

Comparison Between Ohmic and Conventional Heating of Pineapple and Longan in Sucrose Solution

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ABSTRACT

Ohmic heating is an innovative thermal processing method in which an alternating electric current is directly released through food materials to generate heat. The temperature inside the food during ohmic heating can be raised rapidly and uniformly depending on the electrical conductivity of the food. In this research, the electrical conductivities of pineapple, longan and sucrose solution were measured. Furthermore, mixtures of fruit and sucrose solution at 12 °Brix were heated from 30 °C to about 90 °C by ohmic and conventional methods. The aims were to: 1) investigate the possibility of applying ohmic heating to the mixture of fruit and sucrose solution; and 2) to compare the quality of ohmically heated samples with that of conventionally heated counterparts using the same heating rate. The results indicated that the electrical conductivities of pineapple and longan were in the ranges 0.1–1.3 and 0.3–1.0 S.m⁻¹, respectively. Moreover, it appeared from the analysis of variance that there was no significant difference in the textural attributes between ohmically and conventionally heated samples whereas the color values were significantly different. In addition, a positive effect of ohmic heating on microbial reduction was found for the pineapple pieces with the numbers of mesophilic bacteria, molds and yeast in the ohmically treated samples being significantly lower than those of conventionally heated specimens. The energy consumption was comparable between the two techniques. The findings in this work confirmed that the ohmic method could be an interesting option for heating these products.

Keywords: electrical conductivity, longan, ohmic heating, pineapple

INTRODUCTION

Thailand is one of the countries that has abundant production of tropical fruits, especially of pineapple and longan (Chomchalow *et al.*, 2008). However, fresh fruits are perishable and have a limited shelf life so thermal processing is the most common method used to destroy microorganisms (Rodrigues and Fernandes, 2012). One of the most important thermally-processed products manufactured from pineapple and longan

is fruit pieces in sucrose solution (Food and Agriculture Organization of the United Nations, 1997). For the conventional heating method, the temperature of particulate food must rely on heat transfer mechanisms, especially heat conduction and convection which are usually limited due to the thermo-physical properties of food and fouling on the heat contact surface (Lalande *et al.*, 1985; Bansal and Chen, 2006). Furthermore, the conventional heating process generally requires a costly boiler to produce the heating medium; on the

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other hand, the ohmic heating system does not.

Ohmic heating is based on the passage of an alternating electrical current (AC) through the food product such as a liquid-particulate food system, which serves as an electrical resistance, in which heat is generated. The advantages of ohmic heating when compared to conventional heating include more uniform and faster heating, cleaner and more environmentally friendly production process and higher nutritional value retention in the food (Darvishi *et al.*, 2013).

Apart from the advantages of ohmic heating over conventional heating previously described, there have been publications indicating the positive effect of ohmic heating on microbial reduction in food compared with conventional heating. Cho *et al.* (1999) and Yildiz-Turp *et al.* (2013) stated that the fundamental microbial inactivation mechanism of ohmic heating is thermal; however, an additional mild electroporation process might contribute to the inactivation of the microorganism. Liu *et al.* (1997) claimed that the mechanism of electric current activity on microorganisms included the disruption of the bacterial membrane integrity or electrolysis of molecules on the cell surface. According to the experimental results of Moreno *et al.* (2012), it appeared that the application of ohmic heating treatment especially at electrical field strengths of 13 and 17 V.cm⁻¹, together with either osmotic dehydration or vacuum impregnation, could inhibit the growth of molds and yeasts and mesophiles more efficiently than by applying only either osmotic dehydration or a vacuum impregnation treatment alone. Furthermore, a similar effect of ohmic heating on the growth inhibition of microorganisms was found in the studies of Reznick (1996), Yoon *et al.* (2002), Pereira *et al.* (2007) and Sun *et al.* (2008).

Many factors affect the heating rate of foods undergoing ohmic heating such as the electrical conductivity and the particle size, shape and concentration (Kim *et al.*, 1996). Sastry and Palaniappan (1992) found that the rate of ohmic

heating is directly proportional to the electrical conductivity of the product and the square of the electric field strength.

There have been some studies on the electrical conductivity of juices and paste. Darvishi *et al.* (2012 and 2013) studied the effects of voltage gradients on the ohmic heating rates and pH changes of tomato paste and pomegranate juice. It was found that the electrical conductivity increased almost linearly with the temperature. However, it was observed that electrical conductivity decreased with a temperature rise after bubbling started. Furthermore, the results indicated that the heating time decreased greatly (approximately 78%) when the voltage gradient increased and the pH was decreased. Icier and Ilcali (2005) heated apricot and peach purees in a laboratory-scale static ohmic heater by applying voltage gradients in the range 20–70 V.cm⁻¹. The results showed that the electrical conductivity of fruit purees is strongly dependent on the temperature, ionic concentration and pulp content. The heating rate of the apricot puree was higher than for the peach puree at all applied voltage gradients.

The aims of the current research were: 1) to investigate the possibility of applying the ohmic method to mixtures of fruit and sucrose solution; and 2) to compare the quality of ohmically heated samples with that of their conventionally heated counterparts using the same heating rate.

MATERIALS AND METHODS

Raw material preparation

Sample preparation for measurement of electrical conductivities and pasteurization

The fruit samples consisted of the fresh pineapple “Sriracha” variety and the longan “Beawkeaw” variety which were bought from a local market. The fruits were washed and cut into rectangular cubes (approximately 2 × 2 × 1 cm) before putting them into a small ohmic cell to measure the electrical conductivity. The weight of the mixtures of fruit pieces and sucrose solution

at 12 °Brix were 600 and 400 g, respectively, for pasteurization in the large ohmic cell. There were two sets of ohmic heating devices applied in this work comprising the system for measuring the electrical conductivity and that for pasteurizing the samples as illustrated in Figures 1 and 2, respectively.

Sample preparation for measurement of microbiological quality

Fresh pineapple was stored at 10 ± 1 °C overnight prior to processing. All fruits were within the range 13.8 ± 0.3 °Brix and a pH of 3.8 ± 0.1 . Fruits were peeled with a stainless steel knife and cored using stainless steel cylinder cutter and

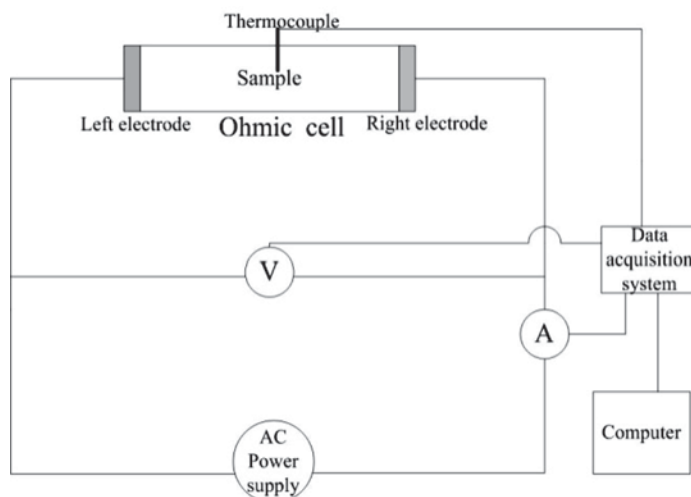


Figure 1 Schematic diagram of the system for electrical conductivity measurements using a small ohmic cell. AC = Alternating current; V = Applied voltage; A = Electric current.

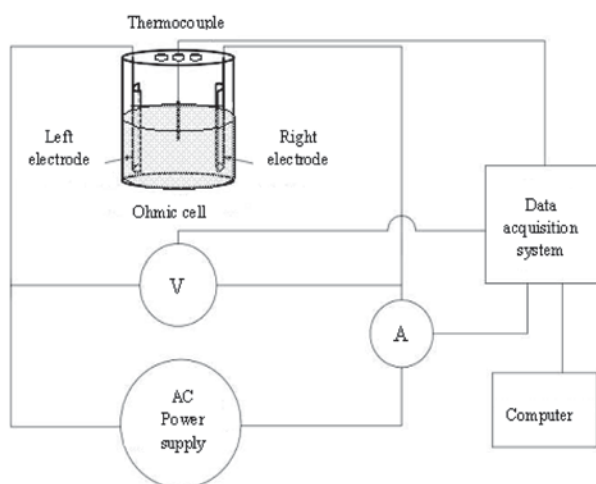


Figure 2 Schematic diagram of the system for ohmic heating experiments using a large ohmic cell. AC = Alternating current; V = Applied voltage; A = Electric current.

then cut into 1 cm thick slices and divided into six 10 g wedges per slice. A portion (150 g) of pineapple wedges was placed in a plastic zip lock pouch filled with 150 mL of packing solution. Polypropylene (PP) pouches (size 180 × 280 mm), 0.055 mm thick (Hungchor Supplier, Bangkok, Thailand) were used. The packing solution was 1% calcium chloride (Fisher Scientific; Dreieich, Germany) and 0.3% ascorbic acid (Sigma-Aldrich Chemie; Steinheim, Germany) solution (adapted from Martinez-Ferrer *et al.*, 2002).

Conventional heating method

The fresh pineapple and longan pieces in sucrose solution were heated from approximately 30 to 80 °C using conventional heating with a hot plate stirrer (model 210T; Fisher Scientific (M) Sdn Bhd; Shah Alam, Selangor, Malaysia). The sample temperature profiles during heating were controlled to be identical for both the conventional and ohmic methods by manually adjusting the applied electrical field strength for the ohmic heating system using the voltage variable transformer. The ohmically-heated and conventionally-heated specimens were subjected to color, pH and textural measurement.

Electrical conductivity measurement using a small ohmic cell

The fresh pineapple and longan were measured for their electrical conductivities using a static ohmic heating device that was built at the Department of Food Science and Technology, Kasetsart University, Bangkok, Thailand. A schematic diagram of the electrical circuit is shown in Figure 1. The cylindrical ohmic cell was made from acrylic pipe while the electrodes were stainless steel grade 316L. The diameter of electrodes was 0.0357 m. The distance between the electrodes was 0.014 m.

The electric field strength applied in this measurement was in the range 35–36 V.cm⁻¹. The sample temperature was measured using a type-T thermocouple located at the center of the ohmic

cell and recorded using a data logger (model DX 1012, Yokogawa Electric Corp.; Tokyo, Japan). The electrical voltage and current were measured using a digital multimeter (model 8808A, Fluke Corp.; Everett, WA, USA) and the electrical conductivity was determined using Equation 1:

$$\sigma = IL/AV \quad (1)$$

where σ is the electrical conductivity measured in siemens per meter, A is the cross sectional area of the electrode measured in square meters, I is the electrical current measured in amperes, L is the distance between the electrodes measured in meters and V is the applied voltage measured in volts.

The experiments were conducted in triplicate for each type of sample.

Pasteurization experiment using a large ohmic cell

Figure 2 shows the cylindrical ohmic cell that was made from glass with an inside diameter of 0.195 m. The curved rectangular electrodes were stainless steel grade 316L with width and height of 0.07 and 0.24 m, respectively. The distance between the centers of electrodes was 0.095 m. The electric field strength applied in the measurement was in the range 21–22 V.cm⁻¹. The large ohmic heating device was used to pasteurize the mixture of fruits and 12 °Brix-sucrose solutions. The sample temperatures were measured at the core position of a fruit piece and in the sucrose solution located near the center of the ohmic cell using type-T thermocouples and recorded using the data logger.

Ohmic heating experiment for measurement of microbiological quality

Initially, pineapple wedges packed in a PP pouch were put in a glass cylindrical container with a diameter of 200 mm and the container was filled with distilled water before heating using the conventional method with a hot plate. The heat was transferred from the heating medium (distilled water) to the packing solution until it reached 70

°C and then it was held for 60 s before cooling down to 10 °C in ice water. After the heating profile of the conventional method had been recorded, the ohmic method was conducted by controlling the temperature profile of the pineapple wedge sample to be similar to that of the conventional method by varying the electrical supply of the transformer. The indirect ohmic heating chamber and the pineapple packed in plastic pouch are depicted in Figure 3. The heating medium used for the ohmic method was 0.5% NaCl solution. Samples were stored at 4 °C until used for microbial growth examination.

Determination of color and pH

The color values of samples were determined using a colorimeter (Mini scan XE, (Hunter Lab; Reston, VA, USA) whereas the pH values were measured at 25 °C using a digital pH meter (Orion model 210A; Thermo Fischer Scientific; Waltham, MA, USA). Both color and pH were measured in triplicate.

Texture profile analysis (TPA)

The samples were determined for force, toughness and adhesiveness values using

the texture profile analysis (TPA) method with a texture analyzer (model TA.XT plus; Stable Micro Systems Ltd.; Goldaming, UK). During measurement, the cubic samples ($2 \times 2 \times 1$ cm) were compressed to 90% of their original height with a puncture probe with a diameter of 5 cm. Force time curves were recorded at a crosshead speed of 5 mm.s⁻¹. The TPA was conducted in triplicate.

Microbial growth examination

Enumerations of natural flora were made using standard techniques (Food and Drug Administration, 2007) that included aerobic plates and mold and yeast counts for conventionally and ohmically treated pineapple samples stored at 4 °C at 0, 5, 10 and 15 days of storage. Analyses were performed in duplicate. Media were obtained from HiMedia (Mumbai, India).

Energy consumption of ohmic and conventional heating

The energy consumption values for pineapple and longan pasteurization were estimated and compared between ohmically heated and conventionally heated counterparts using the same

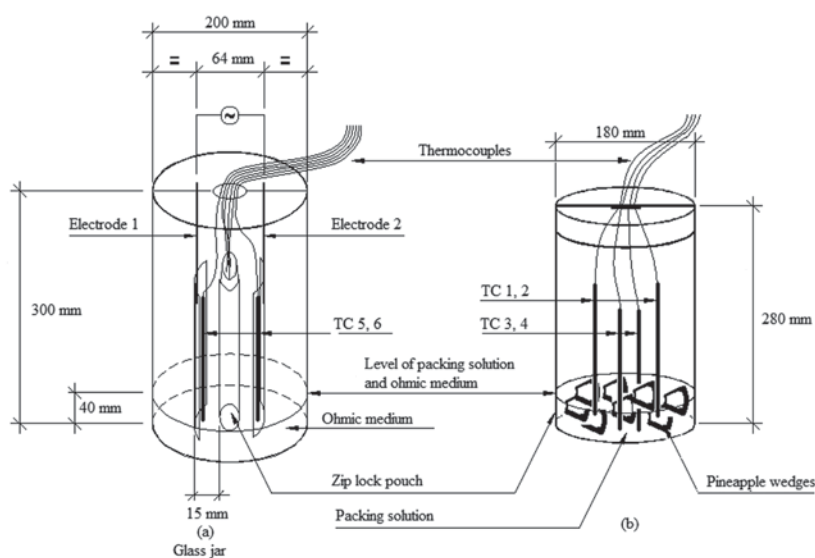


Figure 3 Ohmic heating apparatus for microbiological quality determination: (a) Indirect ohmic heating setup; (b) Pineapple packed in plastic pouch. TC = Thermocouple.

heating rate with the electrical current measured using a digital clamp tester (model 3282; Hioki E.E. Corporation; Nagano, Japan) according to Equation 2:

$$E = V \times I \times t \quad (2)$$

where E is the electrical energy consumption measured in joules, I is the electrical current measured in amperes, V is the applied voltage measured in volts and t is time measured in seconds.

Statistical analysis

The software package SPSS (version 16.0; SPSS Inc.; Chicago, IL, USA) was used for the analysis of variance and Duncan's multiple range test for statistical analysis.

RESULTS AND DISCUSSION

The electrical conductivities of fresh pineapple and longan (Figure 3) ranged between 0.1 and 0.55 and 0.4 to 1.00 S.m⁻¹, respectively. The higher electrical conductivities of longan were due to its higher mineral content than pineapple although the pH of longan is higher (Wall, 2006). The results showed that the electrical conductivities of samples increased when the temperature was raised. However, it was found that the electrical conductivities of fresh pineapple dropped after reaching a high temperature level at 80°C. This phenomenon could be explained by

the occurrence of bubbling (Icier and Ilicali, 2005 and Tumpanuvat and Jittanit, 2012). The bubbles are characterized as electrical insulators; therefore they interrupted the flow of electrical current and lessened the electrical conductivity of the food system as a whole. Zhao *et al.* (1999) also reported that the gas bubbles observed during ohmic heating were the result of either various oxidation and reduction reactions or the water boiling.

The experimental results in Figure 5 indicated that a piece of either pineapple or longan was heated faster than the sucrose solution because the sucrose solution has low electrical conductivity due to its composition. The temperature profiles of pineapple and longan appeared to be different although the same electric field strength was applied, perhaps because of the higher electrical conductivity of longan as indicated in Figure 4. The temperature profiles of the ohmically heated and conventionally heated pineapple and longan were controlled to be analogous as illustrated in Figure 6. The results showed that pieces of fruit have a more rapid heating rate than the solution. This result is interesting for the food industry because if the fruit temperature is higher than the surrounding liquid, the completion of the pasteurization or sterilization processes can be detected by the liquid temperature that is easier to measure than the solid temperature, especially for an in-line process.

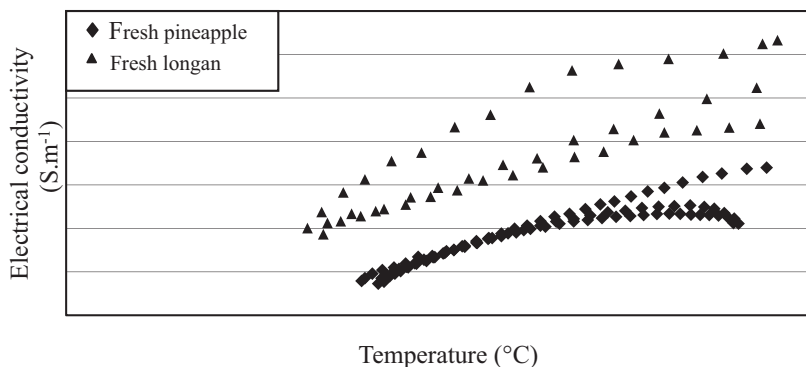


Figure 4 Electrical conductivity of fresh pineapple and longan fruits from small ohmic cell.

The linear models developed by fitting the experimental data of electrical conductivities and temperatures of fresh pineapple and longan during ohmic heating are presented in Table 1. The goodness of fit for these models was fairly high as indicated by the coefficient of determination and the root mean sum of squares.

The properties of samples based on the pH, color and texture were determined. Table 2 shows the comparison between the values of the pH of ohmically heated samples with those of the conventionally heated counterparts exposed to the same heating rate. The results indicated that both methods caused a decrease in the pH after

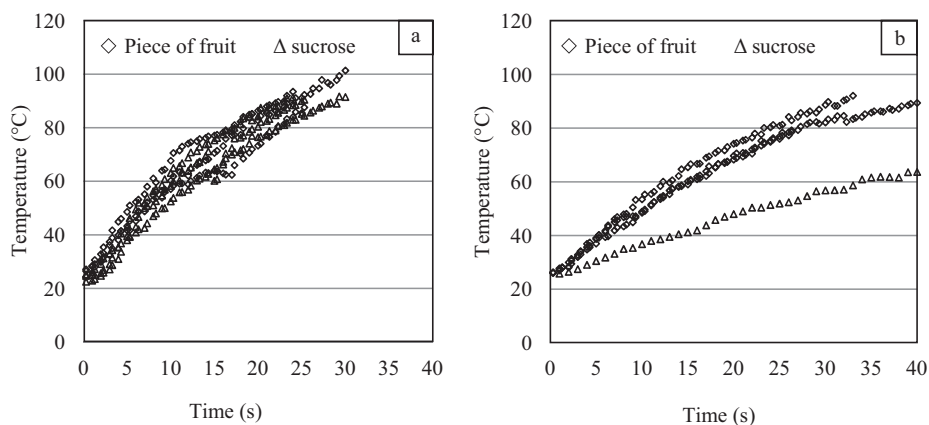


Figure 5 Temperature profiles of ohmically heated samples using large ohmic cell: (a) pineapple; (b) longan.

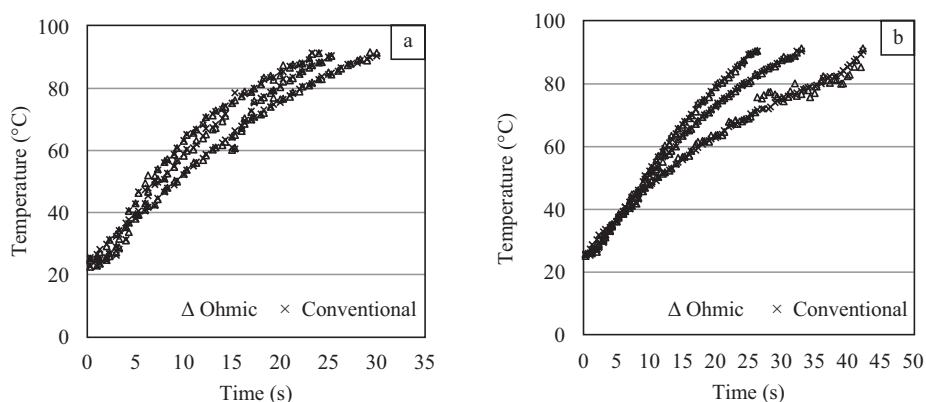


Figure 6 Temperature profiles of ohmically-heated and conventionally-heated samples using large ohmic cell: (a) Piece of pineapple in solution; (b) Piece of longan in solution.

Table 1 Empirical models expressing the relationship between electrical conductivities and temperatures of samples.

Sample	Model	R ²	RMSE (S·m ⁻¹)
Fresh pineapple	$\sigma = 0.0082T + 0.0916$	0.84	0.05
Fresh longan	$\sigma = 0.0123T + 0.0825$	0.73	0.13

σ = Electrical conductivity measured in siemens per meter; T = Temperature (°C); R² = Coefficient of determination; RMSE = Root mean square error.

heating. This phenomenon was probably due to the occurrence of hydrolysis and corrosion reactions between the electrodes. This result was similar to that reported by Darvishi *et al.* (2012) who found that the pH of tomato samples decreased with an increasing voltage gradient. This behavior was probably due to the hydrolysis of the tomato samples and the corrosion of the electrodes that might have occurred during the ohmic heating.

Table 3 shows the color values of the fresh and heated samples. It was found that the lightness values of heated pineapple and longan changed after heating by either method. The redness values of all samples were negative meaning that the fruit samples had a green color. The yellowness of pineapple and longan appeared to decrease after heating especially for longan using ohmic heating and for pineapple using conventional heating. The changes in color could have been due to: 1) the leaching of the pigments from the cell structure to the solution; and 2) a non-enzymatic browning reaction occurring

during the heating process. The results showed that ohmic heating could provide a more similar color to the fresh sample than conventional heating in some cases. As shown in Table 4, there were no significant differences in the textural attributes of force and toughness for all pineapple samples while the adhesiveness value of conventionally heated pineapple was significantly different from the others. For longan, the conventionally heated samples had force, toughness and adhesiveness values significantly different from the fresh samples while the ohmically heated samples showed no significant differences in force and toughness values from the fresh samples. These results showed the potential of ohmic heating to produce more comparable texture of the heated sample to the original fresh sample when compared with the conventional heating method due to the heating process. This result was similar to the findings of Eliot *et al.* (1999) who studied the influence of precooking using the ohmic method on the firmness of cauliflower. They found that

Table 2 Mean values ($\pm$ SD) of pH of samples before and after heating

Sample	pH	
	Before heating	After heating
Ohmically heated pineapple	4.26 $\pm$ 0.04 ^a	4.07 $\pm$ 0.10 ^b
Conventionally heated pineapple	4.24 $\pm$ 0.15 ^a	4.11 $\pm$ 0.04 ^b
Ohmically heated longan	7.67 $\pm$ 0.36 ^a	7.16 $\pm$ 0.13 ^b
Conventionally heated longan	7.48 $\pm$ 0.02 ^a	7.21 $\pm$ 0.05 ^b

Means followed by the same lowercase superscript letter in the same row are not significantly different at $P > 0.05$.

Table 3 Mean color values ($\pm$ SD) of fresh and heated samples

Sample	Lightness L*	Redness a*	Yellowness b*
Fresh pineapple	62.62 $\pm$ 0.83 ^c	-1.92 $\pm$ 0.28 ^b	31.64 $\pm$ 0.92 ^b
Ohmically heated pineapple	57.51 $\pm$ 0.73 ^b	-1.59 $\pm$ 0.30 ^a	31.17 $\pm$ 2.77 ^b
Conventionally heated pineapple	54.65 $\pm$ 0.42 ^a	-1.52 $\pm$ 0.22 ^a	27.55 $\pm$ 1.03 ^a
Fresh longan	56.64 $\pm$ 0.45 ^b	-0.99 $\pm$ 0.38 ^a	9.35 $\pm$ 0.91 ^b
Ohmically heated longan	53.68 $\pm$ 0.26 ^a	-0.85 $\pm$ 0.13 ^a	4.42 $\pm$ 0.21 ^a
Conventionally heated longan	68.83 $\pm$ 0.72 ^c	-0.99 $\pm$ 0.19 ^a	8.73 $\pm$ 0.55 ^b

Means followed by the same lowercase superscript letter in the same row are not significantly different at $P > 0.05$.

precooking cauliflower florets in salted water at low temperature for 30 min followed by ohmic heating (at 135 °C with a holding time of 30 s) provided a firmer product than the control samples prepared by conventional pre-treatment.

The microbial growth comparison between the ohmically-heated and conventionally-heated pineapple wedges showed that the initial counts of mesophilic bacteria (aerobic total count) and molds and yeast in fresh pineapples were 3.43×10^2 colony forming units (CFU).g⁻¹ and 3.03×10^2 CFU.g⁻¹, respectively. It was also found that the microbial growth in the conventionally heated pineapple wedges increased when the storage time was extended. However, the ohmic heating treatment had a greater inhibitory effect on microbial growth than the conventional counterpart. The population of mesophilic bacteria increased rapidly to 2×10^4 CFU.g⁻¹ in the samples treated by conventional heating but molds and yeasts in the samples rapidly increased to more than 2×10^3 CFU.g⁻¹ at day 15 of storage. After 15 d of storage at 4 °C, the samples treated by the ohmic method had a lower level of microbial growth (less than 1×10^2 CFU.g⁻¹ mesophilic bacteria plus mold and yeast) in the pineapple. Consequently, the indirect ohmic heating method could offer an alternative heating method as a minimal heat treatment process for pineapple stored at 4 °C. This experimental result was similar to that of Moreno *et al.* (2012) who indicated that an ohmic heating treatment had a positive effect

on the growth inhibition of molds and yeasts and mesophiles in strawberry during cold storage. The ohmic heating may present mild non-thermal cellular damage due to the presence of the electric field (Pereira *et al.*, 2007). The principal reason for the additional effect of the ohmic treatment may be its low frequency (usually 50–60 Hz), which allows cell walls to build up charges and form pores (Food and Drug Administration, 2000).

The total energy consumption for ohmic heating of pineapple and longan was 620.466 and 389.645 kJ, respectively, while that of the conventional heated pineapple and longan was 621.486 and 389.772 kJ, respectively. These results showed that the ohmic heating consumed a similar energy amount to conventional heating; therefore, the energy consumption might not be the main benefit of ohmic heating, but rather the product quality. However, in this study the heating rate of the ohmic and conventional methods were controlled to be the same. If the higher heating rate of the ohmic method were applied, there may be a lower energy consumption for the ohmic method.

CONCLUSION

The electrical conductivity of fresh pineapple and longan were in the range 0.1 to 0.55 and 0.4 to 1.0 S·m⁻¹, respectively. The experimental results indicated that ohmic heating has the potential to provide higher quality heated

Table 4 Mean textural attribute values ($\pm$ SD) of ohmically heated and conventionally heated samples.

Samples	Force (N)	Toughness (N)	Adhesiveness (mJ)
Fresh pineapple	6.88 ± 0.65^a	-0.12 ± 0.03^a	-0.32 ± 0.07^a
Ohmically heated pineapple	6.97 ± 0.56^a	-0.12 ± 0.01^a	-0.39 ± 0.05^a
Conventionally heated pineapple	6.30 ± 0.29^a	-0.11 ± 0.03^a	-0.19 ± 0.03^b
Fresh longan	5.62 ± 0.93^a	-0.04 ± 0.01^b	-0.14 ± 0.06^a
Ohmically heated longan	6.35 ± 0.09^a	-0.06 ± 0.02^{ab}	-0.08 ± 0.01^b
Conventionally heated longan	7.59 ± 1.02^b	-0.07 ± 0.01^a	-0.08 ± 0.02^b

Means followed by the same lowercase superscript letter in the same row are not significantly different at $P > 0.05$.

fruit mixtures than conventional heating based on color and texture if the same heating rate is applied because ohmic heating can generate heat inside the fruit pieces similarly to or even faster than the surrounding sucrose solution whereas conventional heating relies on heat convection and conduction leading to a lag between the temperatures of the fruit pieces and the surrounding liquid. Ohmic heating of pineapple wedges produced a positive effect of microbial reduction. In addition, the ohmic heating consumed a similar amount of energy to conventional heating when the heating rate of the ohmic and conventional methods was controlled to be the same.

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