EFFECT OF HIGH-PRESSURE PROCESSING ON TEXTURE AND DRYING BEHAVIOR OF PINEAPPLE

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ABSTRACT

The effect of high-pressure processing on texture and drying behavior of pineapple slices was investigated. Pineapple slices were high pressure processed at 50, 100, 300, 500 and 700 MPa at 25C for 10 min. The control, hot water-blanched and high-pressure processed samples were then dehydrated at 70C. Application of high pressure reduced the sample hardness, springiness and chewiness while it had no significant effect on cohesiveness of pineapple. Elevated pressure treatment (≥500 MPa) reduced drying time more effectively than for the other pretreated samples. Experimental dehydration data were empirically fitted using six thin-layer drying models. Among the models tested, logarithmic model best described the drying behavior of pineapple slices. The effective moisture diffusivity was found to increase with an increase in the level of pressure up to 500 MPa, and the samples processed at 500 and 700 MPa had higher diffusivity values than blanched samples.

PRACTICAL APPLICATIONS

This work shows that high-pressure blanching of pineapple can be an alternative for hot water blanching, before dehydration. The results may find application in development of quality snack food from pineapple fruits.

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INTRODUCTION

Pineapple (*Ananas comosus* L.) is one of the important tropical fruit crops of the world. Fresh pineapples for dessert purpose and processed products like canned pineapple are traded worldwide. Due to the continuous increase in demand, considerable potential exists for expansion of trade of raw and processed pineapples. Dried pineapple slices will be an alternative for export of raw produce because larger quantities can be handled, transported and marketed all over the world without any loss in quality. Drying is one of the simplest and oldest methods of preservation of fruits. However, longer drying times and uncontrolled drying conditions may lead to poor quality of end product. Hot water blanching and chemical pretreatments are practiced to increase the drying rate during drying and quality of the end product (Kingsly *et al.* 2007). Blanching is carried out to inactivate the enzymes causing discoloration and altering the flavor of the end product. Due to the high temperature involved, blanching may also induce unwarranted effects by changing the sensory characteristics, texture and loss of nutrients (Quaglia *et al.* 1996).

High-pressure processing (HPP) of fruits can be used as a nonthermal alternative to blanching (Matser *et al.* 2000). In this method of processing, food materials are subjected to high pressures (up to 900 MPa) isostatically, so that inactivation of microorganisms and spoilage-catalyzing enzymes is achieved without altering the physical and quality attributes (Rastogi *et al.* 2007). Because the fruit is not subjected to high temperature, this process offers several advantages such as better flavor, texture, nutrient retention and color as compared to thermally processed foods (Balasubramaniam 2003). High-pressure processing also aids in drying by making the cells more permeable by changing the cell wall structures, thereby increasing the rate of mass transfer (Rastogi and Niranjan 1998). Eshtiaghi and Knorr (1993) reported that high-pressure processing can be employed for blanching of potatoes instead of hot water or steam blanching. The studies conducted by Al-Khuseibi *et al.* (2005) revealed that application of high pressure, instead of thermal treatment, retained texture and color of dried potato cubes. The results indicated that high-pressure processing improved the moisture transfer rates. Ade-Omowaye *et al.* (2001) determined the effect of high pressure on dehydration characteristics of red paprika. The results indicated that high-pressure processing increased drying rates by increased cell permeabilization.

Mostly the reported pretreatment methods (Rahman and Lamb 1991; Nicoleti *et al.* 2001; Tan *et al.* 2001) before air-drying of pineapple are chemical in nature, and also mathematical models to describe the drying behavior of pineapple slices are scanty. The objective of the present study was to investigate the potential of high-pressure processing of pineapple as an alternative to hot water blanching. The specific objectives were (1) to study the effect of high pressure on texture of fresh pineapple, (2) to investigate and model the drying behavior of differently treated pineapple slices and (3) to calculate the moisture diffusivity.

MATERIALS AND METHODS

Raw Material

Pineapples (*A. comosus* L.) of Smooth Cayenne variety were used for the experiments. Ripe fruits (total soluble solids, 10–11°Brix; moisture content, 89.64% [wet basis]; and water activity [A_w], 0.982) were purchased from a local market (Columbus, OH) and stored at 4C. Total soluble solids were measured using a portable refractometer (Fisher Scientific, Pittsburg, PA), moisture content using the oven drying method (AOAC 1984) and water activity using a water activity meter (model TE8255, Decagon Aqualab, Pullman, WA). The same batch of fruits was used for all the experiments. After peeling and decoring the pineapples, these were cut into cylindrical pieces of diameter 17.5 mm and height 5 mm by using a cork borer (Fisher Scientific) and a sharp knife.

Pretreatments

High-pressure Processing. High-pressure processing of pineapple slices was carried out using a Quintus high-pressure food processor (QFP-6, Flow Autoclave Systems, Columbus, OH). The pressure transmitting fluid was a 1:1 mixture of distilled water and food grade propylene glycol (Houghto-Safe 620-TY, Houghton International Inc., Valley Forge, PA). The pineapple samples were vacuum packed in high-barrier pouches. The samples were processed at various pressures (50 to 700 MPa) for 10-min pressure holding time at 25 ± 1C. The pressure holding time did not include pressure come-up and depressurization time. The rate of pressurization was approximately 258 MPa/min and depressurization occurred in less than 4 s. During each pressure treatment, three pouches containing 30 samples were processed. To achieve a final process temperature of 25C during the pressure holding time, the sample initial temperature before HPP was lowered (4 to 23.5C for 50 to 700 MPa treatment) taking into account the rise in temperature due to heat of compression (Ting *et al.* 2002; Rasanayagam *et al.* 2003). A water jacket surrounding the pressure chamber was maintained at the desired process temperature of 25C. This helped to minimize heat exchange during extended pressure holding times. After processing, the pouch was cut open, samples were rinsed in distilled water (at room temperature), wiped with a tissue paper to remove any residual water adhered to the surface and then subjected to further dehydration.

Hot Water Blanching. Hot water blanching was carried out by suspending the samples in boiling water in a water bath for 3 min with a sample water ratio of 1:20. One batch consisted of 30 pineapple samples. These samples after blanching were cooled by submerging these samples into cold tap water. The samples were then wiped with a tissue paper to remove adhering surface water. Untreated samples were kept as control. The drying experiments were carried out in triplicate and mean values were reported.

Texture Measurement

An Instron 5542 (Instron Inc., Canton, MA) with a 500-kg load cell was used to conduct texture profile analysis (TPA) of control and high-pressure pretreated pineapple samples at room temperature (~25C). The cylindrical sample (17.5 × 5 mm) was compressed (80% compression) on a nonlubricated platform using a flat disk probe (diameter, 38 mm), with a constant crosshead speed of 1 mm/s. The peak force required to compress the samples was referred to as a measure of hardness (Bourne 1978). The cohesiveness, springiness and chewiness were determined from TPA following the definition as described by Bourne (1978). Cohesiveness is expressed as the dimensionless quotient of the areas represented by the work to be done for two bites. Springiness (elasticity) is defined as the proportion of compression distance recovered between the first and the second compression. Chewiness is the product of hardness, cohesiveness and springiness. Ten measurements were made for each treatment.

Drying Experiments and Mathematical Modeling

Drying experiments of differently pretreated samples were performed in a cabinet drier (model TS 160 A, Cabela's Food Dehydrator, Sidney, NE) at 70C in a single layer. The air flow rate was 1.32 m/s (measured by a hot wire aerometer). Moisture loss was recorded at 30-min intervals for the first 3 h of drying and thereafter at 1-h intervals, until the time there was no large variation in the moisture loss. The final moisture content of the dehydrated pineapple slices was 5.84 ± 0.75% on a wet basis:

$$MR = \frac{(M - M_e)}{(M_0 - M_e)} \tag{1}$$

where M is the moisture content at time t, and M_0 and M_e, the initial and equilibrium moisture contents, respectively, on dry basis.

Equilibrium moisture content was calculated from any two successive observations of moisture content M_n and M_{n+1} (dry basis) and their corresponding drying times t_n and t_{n+1} and fitting in the following equation (Singh *et al.* 1986):

$$M_n = z \times M_{n+1} + (1-z) M_e \qquad (2)$$

where $z = \exp(k\Delta t)$ and $\Delta t = t_{n+1} - t_n$; k, equation constant; M_e, equilibrium moisture content on dry basis.

The drying curves obtained were fitted with six empirical and theoretical thin-layer drying expressions (Table 1). Some of these models were recently used for determination of moisture ratio with time during thin-layer drying by Togrul and Pehlivan (2002), Friant *et al.* (2004), Akpinar and Bicer (2005) and Simal *et al.* (2005). For estimating the model constants and correlation coefficient (r^2), nonlinear regression was performed using a statistical analysis program (version 11, Statistical Package for Social Scientists, SPSS Inc., Chicago, IL). In addition to correlation coefficient, the goodness of fit was determined by various statistical parameters such as reduced chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE). These parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{pre},i}\right)^2}{N-n} \qquad (3)$$

TABLE 1.
THIN-LAYER DRYING MODELS

Equation	Name	References
$MR = \exp(-kt^n)$	Page	Zhang and Litchfield (1991)
$MR = \exp(-[kt]^n)$	Modified Page	Overhults *et al.* (1973)
$MR = a\exp(-kt)$	Henderson and Pabis	Henderson and Pabis (1961)
$MR = a\exp(-kt) + c$	Logarithmic	Yaldiz *et al.* (2001)
$MR = a\exp(-k_0t) + b\exp(-k_1t)$	Two-term	Sharaf-Eldeen *et al.* (1980)
$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-[2n+1]^2\pi^2 D_{\mathrm{eff}}t}{4L^2}\right)$	Diffusion Model	Simal *et al.* (2005)

k, k_0, k_1, a, b, c and n are model constants; D_{eff} is effective moisture diffusivity; and L is half-thickness of the slab.

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{\text{pre},i} - MR_{\text{exp},i}\right) \tag{4}$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}\left[MR_{\text{pre},i} - MR_{\text{exp},i}\right]^2\right)^{1/2} \tag{5}$$

where N is the total number of observations, n is the number of drying constants, $MR_{\text{exp},i}$ is experimental values and $MR_{\text{pre},i}$ is predicted moisture ratio values.

Calculation of Effective Moisture Diffusivity

Fick's unsteady state diffusion equation can be written as (Crank 1975)

$$\frac{\partial M}{\partial t} = D_{\text{eff}}\frac{\partial^2 M}{\partial x^2} \tag{6}$$

where M is moisture content, t is time, D_{eff} is diffusion coefficient and x is diffusion path.

For an infinite slab being subjected to dehydration from both the major faces with assumptions: (1) uniform initial moisture distribution; (2) no shrinkage during osmotic dehydration; and the following initial and boundary conditions:

$$M = M_0 \qquad \text{at } t = 0 - L < x > +L \tag{7}$$

$$M = M_1 \qquad \text{at } t > 0 \; x = L \tag{8}$$

The solution of Eq. (6) can be written for moisture ratio (MR) (Crank 1975):

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-[2n+1]^2\pi^2 D_{\text{eff}}t}{4L^2}\right) \tag{9}$$

For longer drying times (assuming $n = 0$), Eq. (9) can be written in logarithmic form as

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}}t}{4L^2} \tag{10}$$

The experimental values of ln MR were plotted against t/L^2 and from the slope of the curve, moisture diffusivity was calculated.

Statistical Analysis

The data were analyzed using the statistical package (version 8.0, SAS Institute, Inc, Cary, NC) to perform analysis of variance (ANOVA) and Duncan's multiple range test (DMRT). The mean values obtained from ANOVA were subjected to DMRT for testing pairwise comparison.

RESULTS AND DISCUSSION

Effect of High Pressure on Texture of Pineapple

The hardness (Fig. 1a) of the pineapple slices decreased with increase in pressure, but the change was not significant ($P > 0.05$) over 100–500 MPa pressure range. There were no differences in the cohesiveness of fresh and

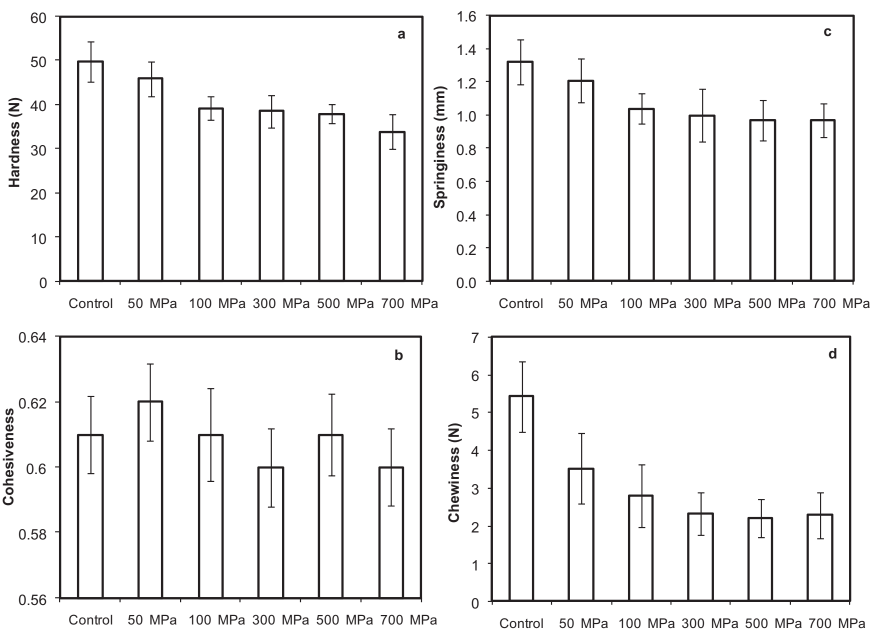

FIG. 1. EFFECT OF PRESSURE ON TEXTURAL PARAMETERS: (a) HARDNESS, (b) COHESIVENESS, (c) SPRINGINESS AND (d) CHEWINESS

Data points with error bars indicate mean ± SD.

high-pressure-pretreated samples (Fig. 1b) ($P > 0.05$) and the cohesiveness value was around 0.58–0.61. Springiness (Fig. 1c) of the high-pressure-treated sample was lower than that of fresh samples. Chewiness greatly reduced after high-pressure treatment (Fig. 1d). But the increase in pressure from 100 to 700 MPa did not result in significant change ($P > 0.05$). Quaglia *et al.* (1996) and Al-Khuseibi *et al.* (2005) also observed that pressure level during high-pressure processing did not have any adverse effect on product texture for green peas and potatoes, respectively.

Drying Behavior and Mathematical Modeling

At elevated pressures, some moisture loss was noted in pressure-treated pineapple slices (Fig. 2). The observation was similar to the findings of Rastogi and Niranjan (1998) who found the loss of moisture due to compression and decompression during high-pressure processing. Prestamo and Arroyo (1998) also observed that application of high pressure induces moisture movement from inner core to outside and this movement might have resulted in initial moisture loss. This might also reduce dehydration time especially for the samples treated at 500 and 700 MPa. Higher permeability of cells after elevated pressure treatment could have increased the drying rate (Rastogi and Niranjan 1998; Ade-Omowaye *et al.* 2001). A similar result has been reported by Al-Khuseibi *et al.* (2005) for potato cubes.

The equilibrium moisture content (kg water/kg dry matter) for control, hot water blanched, pressure treated at 50, 100, 300, 500 and 700 MPa was

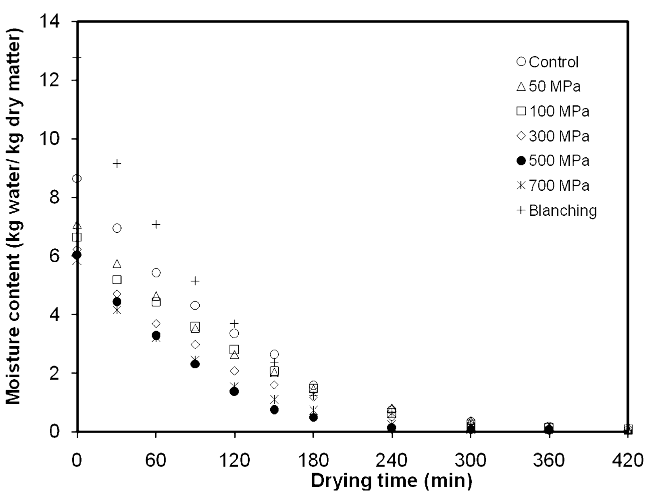

FIG. 2. VARIATION OF MOISTURE CONTENT DURING DRYING OF PINEAPPLE

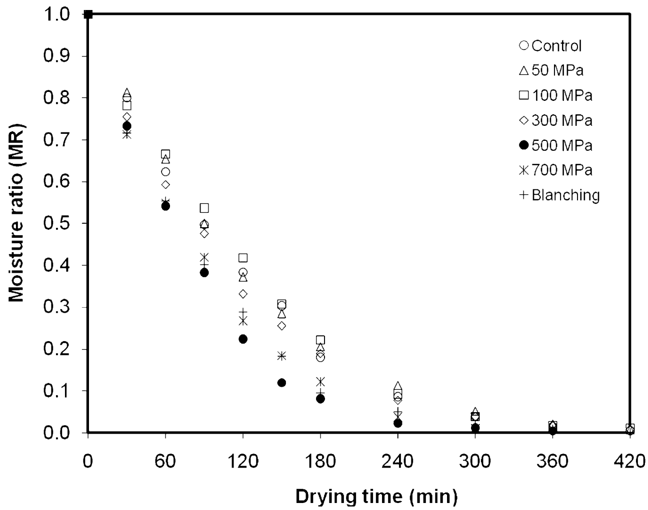

FIG. 3. MOISTURE RATIO OF DIFFERENTLY TREATED PINEAPPLE SLICES

0.024, 0.028, 0.019, 0.017, 0.017, 0.022 and 0.019, respectively. Moisture ratio data of pineapple slices (Fig. 3) dried at thin layers with different pretreatments were fitted into thin-layer drying models listed in Table 1. Higher r^2 and low χ^2, MBE and RMSE values were used as the criteria to choose the best model that described the drying behavior of pineapple slices. In all cases, the value of $r^2 > 0.9$, indicating a goodness of fit. Among the empirical models evaluated, the logarithmic model was found to represent the drying behavior of pineapple samples based on the criteria used. The logarithmic model has been used for describing the drying behavior of peach slices (Kingsly *et al.* 2007) and rosehip (Erenturk *et al.* 2004). The values of r^2, χ^2, MBE and RMSE of the selected model are summarized in Table 2. Although the statistical parameters of the empirical models are low, only the theoretical model (diffusion model) takes into consideration the geometry of samples. Because the correlation coefficient was also not less than 0.90, the diffusion model may be appropriate for simulation of drying under different conditions (Simal *et al.* 2005).

Effective moisture diffusivity ranged from 3.6 to 4.7×10^{-9} m^2/s (Table 3) and the values are within the general range of 10^{-9} to 10^{-10} m^2/s for drying of food materials (Sacilik and Unal 2005). Nicoleti *et al.* (2001) also found values in the similar range for air-drying of pineapple. The high-pressure-pretreated (50 to 700 MPa) as well as hot water-blanched pineapple slices had higher moisture diffusivity values because the pretreatment resulted in increased internal mass transfer during drying. The moisture diffusivity values

TABLE 2.
STATISTICAL PARAMETERS OF THE LOGARITHMIC MODEL

Pretreatment	Model constants	r^2	χ^2	RMSE	MBE
Control	$a = 1.08$; $k = 0.008$; $c = -0.06$	0.99	0.0005	0.0019	−0.0019
50 MPa	$a = 1.07$; $k = 0.007$; $c = -0.05$	0.99	4.91×10^{-5}	0.0063	-5.13×10^{-6}
100 MPa	$a = 1.09$; $k = 0.007$; $c = -0.08$	0.99	0.0007	0.0233	1.00×10^{-5}
300 MPa	$a = 1.04$; $k = 0.008$; $c = -0.04$	0.99	0.0003	0.0134	-1.40×10^{-5}
500 MPa	$a = 1.06$; $k = 0.011$; $c = -0.04$	0.99	0.0004	0.0167	9.32×10^{-6}
700 MPa	$a = 1.04$; $k = 0.009$; $c = -0.04$	0.99	0.0005	0.0178	-8.97×10^{-6}
Hot water blanched	$a = 1.03$; $k = 0.010$; $c = -0.03$	0.99	0.0005	0.0189	−0.004

r^2, correlation coefficient; χ^2, chi-square; RMSE, root mean square error; MBE, mean bias error.

TABLE 3.
EFFECTIVE MOISTURE DIFFUSIVITY OF PINEAPPLE SLICES AS CALCULATED BASED ON DIFFUSION MODEL (AS PER EQ. 9)

Pretreatment	$D_{\text{eff}} \times 10^9$ (m^2/s)	r^2
Control	3.60	0.90
50 MPa	3.65	0.93
100 MPa	3.70	0.91
300 MPa	3.90	0.93
500 MPa	4.70	0.96
700 MPa	4.70	0.93
Hot water blanched	4.30	0.93

D_{eff}, diffusion coefficient; r^2, correlation coefficient.

were found to increase with an increase in pretreatment pressure. Diffusivity of pineapple processed above 500 MPa was higher than that of hot water-blanched samples. It shows that high-pressure treatment can be used as an effective alternative of thermal blanching before drying.

CONCLUSIONS

The textural parameters of high-pressure-processed samples were lower than those of the fresh samples. Hardness, springiness and chewiness reduced after high-pressure processing, while there was no significant effect on cohesiveness. The increased moisture transfer rate of samples high pressure processed at 500 and 700 MPa reduced the drying time. Reduction in textural parameters and reduced drying time indicated the cell permeabilization during high-pressure treatment. The logarithmic model showed better fit for drying of pineapple slices with high correlation coefficient. Effective moisture diffusivity of pineapple slices ranged from 3.6 to 4.7×10^{-9} m^2/s. The pretreatment of high-pressure processing above 500 MPa increased the mass transfer during drying and was higher than the moisture diffusivity of hot water-blanched samples. To overcome the disadvantages of hot water blanching like leaching and destruction of nutrients, high-pressure processing of pineapple slices at 500 MPa for 10 min can be used as an alternative before drying.

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