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DIELECTRIC PROPERTIES OF SWEET POTATO PUREES AT 915 MHZ AS AFFECTED BY TEMPERATURE AND CHEMICAL COMPOSITION

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A process for rapid sterilization and aseptic packaging of sweet potato puree using a continuous flow microwave system operating at 915 MHz has been successfully developed. In microwave processing, dielectric properties have a major role in determining the interaction between purees and the electromagnetic energy. The objective of this research was to determine how dielectric properties are affected by temperature and chemical composition of purees derived from thirteen sweet potato cultivars with varying flesh colors. Results indicated that temperature, moisture, sugar and starch content had a pronounced effect ($p < 0.001$) on dielectric properties measured from 15°C to 145°C at 915 MHz. Dielectric constant decreased with increasing temperature, while dielectric loss factor increased quadratically. Power penetration depth of all cultivars decreased with increasing temperature. Predictive equations were developed for dielectric constant ($R^2 = 0.82$) and dielectric loss factor ($R^2 = 0.90$) as a function of temperature, moisture, sugar, and starch. The predictive equations would be useful in determining the dielectric properties of sweet potato purees for the microwave processing technology.

Keywords: ***Sweet potatoes, Purees, Nutritional constituents, Microwave heating, Dielectric properties, Predictive equations.***

INTRODUCTION

Sweet potatoes (*Ipomoea batatas*) are a highly nutritious vegetable containing high energy, dietary fiber, biologically active phytochemicals, vitamins, and minerals which offer great benefit for use as a functional food ingredient. A process has been recently

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developed for converting sweet potato roots into high-quality puree wherein the material can be rapidly sterilized in a continuous flow microwave system operating at 915 MHZ, and aseptically packaged into flexible containers.[1] The developed technology provides an alternative method to convert sweet potatoes into a shelf-stable ingredient which would be readily available for the food processing industry and eventually result in increased consumption of this nutritious vegetable.

The degree of heating of a food material subjected to microwave processing is strongly influenced by the dielectric properties of the food. This is because dielectric properties play a major role in determining the interaction between the food material being processed and the electromagnetic energy.[2] The dielectric properties that are important in estimating power absorption and penetration depth (D_p) during microwave processing are dielectric constant (ε') and dielectric loss factor (ε''). D_p is needed in the determination of the temperature distribution within a food heated by microwave energy. Microwave frequency, temperature, and chemical constituents such as moisture, salt, and ash contents have significant effects on ε', ε'' and D_p of food materials.[2]

Several attempts have been made to model dielectric properties as a function of processing variables and chemical composition. These attempts include modeling a single food item, as well as a combined data of a wide range of food commodities.[3,4,5,6,7] Sun and others[5] compiled the literature data on dielectric properties, moisture, and ash contents of fruits, vegetables, fish, and meats to develop predictive equations. They concluded that it was difficult to develop a generic composition-based equation for dielectric properties for all food products. Therefore, it is necessary to develop the equations for a specific product or a group of products. Calay and others.[3] grouped food materials into grains, meats, vegetables, fruits, and developed the predictive equations for dielectric properties based on moisture, salt, fat, and temperature with coefficients of determination (R^2) between 0.70 to 0.82. Sipahioglu and Barringer[6] developed predictive models describing the dielectric properties at 2450 MHz as a function of temperature (5–130°C), ash, and moisture content of a variety of 5 fruits and 10 vegetables. The dielectric properties of some vegetables such as yam, white potato, and spinach did not fit within the developed equations. The problem was attributed to the transition in the physical properties of the carbohydrate components in these vegetables during heating. Guan and others[4] developed the equations for dielectric properties of mashed white potatoes with a range of moisture and salt contents subjected to pasteurization and sterilization by radio-frequency and microwave processes (1–1800 MHZ and 20–120°C). However, the major constituents in starchy vegetables such as starch and sugars content were not considered in the developed regression equations.

Dielectric properties of Beauregard sweet potato puree as affected by microwave frequency (900–2500 MHz) and temperature within a limited range of 5 to 80°C were reported by Fasina and others.[8] Both temperature and frequency had significant effects on the dielectric properties of the sweet potato puree evaluated. However, dielectric properties for various sweet potato cultivars with a large variation in chemical composition at temperatures above 100°C have not been studied. The variation in chemical composition of the purees by different cultivars, growing conditions and post-harvest handling of raw materials may affect the microwave heating behavior of the purees. In microwave-assisted aseptic processing, temperatures above 120°C are required for sterilization. Ohlsson and Bengston[9] measured the dielectric properties of commercially processed foods at a temperature range of 40–140°C at different frequencies. They observed that the dielectric data could not be extrapolated from low temperatures to sterilization temperatures. Previous studies have also indicated that matching the dielectric properties of the material with the required microwave energy for adequate thermal treatment is very important to avoid over- or under- heating in aseptic processing of sweet potato puree.[1]

The objective of this research was to determine the effects of temperature (15 to 145°C) and chemical components on the dielectric properties of purees derived from sweet potato cultivars with varying flesh colors. The study covers the typical conditions utilized in aseptic processing of vegetable purees using a continuous microwave heating system.[1]

MATERIALS AND METHODS

Sample Preparation

Thirteen sweet potato cultivars grown at two experimental stations of the Horticultural Science Department at NC State University were used in this study. The harvested roots were cured at 30°C, 80 to 90% relative humidity for 7 days, and stored at 13 to16°C, 80–90% relative humidity for 3 months. Roots were hand-peeled and cut into 1 cm thick slices. One kilogram of sweet potato slices were steamed in a vegetable steamer for 1 hr. The steamed samples were cooled to room temperature in a closed container to prevent moisture loss. Pureeing of the steamed samples was accomplished using a food processor, and the puree was packaged in glass jars for frozen storage at –20°C. The visual flesh color of the sweet potato cultivars and the color characteristics of the puree samples are shown in Table 1. The color values (L*, a*, b*) of the purees were measured with a Hunter colorimeter (Model DP9000 Hunter, Associated Laboratory Inc., Reston, VA) as described by Coronel and others.[1]

Table 1 Flesh color of the sweet potato cultivars and hunter color values of the Purees.

		Puree color values		
Cultivar	Flesh color	L*	a*	b*
Beauregard	Orange	52.1^{b}	$17.4^{a\,b\,c}$	59.7^{a}
Bon 99–447	Cream	$59.2^{a\,b}$	-4.3^{d}	23.8^{d}
Covington	Orange	52.9^{b}	$18.0^{a\,b\,c}$	61.2^{a}
FTA 94	White	70.1^{a}	-4.8^{d}	21.6^{d}
Hernandez	Orange	51.0^{b}	24.3^{a}	61.6^{a}
NC 415	Purple	16.2^{d}	$19.4^{a\,b}$	-8.1^{d}
Norton	Yellow	$63.7^{a\,b}$	-3.3^{d}	$47.6^{b\,c}$
O'Henry	Yellow	$63.5^{a\,b}$	-5.6^{d}	39.2^{c}
Okinawa	Purple	$28.6^{c\,d}$	11.7^{c}	-11.8^{d}
Picadito	White	$57.2^{a\,b}$	-1.1^{d}	13.2^{d}
Porto Rico	Orange	54.8^{b}	$12.3^{b\,c}$	$56.9^{a\,b}$
Pur 01–192	Purple	31.3^{c}	$16.0^{b\,c}$	-3.7^{d}
Suwon 122	Yellow	$55.3^{a\,b}$	-5.3^{d}	39.7^{c}

Different letters within columns indicate a significant difference at $p < 0.05$. L* (lightness, 0 for back, 100 for white), a* (-a* = greenness, + a* = redness), b* (-b* = blue, + b* = yellowness).

Dielectric Properties

An open-ended coaxial probe (HP 85070B, Agilent Technologies, Palo Alto, CA) and an automated network analyzer (HP 8753C, Agilent Technologies, Palo Alto, CA) were used to determine the dielectric properties of sweet potato purees. The calibration of the system was performed with short block, air, and water as described in the instruction manual of the Agilent Technologies (1998). The sample was filled in a container which as heated in an oil bath (Model RTE111, Neslab Instruments Inc, Newington, NH). The dielectric properties (ε'' and ε') were measured from 15°C to 145°C at 5°C intervals at 915 MHz. Three repetitive measurements were performed at each temperature for each duplicate sample of the purees.

Power Penetration Depth

The power penetration depth is the depth within a product where the power is reduced to 1/e (Euler number e = 2.718) or 37% of the power at the surface of the food material. The power penetration depth is calculated by Eq. (1):

$$D_P = \frac{c}{2\Pi f\sqrt{2\varepsilon_r^{'}[1+\sqrt{\tan\delta^2}-1]}} \tag{1}$$

where f = 915 MHz, $c = 3.0 \times 10^8$ m/s and loss tangent $\delta = \varepsilon''/\varepsilon'$.[10,11]

Moisture Content

Moisture content was determined by drying 5 g of the puree sample in a convection oven for 6 hours at 70°C followed by 18 hours at 105°C.[12] Measurements were performed in triplicates for all puree samples.

Sugar and Starch

Sweet potato puree samples (15 g) were tissumized with 30 ml of 95% ethanol using a Tekmar Tissumizer (SDT-1810, Tekmar Company, Cincinnati, OH) for 1 minute, and centrifuged for 10 minutes at 5,000 rpm. The extraction was repeated 2 more times, the sugar extracts were combined in a 100 ml volumetric flask, filled to volume with ethanol, and stored frozen at –20°C. The alcohol insoluble solids (AIS) residue was collected and dried at 100°C for 24 hours in a convection oven to be used in determination of starch content.

A 2 ml aliquot of sugar extract was transferred into a 10 ml beaker and the ethanol was allowed to evaporate off overnight. The residue was dissolved with 1 ml of internal standards (cellobiose solution) and diluted with deionized water for analysis by high performance liquid chromatography (HPLC) using a Dionex BioLC AD 50 HPLC system (Dionex Co., Sunnyvale, CA). Ten microliters of the sample was injected and eluted through a Carbo PAC PA-1 column (250 × 4.6 mm id) (Dionex Corporation, Sunnyvale, CA) at 30°C with the mobile phase consisting of 200 mM sodium hydroxide at an isocratic flow rate of 1.0 ml/minute. A Dionex PAD (pulse amperometric detector) was utilized to detect the peak and identified sugars based on the retention time. The sugar content was determined by the peak heights of sucrose, glucose, fructose, and maltose, which were compared to the standard solution of cellobiose.[13] The total sugar content was obtained by summation of the individual sugars from each chromatogram.

Starch content was determined according to AOAC Method 996.11 with an assay kit (Megazyme International Ltd, Bray, Co. Wicklow, Ireland).[14] The AIS milled residue (100 mg) was first washed with 0.2 ml of 80% ethanol. The residue was then dissolved in 2 ml of dimethyl sulfoxide and incubated at 100°C to account for any resistant starch. Thermostable alpha amylase (3 ml) was added to the tube and incubated at 100°C for 5 mins to partially hydrolyze and solubilize the starch. Subsequently, the samples were treated with amyloglucosidase and incubated for 30 minutes at 50°C to hydrolyze the starch dextrins to glucose. The entire content of the tubes was then transferred to 100 ml volumetric flasks followed by filling to volume with distilled water, and an aliquot was taken for centrifuge at 3000 rpm for 10 minutes. The supernatant was then transferred to a glass test tube and mixed with a glucose determination reagent and incubated at 50°C for 20 mins. A spectrophotometer (Cary 300 UV-Visible Spectrophotometer, Varian Inc., Palo Alto, CA) was used to determine the absorbance of the solution at 510 nm against a reagent blank. Calculation of starch content was based on the absorbance of the sample with reference to a glucose standard.

Lipids

Lipid content was determined on freeze-dried puree samples (5 g) by a pulsed proton NMR using a Maran pulsed NMR (Resonance Instruments, Witney, Oxfordshire, UK) by the Field Induction Decay-Spin Echo procedure.[15] Lipid and moisture content were measured and percent of lipid based on dry weight was determined by correcting for moisture content. Measurements were performed in triplicate for all puree samples.

Protein, Minerals, and Ash

Protein, ash, and mineral contents of the sweet potato purees were determined by the Department of Soil Science Analytical Services Lab at NC State. Protein content determination was completed using the Kjeldahl analysis with a protein factor of 6.25 according to the AOAC Method 991.20.1. Ash content was determined by AOAC Method 925.51A.[14] The minerals; phosphorous, calcium, magnesium, potassium, iron, and sodium content were analyzed following the procedure described by Walter and others.[16] The freeze-dried puree samples underwent dry combustion and dissolution of the residue in acid. The mineral digest was then analyzed on a Perkin Elmer Ion Coupled Plasma (ICP) Spectrometer (Perkin Elmer Corp, Norwalk, CT). Duplicate measurements were performed on each puree sample.

Statistical Analysis

The SAS software (SAS Release 8.02, Cary, NC) was used to perform regression analysis and develop the predictive equations. The response variables, dielectric constant and dielectric loss factor, were fitted using Mallows C(p) to select initial models prior to performing the multiple linear regressions.[16] The selected models from Mallows C(p) were then used to perform a multiple regression with a mix model (fixed and random effects). The fixed effects were temperature, moisture, sugar, fat, protein, and, ash with all experimental data being of interest, and cultivar was the random effect with a sample of 13 cultivars selected from larger population of sweet potato cultivars. The equations and all predictors included in the equations had a significance of $p < 0.001$ and the quality of fit was determined based on the adjusted R^2. Testing simultaneous hypotheses was completed to compare the reduced model and the full model to ensure significance ($p < 0.05$) for the additional predictors based on the F value. Multiple pair-wise comparisons were completed with the Tukey test at 5% probability level for determining whether the means are significantly different for the chemical composition data.[17]

RESULTS AND DISCUSSION

Chemical Composition

As indicated in Table 1, the sweet potato purees derived from the 13 cultivars had a wide range of the chemical components analyzed: moisture, 65.6% to 80.5%, starch, 2.3% to 12.5%, total sugars, 3.8 % to 14.5%, proteins, 0.9% to 1.7%, and lipids, 0.09% to 0.16%. Significant differences ($p < 0.05$) were observed among the cultivars with regard to the contents of these components. These results were within the ranges reported in the literature for various sweet potato genotypes.[18,19] Similar to other starchy vegetables, sweet potatoes have low protein and lipid content. For moisture content, Collins and Walter[20] reported a range of 60% to 84% (16% to 40% dry matter) for raw roots of various sweet potato cultivars at harvest which is similar to the values we obtained. Of the dry matters, starch was the major constituent in raw sweet potatoes.

During steam cooking in the pureeing process, starch granules were gelatinized and hydrolyzed into maltose and dextrins by the amylolytic enzymes naturally present in sweet potatoes. Walter and others[21] reported that approximately 52–82% of starch in Jewel sweet potatoes was hydrolyzed, depending on the heat treatment. With these levels of starch hydrolysis, the sugar content (sucrose, glucose, fructose, and maltose) and the remaining starch in the purees were in the range of 8.2–11.7% and 1.7–4.5%, respectively. In general, the cooking process affects the carbohydrate composition of the purees by decreasing the starch fraction and increasing the sugar content.[22–24] The starch and sugar contents in the sweet potato purees shown in Table 1 were comparable with the values reported by Walter and others[21] for orange-fleshed sweet potatoes and by Chattopadhyay and others[25] for cultivars with other flesh colors. Maltose was the predominant sugar in the purees from all the cultivars (Table 2) followed by sucrose, glucose, and fructose. The results are in accordance with the values of the cooked roots of several Filipino and American sweet potato cultivars,[26] and the world-wide collected clones from the U.S. Department of Agriculture National Plant Germplasm System Collection.[27]

Ash content has been used as a good indicator of total salts within food materials.[2] The ash contents of the purees from the evaluated cultivars were 0.69–1.05% (Table 2). Statistical analysis indicated that the differences among the cultivars were not significant ($p > 0.05$). Low concentrations of these components have been reported for various sweet potato cultivars.[19] The mineral composition in the sweet potato purees are shown in Table 4. Sweet potatoes are known to be a relatively good source of potassium, phosphorus, magnesium, and calcium.[22]

Dielectric Constant

The dielectric constants of sweet potato purees from Covington, Bon 99, and Suwon 122 decreased with increasing temperature (Fig. 1). The purees from other

Table 2 Chemical composition (% wet weight basis) of sweet potato purees.

Cultivar	Moisture	Starch	Total Sugar	Protein	Lipid	Ash
Beauregard	80.5^{a}	2.3^{c}	$14.5^{a,b}$	$0.97^{d,e}$	0.09^{d}	0.69^{a}
Bon 99-447	$75.3^{a,b,c}$	$10.6^{a,b}$	10.6^{b}	$0.92^{d,e}$	$0.11^{b,c,d}$	0.97^{a}
Covington	80.7^{a}	1.9^{c}	$12.4^{a,b}$	$1.11^{c,d}$	$0.10^{d,c}$	0.84^{a}
FTA 94	$66.9^{c,d}$	$10.2^{a,b}$	5.4^{c}	1.68^{a}	$0.16^{a,b}$	1.05^{a}
Hernandez	$76.7^{a,b}$	3.83^{c}	15.4^{a}	$1.27^{b,c}$	$0.11^{b,c,d}$	1.00^{a}
NC 415	$70.0^{b,c,d}$	$12.0^{a,b}$	$13.8^{a,b}$	1.40^{b}	$0.13^{a,b,c,d}$	0.88^{a}
Norton	$74.1^{a,b,c,d}$	$6.6^{b,c}$	$12.7^{a,b}$	$1.00^{d,e}$	$0.12^{b,c,d}$	0.84^{a}
O'Henry	79.4^{a}	2.7^{c}	$12.9^{a,b}$	$1.03^{d,e}$	$0.10^{d,c}$	0.81^{a}
Okinawa	$68.0^{b,c,d}$	3.2^{c}	5.8^{c}	$1.47^{a,b}$	$0.14^{a,b,c,d}$	0.92^{a}
Picadito	$68.7^{b,c,d}$	12.5^{a}	6.2^{c}	0.86^{e}	$0.15^{a,b}$	0.85^{a}
Porto Rico	$73.1^{a,b,c,d}$	2.8^{c}	$14.5^{a,b}$	$1.28^{b,c}$	$0.13^{a,b,c,d}$	0.82^{a}
Pur 01-192	$67.5^{c,d}$	13.2^{a}	5.3^{c}	$1.07^{c,d,e}$	$0.16^{a,b}$	0.96^{a}
Suwon 122	65.6^{d}	$11.3^{a,b}$	5.5^{c}	1.61^{a}	$0.16^{a,b}$	1.00^{a}

Different letters within columns indicate a significant difference at $p < 0.05$.

Table 3 Sugar content (% wet weight basis) of the sweet potato purees.

Cultivar	Glucose	Fructose	Sucrose	Maltose
Beauregard	$2.2^{a,b}$	$1.8^{a,b}$	$3.3^{a,b}$	$7.2^{b,c}$
Bon 99–447	$0.7^{d,e,f}$	$0.5^{b,c,d,e}$	$2.2^{b,c}$	$7.2^{b,c}$
Covington	$1.5^{b,c}$	$1.1^{a,b,c,d,e}$	3.7^{a}	6.1^{c}
FTA 94	0.3^{f}	0.2^{e}	1.1^{c}	3.8^{d}
Hernandez	2.8^{a}	2.3^{a}	$3.0^{a,b}$	$7.4^{a,b,c}$
NC 415	$1.6^{b,c}$	$1.2^{a,b,c,d,e}$	1.7^{c}	9.3^{a}
Norton	$1.5^{b,c,d}$	$1.8^{a,b,c}$	$2.3^{b,c}$	$7.3^{b,c}$
O'Henry	$1.9^{b,c}$	$1.7^{a,b,c,d}$	1.7^{c}	$7.6^{a,b,c}$
Okinawa	0.5^{f}	$0.3^{c,d,e}$	1.3^{c}	3.7^{d}
Picadito	$0.6^{e,f}$	$0.4^{b,c,d,e}$	1.14^{c}	4.1^{d}
Porto Rico	$1.3^{c,d,e}$	$1.1^{a,b,c,d,e}$	$3.3^{a,b}$	$8.8^{a,b}$
Pur 01–192	0.3^{f}	$0.2^{d,e}$	1.1^{c}	3.6^{d}
Suwon 122	0.2^{f}	0.1^{e}	1.3^{c}	3.9^{d}

Different letters within columns indicate a significant difference at $p < 0.05$.

cultivars exhibited a similar trend (data not shown). The samples presented in Fig. 1 covered the highest (80%) and lowest (65%) moisture contents in the purees of the cultivars included in this study. In general, the higher the moisture content, the higher the dielectric constants. These results are in accordance with previous reports on the effects of temperature and moisture on the dielectric constant of various food materials.[4,6,5,28] It has been known that increase in temperature causes a decrease in dielectric relaxation time which results in lower dielectric constant.[29] The relaxation time decreases as temperature increases because it is associated with the time for the dipoles to revert to random orientation when the electric field is removed. As in other fruits and vegetables, most of the water in sweet potato purees exists as free water. Therefore it was anticipated that the dielectric constant would increase with increasing moisture content, especially when the moisture level was higher than 35%.[29] Water is a strong polar molecule and tends to reorient with the changes in electromagnetic polarity, resulting in elevation of dielectric constant.

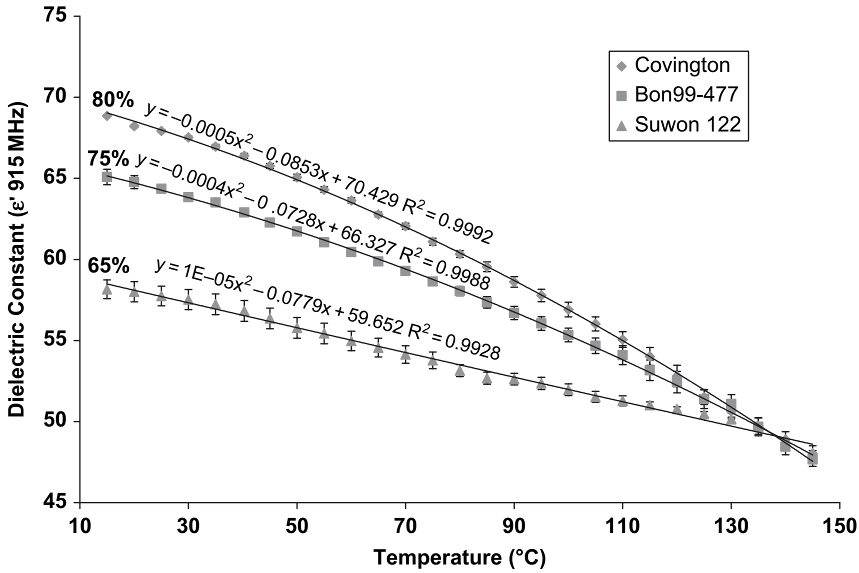

Figure 1 The effect of moisture and temperature on the dielectric constant of sweet potato purees (Bars indicate standard errors).

Table 4 Mineral content (mg/100g wet weight basis) of sweet potato purees.

Cultivar	P	K	Ca	Mg	Fe	Na
Beauregard	25.3^{g}	276.3^{d}	$14.1^{c,d}$	15.6^{e}	1.3^{a}	45.3^{a}
Bon 99–447	$47.2^{c,d}$	$374.0^{a,b,c}$	$21.7^{a,b,c}$	$24.5^{c,d}$	0.7^{a}	$19.8^{a,b}$
Covington	32.5^{f}	$337.9^{a,b,c}$	$23.7^{a,b}$	$24.7^{c,d}$	1.8^{a}	$30.5^{a,b}$
FTA 94	$59.1^{a,b}$	396.0^{a}	$22.2^{a,b,c}$	$32.0^{a,b}$	1.1^{a}	$16.7^{a,b}$
Hernandez	$41.0^{d,e}$	$353.2^{a,b,c}$	27.9^{a}	$28.6^{b,c}$	0.9^{a}	$32.5^{a,b}$
NC 415	$53.1^{b,c}$	$321.0^{b,c,d}$	26.8^{a}	$26.9^{b,c}$	1.6^{a}	10.9^{b}
Norton	$37.7^{e,f}$	$317.4^{c,d}$	12.3^{d}	17.1^{e}	0.9^{a}	$20.3^{a,b}$
O'Henry	$30.9^{f,g}$	$336.2^{a,b,c}$	$15.9^{b,c,d}$	16.9^{e}	0.9^{a}	$17.4^{a,b}$
Okinawa	63.3^{a}	$358.1^{a,b,c}$	$22.6^{a,b,c}$	35.3^{a}	1.1^{a}	$21.6^{a,b}$
Picadito	45.5^{d}	$323.3^{b,c,d}$	$16.6^{b,c,d}$	17.3^{e}	1.1^{a}	$16.7^{a,b}$
Porto Rico	$37.8^{e,f}$	$314.5^{c,d}$	$15.3^{b,c,d}$	$18.3^{d,e}$	1.0^{a}	$26.1^{a,b}$
Pur 01–192	$47.2^{c,d}$	$355.8^{a,b,c}$	$21.1^{a,b,c,d}$	$24.6^{c,d}$	0.9^{a}	$28.7^{a,b}$
Suwon 122	$46.7^{d,c}$	$381.6^{a,b}$	12.1^{d}	$28.3^{b,c}$	1.0^{a}	11.5^{b}

Different letters within columns indicate a significant difference at $p < 0.05$.

The dielectric constant values for the purees from the orange-fleshed cultivars, Beauregard, Covington, and Hernandez were 69.7, 68.9, and 68.1 at 15°C and gradually decreased to 49.4, 48.0, and 48.6 at 145°C, respectively. These results were comparable to the dielectric constant values at the corresponding temperature reported for the Beauregard sweet potato purees by Coronel and others, and Fasina and others.[1,8] For the purees from the cultivars with cream, white, yellow, and purple flesh color with moisture content less than 70% such as FTA 94, Okinawa, Suwon 122 and NC 415, the dielectric constant values were 56.6, 55.2, 59.6, and 56.3 at 15°C and 47.6, 46.93, 47.4, and 47.6 at 145°C, respectively. In comparison with the dielectric constant of other food materials, the results for sweet potato purees in this study were within the ranges reported for other common fruits and vegetables.[4,6,30]

The predictive model describing dielectric constant as a function of temperature and moisture content in sweet potato purees is as follows:

$$\varepsilon' = 64.5876 + 0.0056M - 0.2223T - 0.0046MT, \tag{2}$$

where M = Moisture (%) and T = Temperature (°C).

Both moisture and temperature had a significant effect ($p < 0.001$) on the dielectric constant. However, the regression equation had a R^2 value of only 0.76, indicating that other components within the material possibly affected the dielectric constant within the predictive equation. For starchy vegetables such as sweet potatoes, it is imperative to examine the contribution of sugar and starch contents in the dielectric constant model. The information on this aspect is limited in the literature.

The predictive model describing the dielectric constant as a function of temperature, moisture, sugar, and starch of sweet potato purees is shown in Eq. 3. This model had a R^2 value of 0.82 and sugars and starch did have significant effects on the model for the dielectric constants. In addition, a test statement (proc command) comparing the initial and final models had a high F value, indicating that the additional variables were significant ($p < 0.001$).

$$\varepsilon' = 27.9421 + 0.7218M + 0.2223T + 6.0604St - 1.1375Su - 0.0046MT - 0.0941MSt, \tag{3}$$

where M = Moisture (%); T = Temperature (°C); St = Starch (%); and Su = Sugar (%).

The average percent error of the predicted values of dielectric constant was 9.96%. The best model fit was for the Covington puree (4.21%). The largest outlier for the model was the Okinawa sample (16.70%). The outliners were the low moisture samples at the low temperature range. As the temperature increased, the fit improved for the purees. Similar results were reported by Sipahioglu and Barringer.[6]

Starch, and starch-moisture interaction significantly affected the dielectric constant ($p < 0.001$). The dielectric constant was negatively affected by the interaction between moisture and starch (Eq. 3). Starch binds water molecules through hydrogen bonding and therefore, increasing the starch concentration decreases the dielectric constant of starch solutions.[31] Similar results were reported by Bircan and Barringer for starch solutions.[32] Mao and others[33] reported that potato starch and corn starch had no effect on the dielectric constant of surimi. However, our results for starch had a positive effect in the dielectric constant model, which is not in accordance with the previous studies. Roebuck and others[34] observed that gelatinized starch binds less water to its structure, and therefore the solutions containing gelatinized starch has higher dielectric constant than native starch suspensions. The starch in sweet potato purees were gelatinized during the pureeing process. Cultivars with higher starch content would affect the volume fraction of free water, viscosity, and density of the purees. Further studies are required to elucidate the effects of these parameters on dielectric constant of starchy materials.

The sugar content of the purees has a negative effect on the dielectric constant (Eq. 3). A similar trend was seen for glucose solutions at 2450 MHz and sucrose solutions at 2450 MHz.[35,36] Sugar molecules which are relatively large, uncharged, and non-polar can inhibit orientation polarization by the electromagnetic energy.[3,36]

Ash content is a good indicator of the total salts found within the sweet potato puree. Previous studies indicated that an increase in ash content would decrease the dielectric constant. Ash binds the free water which restricts its ability to respond to the changing field polarity.[3,5,37] However, the ash content did not have a significant effect in the dielectric constant model ($p > 0.05$). This can be attributed to the non-significant difference among the ash content within the puree samples (Table 2).

Dielectric Loss Factor

The dielectric loss factor of the sweet potato purees from Covington, Bon 99, and Suwon 122 increased quadratically with temperature (Fig. 2). Similar trends were obtained for the purees from other cultivars (data not shown). Similar to dielectric constant, dielectric loss factor increases with moisture content. These results are in agreement with the previous reports on the effects of temperature and moisture on the dielectric loss factor of different food materials.[2,4,6] The increase in dielectric loss factor with increasing temperature is attributed to the reduction in viscosity of the puree resulting in increased mobility of ions and higher electrical conductivity.[38] The combination role of ionic conductivity and dipole rotation of free water within the food material contributed to the increase in dielectric loss factor.[39] At the microwave processing frequency of 915 MHz, dipole rotation decreases with temperature and ionic conductivity increases, thereby affecting the dielectric loss factor.[37,39]

The dielectric loss factor values for the purees from the orange-fleshed cultivars (Beauregard, Covington and Hernandez) were 14.5, 18.4, and 16.0 at 15°C and gradually increased to 41.5, 52.4, and 43.4 at 145°C, respectively. These dielectric loss factor values were comparable to the results reported by Coronel and others, and Fasina and others[1,8] for Beauregard sweet potato purees. For the purees from the cultivars with cream, white,

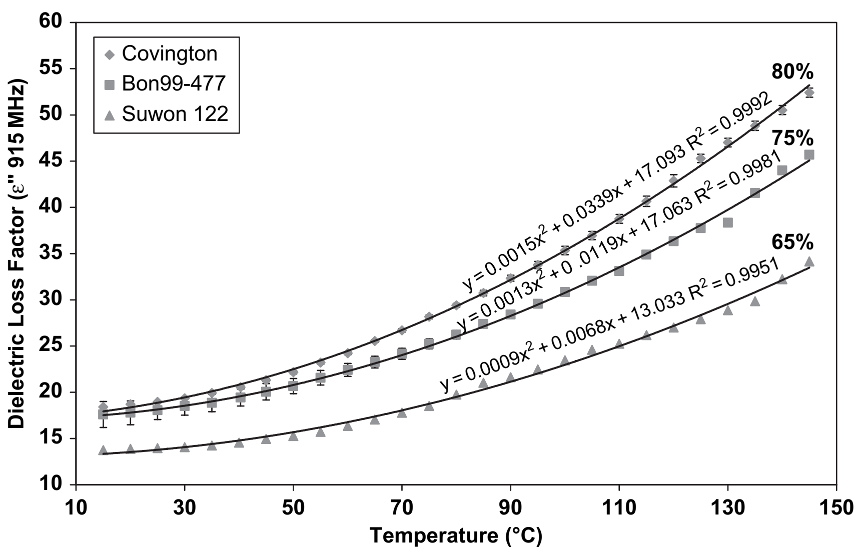

Figure 2 The effect of moisture and temperature on the dielectric loss factor of sweet potato purees (Bars indicate standard errors).

yellow, and purple flesh color with moisture content less than 70%, such as FTA 94, Okinawa, Suwon 122, and NC 415, the dielectric loss factor values were 15.4, 14.3, 16.1, and 13.5 at 15°C and 42.1, 37.5, 38.29, and 35.4 at 145°C. Dielectric loss factor of the sweet potato purees were comparable with the reported ranges for other fruits and vegetables.[4,6,30]

The dielectric loss factor as function of temperature and moisture content of sweet potato purees is shown in Eq. (4):

$$\varepsilon' = -8.2227 + 0.2360M + 0.2041T, \tag{4}$$

where M = Moisture (%) and T = Temperature (°C).

Moisture and temperature had a significant effect ($p < 0.001$) on the dielectric loss factor with a R^2 value of 0.85. However, other chemical components could possibly affect the dielectric loss factor within the predictive equation.

The predictive model shown in Eq. (5) describes the dielectric loss factor as a function of temperature, moisture, sugar, and starch content of sweet potato purees. Similar to dielectric constant, the ash content also did not have significant affect within the dielectric loss factor model. This model had a R^2 value of 0.90 and sugars and starch had significant effect ($p < 0.001$) on the dielectric loss factor model. As with the dielectric constant models, a test statement (proc command) comparing the initial and final models was performed with a high F value being obtained. This indicated that the additional predictors except for temperature (T) have a significant effect ($p < 0.001$) on the model. T^2 had a significant effect on dielectric loss factor based on the quadratic trend of the data over the temperature range shown in Figure 2.

$$\varepsilon'' = -20.7449 + 0.7553M + 0.0046T + 0.0012T^2 + 6.5518St - 0.9263Su - 0.1135MSt, \tag{5}$$

where M = Moisture (%); and T = Temperature (°C); St = Starch (%); and Su = Sugar (%).

The predicted values of dielectric loss factor had an average percent error of 16.03%. The best fit within the model was FTA 94 (1.95%). The largest outlier within the model was Okinawa (30.68%). The fit of the model improves with higher temperatures of which comparable findings were reported by Sipahioglu and Barringer.[6] Similar to the dielectric constant, the model fit was better at higher temperatures for dielectric loss factor than dielectric constant. Studies have shown that it is more difficult to predict dielectric loss factor.[3,5,6]

The starch, and starch- moisture interaction both significantly affected the dielectric loss factor ($p < 0.001$) as previously mentioned for dielectric constant. The negative effect the starch-moisture interaction on dielectric loss factor can be attributed to the binding or interaction of water molecules with starch which decreased water polarization.[31,32] However, the dielectric loss factor model also demonstrated starch to have a positive effect, which is not in agreement with these previous studies. Further studies are necessary to clarify the effects of higher starch in relations to volume fraction of free water, viscosity, and density of the purees on dielectric loss factor of starchy materials.

The sugar content of the purees had a negative effect on the dielectric loss factor, and similar findings were true for dielectric constant. This effect was attributed to the sugar molecules which form hydrogen bonding with the free water which decreasing the ability for polarization of water molecules.[3,36] Therefore, an increase in the sugar content of the purees decreases the dielectric loss factor. Similar findings were reported for glucose solutions at 2450 MHz and sucrose solutions at 2450 MHz.[35,36]

Power Penetration Depth

The microwave penetration depth at 915 MHz is valuable information to gain understanding of the effective depth of microwave power dissipation. This parameter characterizes and controls the temperature distribution in microwave processed food materials; it is the depth where power decreases to the point that any further penetration would result in negligible heating due to the weak waves. The penetration depth range was 15.7 to 22.2 mm at 70°C, 11.6 to 16.6 mm at 100°C and 8.60 to 13.2 mm at 130°C for microwave processing temperatures. The values for all cultivars are reduced by nearly half when the temperature is increased from 70 to 130°C.

The decreasing trend of the power penetration depth in relation to increasing temperature is shown in Fig. 3. Apparently, the purees with lower moisture content had a higher penetration depth. Similar results were reported for Beauregard sweet potato puree at 915 MHz by Fasina and others.[8] Guan and others also reported comparable values ranging from 11.1 to 14.4 mm at 100°C, for white mashed potatoes at 915 MHz.[4] Both studies reported a decrease in power penetration depth with increase in temperature.[4,8]

CONCLUSIONS

Temperature and variation in chemical composition among sweet potato cultivars particularly moisture, sugar and starch contents had pronounced effects on the predictive models for dielectric properties of the purees. Ash, protein and lipid contents had no effects on dielectric properties. Dielectric constant decreased with increasing temperature

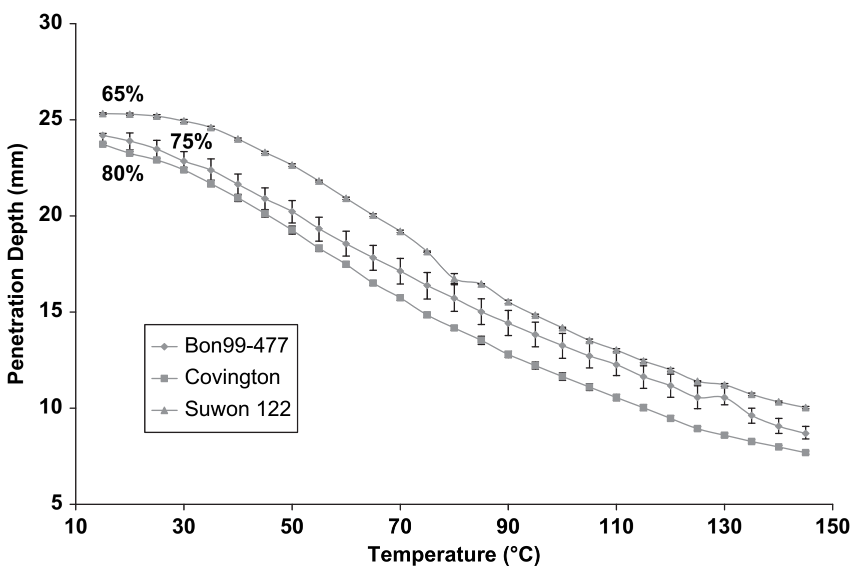

Figure 3 The effect of moisture and temperature on the penetration depth (bars indicate standard errors).

and dielectric loss factor increased quadratically. The dielectric loss factor was better predicted by the model than dielectric constant. Overall, the developed predictive equations can be utilized in determining the heating patterns of sweet potato puree for industrial microwave processing of sweet potato purees.

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NOMENCLATURE

a*	CIE Lab Color Redness to Greenness
b*	CIE Lab Color Yellowness to Blueness
f	Frequency (Hz)
f_{rel}	Relaxation Frequency (Hz)
g	Gram
L*	CIE Lab Color Lightness
mg	Milligrams
T	Temperature (°C)
t	Time (s)
V	Volume (m^3)

Greek Symbols

ε'	Dielectric Constant Relative to Vacuum
ε''	Loss Factor Relative to Vacuum
λ	Wavelength (m)

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