of total phenolic content and other oxidation substrates in plant tissues using Folin-Ciocalteu reagent. *Nature Publishing Group*, 875-877.

Brand-Williams, W., Cuvelier, M., & Berset, C. (1995). Use of a Free Radical Method to Evaluate Antioxidant Activity. *Lebensmittel-Wissenschaft and Technologie*, 25-30.

Bredt, F., Kay, K., Osborne, J., Ingham, B., & Arritt, F. (2014). Thermal Processing of Acidified Foods with pH 4.1 to pH 4.6. *Food Protection Trends*, 132-136.

Cardenosa, V., Girones-Vilaplana, A., Muriel, J. L., Moreno, D. A., & Moreno-Rojas, J. (2016). Influence of genotype, cultivation system and irrigation regime on antioxidant capacity and selected phenolics of blueberries (Vaccinium corymbosum L.). *Food Chemistry*, 276-283.

Coronel, P., Truong, V.-D., Simunovic, J., Sandeep, K. P., & Cartwright, G. D. (2005). Aseptic Processing of Sweetpotato Purees Using a Continuous Flow Microwave System. *Journal of Food Science*, 531-536.

Failla, M. L., Thakkar, S. K., & Kim, J. Y. (2009). In Vitro Bioaccessibility of β-Carotene in Orange Fleshed Sweet Potato (Ipomoea batatas, Lam.). *Journal of Agricultural and Food Chemistry*, 22-27.

Flis, S., Jastrzebski, Z., Arancibia-Avila, J. N., Toledo, F., Leontowicz, H., Leontowicz, M., . . . Gorinstein, S. (2012). Evaluation of inhibition of cancer cell proliferation in vitro with different berries and correlation with their antioxidant levels by advanced analytical methods. *Journal of Pharmaceutical and Biomedical Analysis*, 68-78.

Gao, L., & Mazza, G. (1994). Quantitation and Distribution of Simple and Acylated Anthocyanins and other phenolics in Blueberries. *Journal of Food Science*, 1057-1059.

Gonzalez-Molina, E., Moreno, D. A., & Garcia-Viguera, C. (2008). Genotype and Harvest Time Influence the Phytochemical Quality of Fino Lemon Juice (citrus limon (L.) Burm. F.) for Industrial Use. *Journal of Agricultural and Food Chemistry*, 1669-1675.

Gonzalez-Molina, E., Moreno, D. A., & Garcia-Viguera, C. (2009). A new drink rich in healthy bioactives combining lemon and pomegranate juices. *Journal of Food Chemistry*, 1364-1372.

Grace, M. H., Ribnicky, D. M., Kuhn, P., Poulev, A., Logendra, S., Yousef, G. G., . . . Lila, M. A. (2009). Hypoglycemic activity of a novel anthocyanin-rich formulation from lowbush blueberry, Vaccinium angustifolium Aiton. *Phytomedicine*, 406-415.

Hill, B., Roger, T., & Vorhagen, F. W. (1997). Comparative Analysis of the Quantization of Color Spaces on the Basis of the. *Association for Computing Machinery Transactions on Graphics*, 109-154.

Horbowicz, M., Kosson, R., Grzesiuk, A., & Debski, H. (2008). Anthocyanins of Fruits and Vegetables - Their Occurrence, Analysis, and Role in Human Nutrition. *Vegetable Crops Research Bulletin*, 5-22.

Lawrence A. Chandler, S. J. (1988). Isomerization and Losses of trans-beta-carotene in Sweet Potatoes as Affected by Processing Treatments. *Journal of Food Chemistry*, 129-133.

M. Monica Giusti, R. E. (2001). Characterization and Measurement of Anthocyanins by UV-Visible Spectroscopy. *Current Protocols in Food Analytical Chemistry*, F1.2.1-F1.2.13.

Marinova, D., & Ribarova, F. (2007). HPLC determination of carotenoids in Bulgarian berries. *Journal of Food Composition and Analysis*, 370-374.

McGlynn, W. (2003). The Importance of Food pH in Commercial Canning Operations. Oklahoma State: Oklahoma Cooperative Extension Service, Division of Agricultural Sciences and Natural Resources.

Nath, N., & Ranganna, S. (1981). Determination of Thermal Process Schedule for Acidified Papaya. *Journal of Food Science*, 201-211.

Pedroza, M. A., Amendola, D., Maggi, L., Zalacain, A., Faveri, D. M., & Spigno, G. (2015). Microwave-Assisted Extraction of Phenolic Compounds From Dried Waste Grape Skins. *International Journal of Food Engineering*, 359-370.

Sellappan, S., Akoh, C. C., & Krewer, G. (2002). Phenolic Compounds and Antioxidant Capacity of Georgia-Frown Blueberries and Blackberries. *Journal of Agriculture and Food Chemistry*, 2432-2438.

Steed, L., & Truong, V.-D. (2008). Anthocyanin Content, Antioxidant Activity, and Selected Physical Properties of Flowable Purple-Fleshed Sweetpotato Purees. *Journal of Food Science*, 215-221.

Steed, L., Truong, V.-D., Simunovic, J., Sandeep, K., Kumar, P., Cartwright, G., & Swartzel, K. (2008). Continuous Flow Microwave-Assisted Processing and Aseptic Packaging of Purple-Fleshed Sweetpotato Purees. *Journal of Food Engineering and Physical Properties*, 455-462.

Szajdek, A., & Borrowska, E. (2008). Bioactive Compounds and Health-Promoting Properties of Berry Fruits: A Review. *Plant Foods for Human Nutrition*, 147-156.

Teow, C. C., Truong, V.-D., McFeeters, R. F., Thompson, R. L., Pecota, K. V., & Yencho, G. C. (2007). Antioxidant activities, phenolic and beta-carotene contents of sweet potato genotypes with varying flesh colors. *Journal of Food Chemistry*, 829-838.

Thor, Y. W., Truong, A. N., Simunovic, J., Thompson, R. L., Truong, V. D. (2013). Effect of Acidification and Pasteurization on Carotenoids in Orange-fleshed Sweetpotato Juice. Poster Presentation at Institute of Food Technologists; 2013 July 13-16; Chicago, IL.

Tong, C. H., Lentz, R. R., & Rossen, J. L. (1994). Dielectric Properties of Pea Puree at 915 MHz and 2450 MHz as a Function of Temperature. *Journal of Food Science*, 121-123.

Truong, A. N. (2014). Nutrient Retention in Continuous Flow Microwave Processing of Fruit Purees Containing Particulates. MS Thesis, North Carolina State University.

Truong, V. D., Thompson, R. L., Simunovic, J., Cartwright, C. D., Coronel, P., Sandeep, K. P., Swartzel, K. R. (2012). Carotenoids and Tocopherols in Sweetpotatoes Subjected to Pureeing and Continuout Flow Microwave Sterilization. Poster Presentation at Institute of Food Technologists; 2012 June 26-28; Las Vegas, NV.

U.S. Food and Drug Administration. (2007). Approximate pH of Foods and Food Products. College Park, MD, USA: United States Department of Health and Human Services.

Wang, H., Cao, G., & Prior, R. L. (1997). Oxygen Radical Absorbing Capacity of Anthocyanins. *Journal of Agriculture and Food Chemistry*, 304-309.

Wojdylo, A., Osmianski, J., & Laskowski, P. (2008). Polyphenolic Compounds and Antioxidant Activity of. Journal of Agricultural and Food Chemistry, 6520-6530.

Wolfe, K., Wu, X., & Liu, R. H. (2003). Antioxidant Activity of Apple Peels. *Journal of Act cultural and Food Chemistry*, 609-614.

Yousef, G. G., Brown, A. F., Funakoshi, Y., Mbeunkui, F., Grace, M. H., Ballington, J. R., . . Lila, M. A. (2013). Efficient Quantification of the Health-Relevant Anthocyanin and Phenolic Acid Profiles in Commercial Cultivars and Breeding Selections of Blueberries (Vaccinium spp.). *Journal of Agricultural and Food Chemistry*, 4806-4815.

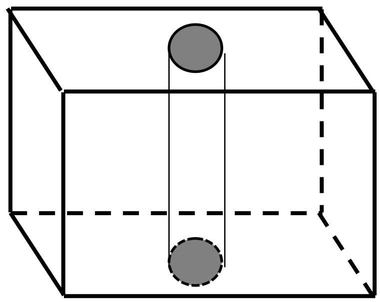

Figure 4.1: Teflon pipe in microwave

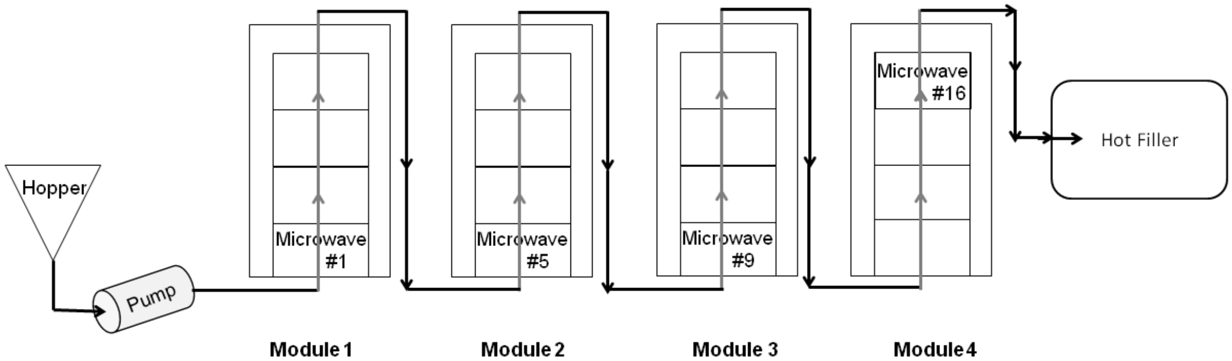

Figure 4.2: Set up of the modular microwave system

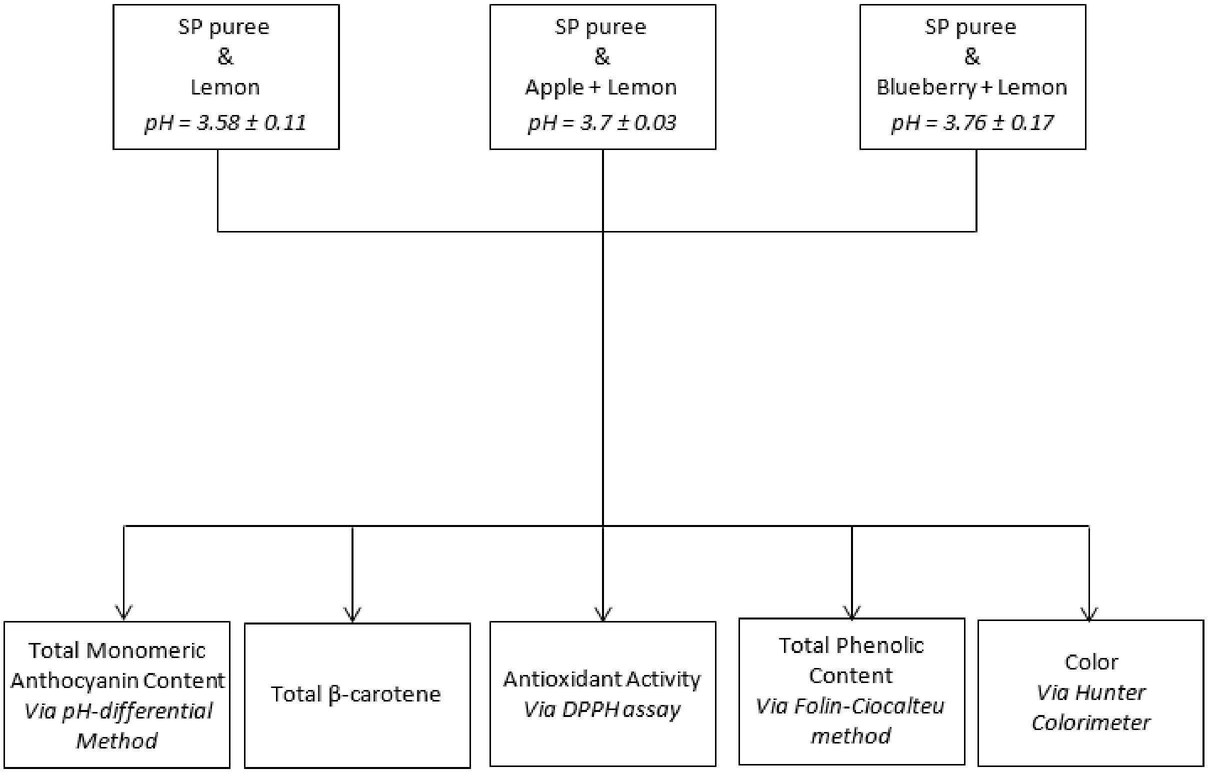

Figure 4.3: Flow chart of sample preparation and nutrient analysis
SP denotes sweetpotato puree

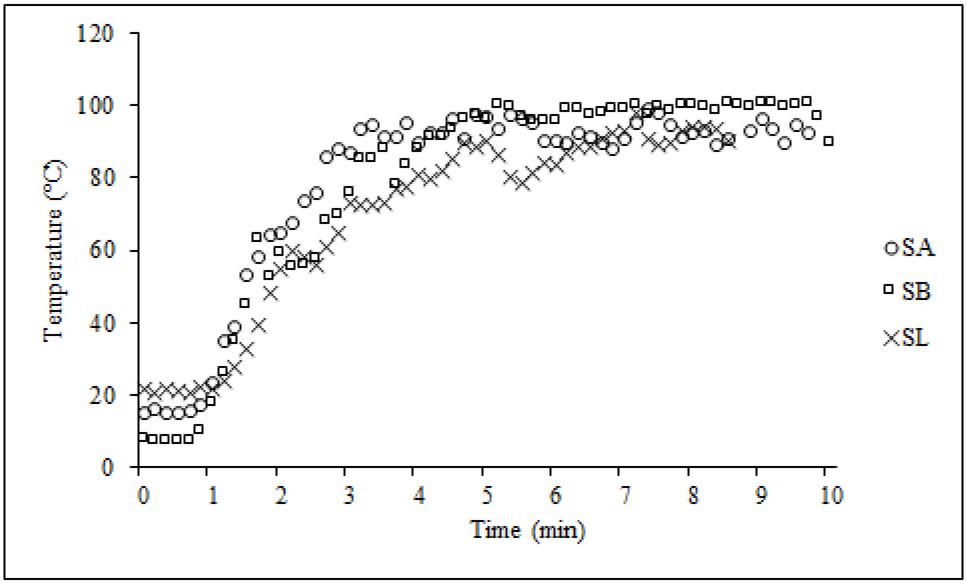

Figure 4.4: Average temperature of sweetpotato-fruit mixed purees at the outlet of the 2450 MHz modular microwave system

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
*The drop in temperature of the SL mixture at approximately 300 seconds was due to loss of power of the microwaves.
Temperatures are the mean of two samples

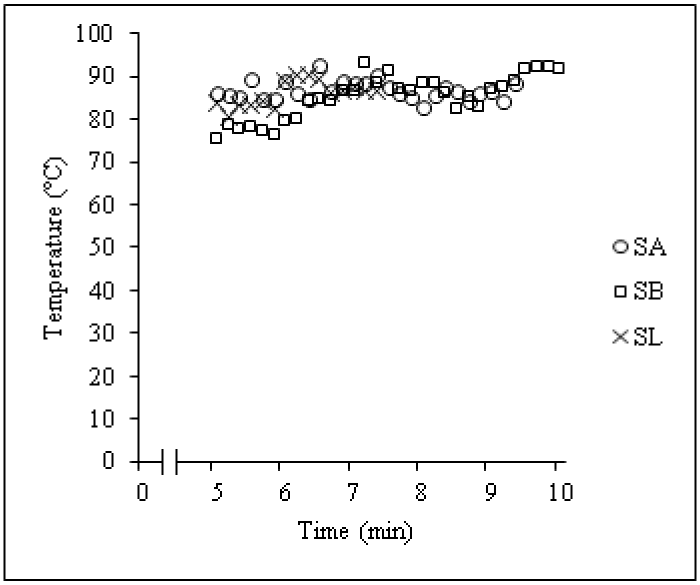

Figure 4.5: Average temperature of sweetpotato-fruit mixed purees at the outlet of the hot filler

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
Temperatures are the mean of two samples

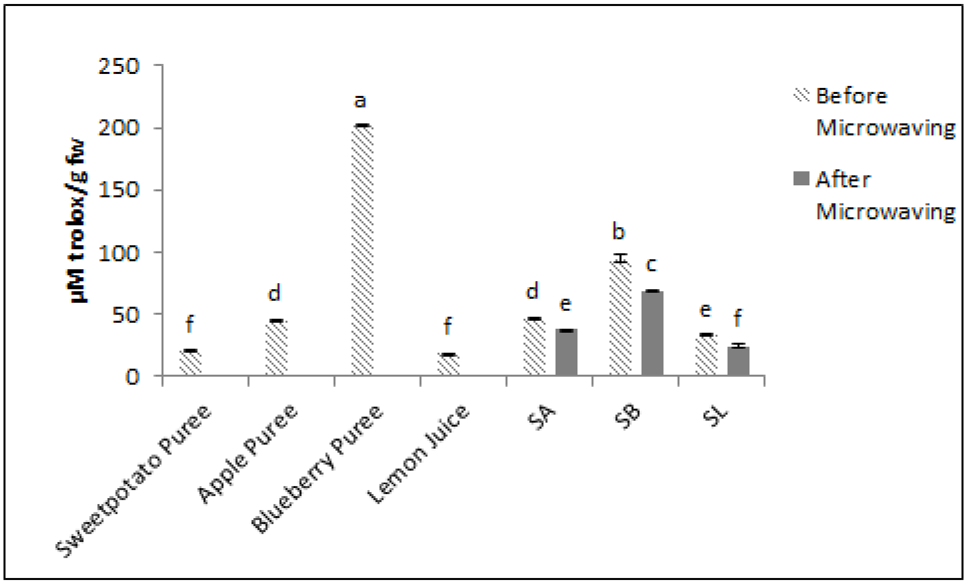

Figure 4.6: Antioxidant Activity in the ingredients and sweetpotato-fruit mixed purees

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.

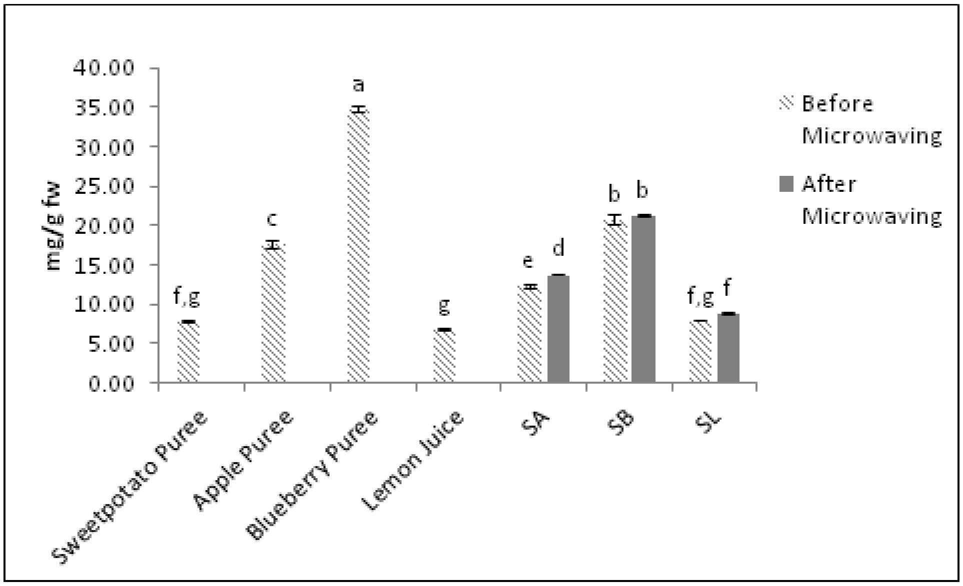

Figure 4.7: Total Phenolic Content in the ingredients and sweetpotato-fruit mixed purees

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.

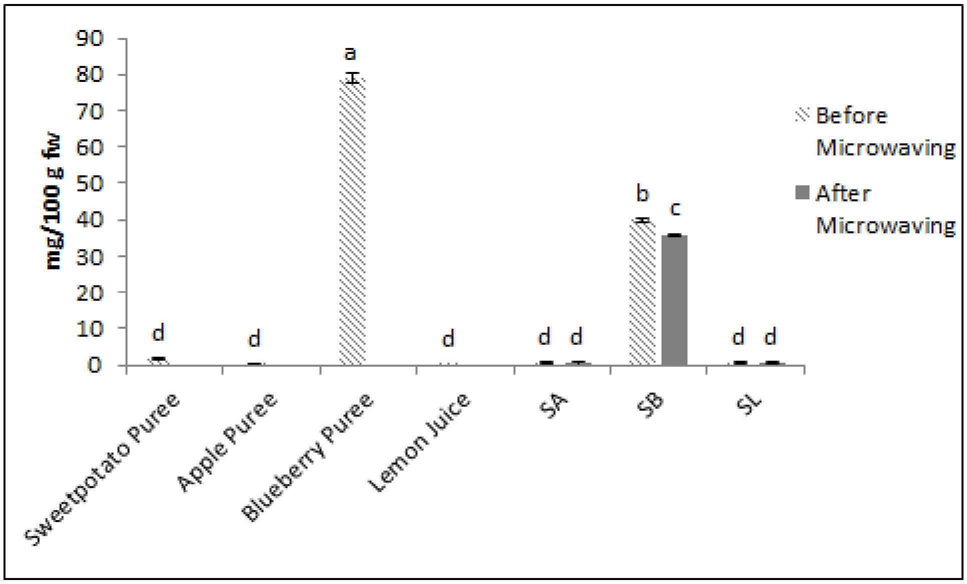

Figure 4.8: Total Monomeric Anthocyanin Content in the ingredients and sweetpotato-fruit mixed purees

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.

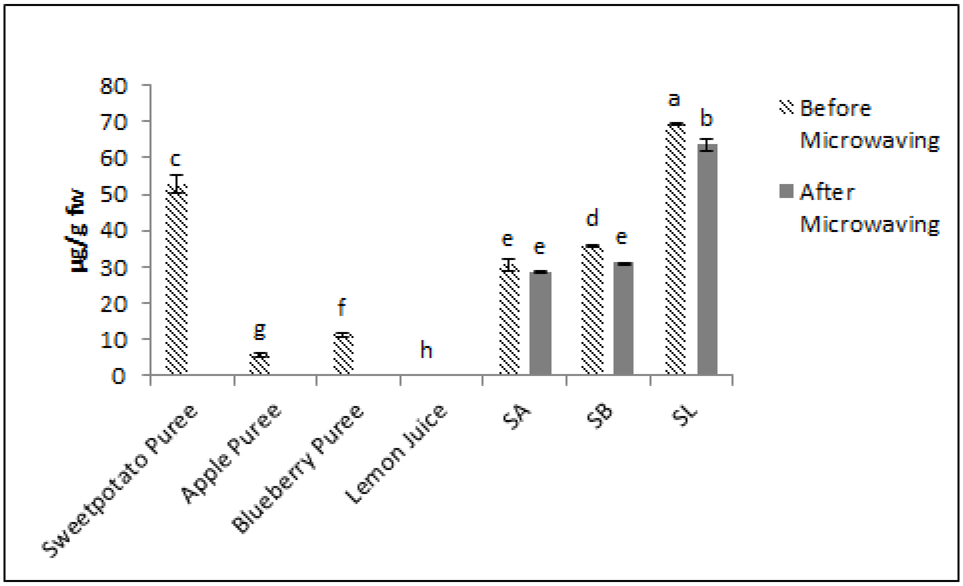

Figure 4.9: Beta-carotene content in the ingredient and sweetpotato-fruit mixed purees

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.

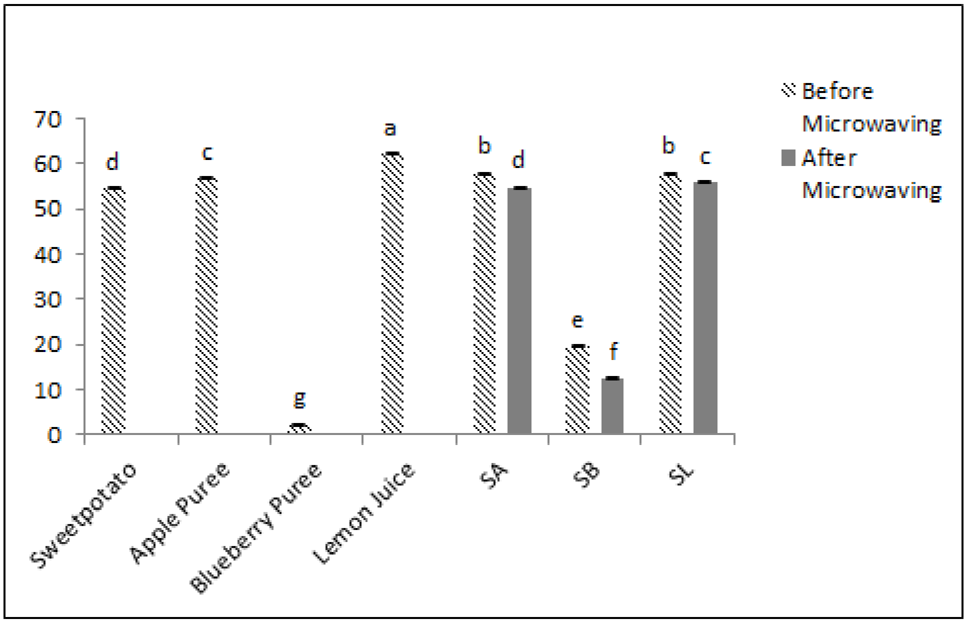

Figure 4.10: L* Value

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.

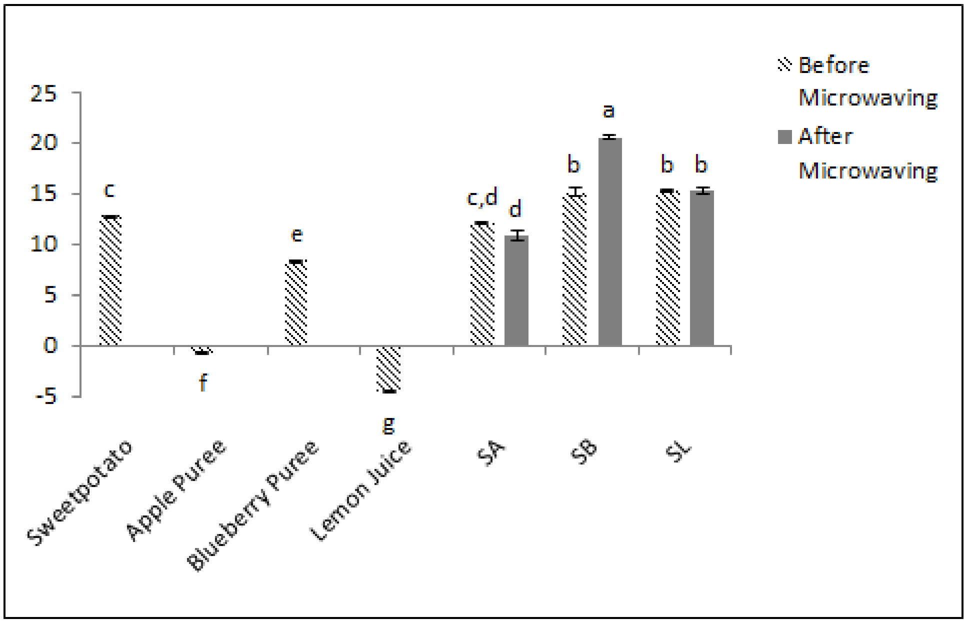

Figure 4.11: a* Value

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.

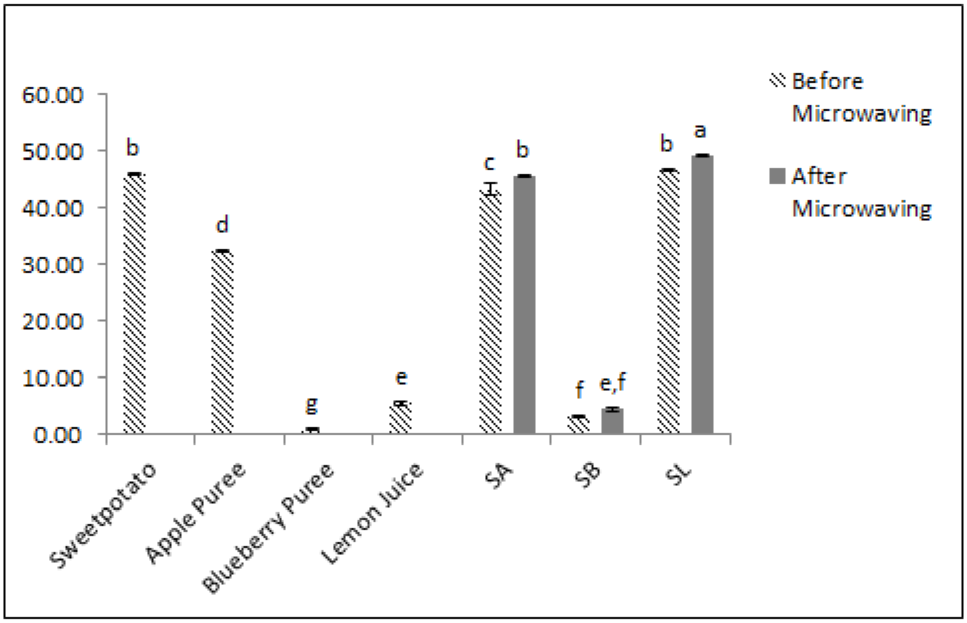

Figure 4.12: b* Value

SA: mixture of sweetpotato puree, apple puree, and lemon juice
SB: mixture of sweetpotato puree, blueberry puree, and lemon juice
SL: mixture of sweetpotato puree and lemon juice
'Before Microwaving' represents measurements taken before samples were processed using the modular microwave system. 'After Microwaving' represents measurements taken after samples were processed using the modular microwave system.

Different letters above bars indicate a significant difference at $p<0.05$.

Error bars represent standard error of the mean.