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Research Article

Impact of High Pressure on the Infusion of Curcuminoids in Pineapple Slices

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Abstract

Osmotic treatment was used as a method for the infusion of curcuminoids in pineapple slices. The effect of high pressure pretreatment (350 MPa) on the infusion of curcuminoids into fresh pineapple slices was studied. The mass transfer rate of moisture, solid and curcuminoids for a range of concentration of osmotic solution (0 to 70°Brix) showed that the mass transfer rates were highest when pure water (aqueous suspension of curcuminoids) was used as a surrounding solution for infusion. Application of high pressure pretreatment resulted in further increase in diffusion coefficient from 0.86×10^{-9} m^2/s to 1.53×10^{-9} m^2/s. The present study concluded that high pressure treatment of solid foods could be a feasible technology for infusion of bioactive compounds into solid food matrix.

Keywords: Bioactive compounds; Cell membrane permeabilisation; Diffusion coefficient; High pressure treatment; Mass transfer; Osmotic treatment

Introduction

Functional foods are increasingly being accepted by the consumers due to rising demand for healthier food products. Generally, functional foods promote health and prevent diseases besides providing the basic function of supplying nutrients [1,2]. Infusion of compounds such as minerals [3], phenolic compounds [4,5], vitamins [6], ascorbic acid [7], microcapsules [8] as well as inulin and piquin-pepper oleoresin [9] using osmotic treatment into solid food was demonstrated

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by many research workers. However, it is relatively a slow and time consuming process. Hence, a few techniques have been acknowledged in order to enhance the rate of osmotically induced mass transfer that include partial vacuum [10,11], pulsed vacuum [12], high pressure [13-15], high intensity pulsed electric field [16,17], ohmic heating [18,19] or ultrasound [20-23]. Application of high pressure treatment accelerated the diffusion of bioactive components into the solid food due to cell membranes permeabilisation resulting in decline in the resistance to infusion [24,25]. The application of high pressure pretreatment was described to increase the water and solute diffusion during osmotic dehydration of pineapples, potato, glutinous rice and turkey breast [26-29]. Sila et al., [30] demonstrated that combined effect of high pressure treatment and $CaCl_2$ treatment improved the texture of carrots during thermal processing. High pressure-assisted infusion of pectin methyl esterase and calcium chloride in strawberry was shown to improve the firmness [13,31]. Mahadevan et al., [32] indicated that high pressure pretreatment increased infusion of quercetin by 3 times into cranberries as compared to untreated ones.

Incorporation of synthetic antioxidants like Butylated Hydroxyanisole (BHA) and Butylated Hydroxy Toluene (BHT) are restricted by legislative laws and regulations due to carcinogenic effects [33]. Therefore, there has been an increasing trend to use natural antioxidants over the synthetic ones. Turmeric (*Curcuma longa* L.) is considered as one of the main source of antioxidants curcuminoids namely Curcumin, Demethoxycurcumin and Bisdemethoxycurcumin [34]. It can improve the visual appearance, delectableness and prolong the storage period of food products [35]. The recommended daily intake of curcuminoids is 0.1 mg/kg body weight [36]. Several biological activities have been also reported in turmeric such as antioxidant, anti-inflammatory, anti-psoriatic, anti-diabetic, antibacterial, and anticancer properties [37-42]. Exhilarated with this idea of to develop pineapple slices with enhanced nutrition and color, it was opined desirable to infuse natural antioxidant (curcuminoids) to enhance the nutrition profile. The present study indicated that high pressure pretreatment enhanced the diffusion coefficients of curcuminoids in pineapple slices. The process could provide great opportunities for food manufacturers to develop value-added products similar to the fresh one and with enhanced nutritional and quality attributes.

The main objectives of the present work were (i) to study the effect of high pressure treatment on the infusion of curcuminoids into pineapple slices, (ii) to determine the diffusivity of water, solute as well as curcuminoids, and (iii) to assess the possible improvement of mass transfer kinetics osmotic treatment due to high pressure treatment.

Materials and Methods

Raw materials

Pineapples (*Ananas comsus* L. (*Merr.*)) were purchased from a local super market in Mysore and stored in cold storage rooms (4±1ºC and 90% RH) and drawn as and when required for the experiment. The pineapple, after peeling and coring, was cut into $15 \times 15 \times 10$ mm slices.

Sample preparation

The water soluble infusate was prepared by suspending 3% curcumin (Sigma-Aldrich) containing propylene glycol and polysorbate in the ratio of 1:1 [43].The moisture content of pineapple as determined by vacuum drying (60ºC for 24 h) was 85% on a wet weight basis. Sucrose was used as the osmotic agent.

High pressure pretreatment

The pineapple slices were high pressure treated in a cylindrical pressure vessel (Volume 1L, maximum working pressure 400 MPa, M/s Khoday Hydraulics Ltd., Mumbai). The time require to reach maximum treatment pressure was 10 min, and decompression took 10 s. The samples were packaged along with the impregnating solution (containing 0.13 g/100 ml infusate) in the ratio of 1:3 in LDPE (Low Density Polyethylene) pouches. The pouches were heat sealed and the samples were treated at 350 MPa for 10 min. The processing conditions were selected based on our earlier work [26]. The water was taken as a medium for transmitting pressure.

Osmotic treatments

High pressure treated samples were subjected to osmotic treatment over a range of sugar concentration (0 to 70ºBrix). The osmotic solutions were added with the infusate containing 0.13 g/100 ml. The solid to liquid was maintained at 1:5 to make ensure that the concentration of osmotic solution did not change significantly. At the end of every hour of immersion time, the samples were withdrawn, rinsed in water and blotted gently, weighed and then dried in a vacuum oven (60ºC for 24 h). Moisture and solid content were determined and expressed in terms of kg of water/kg of initial dry solid and kg of solids/kg of initial dry solid, respectively. All the experiments were done three times and the average of the three value was reported.

Estimation of curcuminoids content

The curcuminoids content in pineapple slices were estimated as per ASTA [44] procedure based on the spectroscopic analysis.

Moisture, solid or curcuminoids diffusion coefficients

Fick's second law solution for diffusion from an infinite flat plate configuration (thickness 2a) results in the following equation for mass transfer [45,46]:

$$X_i = \frac{(x_{ti} - x_{\infty i})}{(x_{oi} - x_{\infty i})} = \sum_{n=1}^{\infty} C_n \exp\left[-D_{ei} t q_n^2 \left(\frac{1}{a^2}\right)\right] \quad (1)$$

Fourier number (for moisture and solid or curcuminoids, F_{oi}) is defined as $D_{eit}/a2$ and substituting the value into Eq. (1) results in the Eq (2):

$$X_i = \frac{(x_{ti} - x_{\infty i})}{(x_{oi} - x_{\infty i})} = \sum_{n=1}^{\infty} C_n \exp\left[-F_{oi} q_n^2\right] \quad (2)$$

Where $C_n = 2\alpha(1 + \alpha)/(1 + \alpha + \alpha^2 q_n^2)$ and q_n's are the positive roots of the equation $\tan(q_n) = -\alpha qn$. X_i is the dimensionless moisture ratio (when i = m) or solid ratio (when i = s); the subscripts *o, ∞* and *t* represent the initial, at equilibrium and at any time concentrations; the subscript '*i*' takes values '*m*', '*s*' and '*c*' for moisture, solid or curcuminoids content, respectively; D_{ei} is the diffusion coefficient; and Here, α is the volume ratio of solution to that of solid. Eq. (2) was graphically represented by plotting log (X_i) against Fourier number

(F_{oi}, Figure 1) and [d(log X_i)/dF_{oi}] is the slope of the theoretical diffusion line and which was found to be 1.075 [46].

Figure 1: Theoretical diffusion curve for flat plate configuration as per Eq. (4).
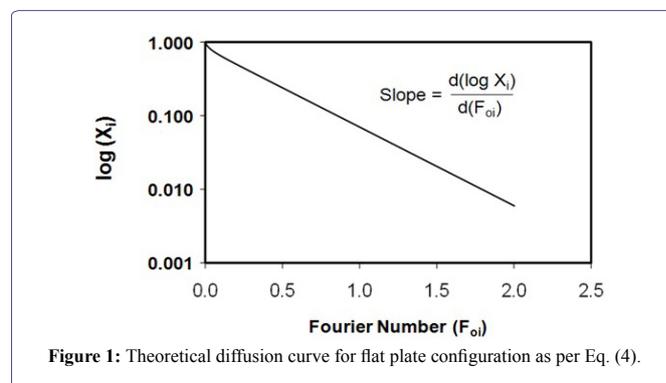
The following equation for mass transfer can be written by considering the equilibrium approach to mass transfer [47]:

$$-\frac{dx_i}{dt} = k_i \left(x_{ti} - x_{\infty i}\right) \quad (3)$$

Where k_i is the mass transfer coefficients. Integration of Eq. (3), with the appropriate limits, resulted in the following equations:

$$\ln \frac{(x_{ti} - x_{\infty i})}{(x_{oi} - x_{\infty i})} = \ln X_i = -k_i t \quad (4)$$

The differentiation of the Eq. (4) resulted in the Eq. (5), which was used to calculate the experimental slopes.

$$\frac{d}{dt}(\log X_i) = -\frac{k_i}{2.3025} \quad (5)$$

In order to obtain mass transfer coefficients (k_i) and equilibrium values ($x_{\infty i}$), the rate of change of moisture, solid or curcuminoids content was plotted against av. moisture, solid or curcuminoids content, respectively [46].

Based on the infinite flat sheet, D_{ei} values were determined from the following equation [46,47]:

$$D_{ei} = \left[\frac{d(\log X_i)/dt}{d(\log X_i)/dF_{oi}}\right] \cdot a^2 \quad (6)$$

Determination of DPPH radical Scavenging Activity (SA)

The free radical scavenging activity of control and high pressure treated pineapple slices was evaluated using the stable radical DPPH as described by [48].

Texture determination

Maximum compressive force was measured using Texture Analyzer (LLOYD-LR-5K, Surrey, UK)and used as a measure of hardness (probe cone of 30º angle, penetration depth of 1 mm, loading speed 5 mm/s, and load cell capacity 25 kg).

Statistical analysis

The statistical significance between groups were determined using

a one-way Analysis of Variance (ANOVA) followed by Turkey-Kramer test, with p≤0.05 indicating significance, using MS-Excel. All the experiments were performed three times and average values were recorded.

Result and Discussion

Impact of osmotic treatment on moisture, solids and curcuminoids mass transfer

The application of high pressure (350 MPa/10 min) alters the moisture, solid and curcuminoids during the course of osmotic treatment (0 to 5 h) for different concentrations of osmotic solution (0-70°Brix). The variations in moisture, solid and curcuminoids with immersion time are presented in figures 2-4. The rate of change of moisture, solid and curcuminoids (dx_m/dt, dx_s/dt, dx_c/dt) contents obtained from figures 2-4 and plotted against the average moisture, solid and curcuminoids (A_m, A_s, A_c) contents, respectively to obtain mass transfer coefficients for moisture, solid and curcuminoids (k_m, k_s, k_c) as well as equilibrium moisture, solid, and curcuminoids ($x_{\infty m}$, $x_{\infty s}$ and $x_{\infty c}$) from the slope and intercept of these plots. The values are presented in (Table 1).
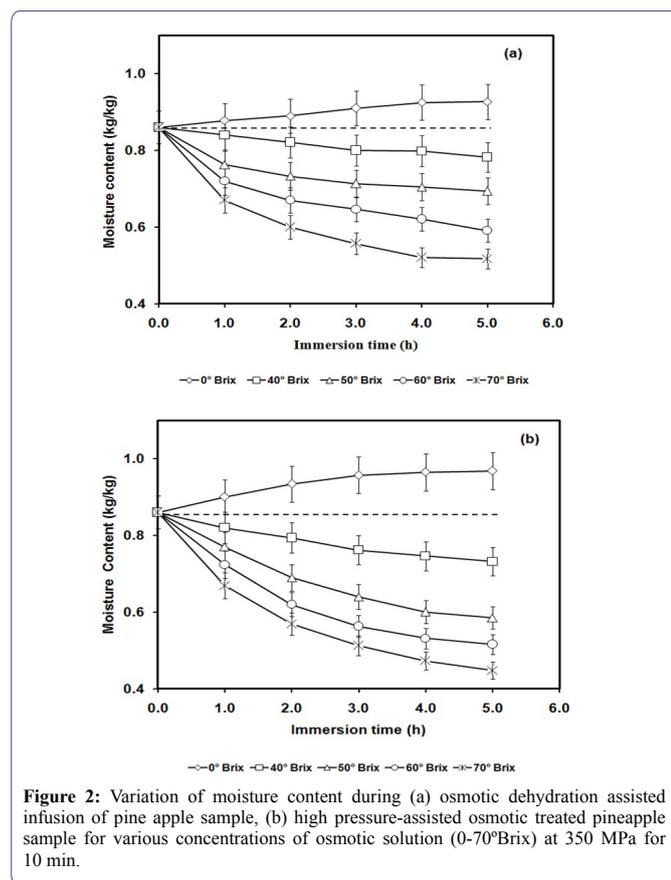

Figure 2: Variation of moisture content during (a) osmotic dehydration assisted infusion of pine apple sample, (b) high pressure-assisted osmotic treated pineapple sample for various concentrations of osmotic solution (0-70ºBrix) at 350 MPa for 10 min.

The pineapple slices subjected to 0ºBrix solution containing aqueous of curcuminoids resulted in diffusion of water into pineapple slices due to the higher osmotic pressure inside the food matrix in comparison to the osmotic medium (Figure 2a). The high pressure treatment (350 MPa) resulted in rise in moisture gain (Figure 2b). At the same time, subjecting the pineapple slices in 0ºBrix solution (water) it also led to diffusion of solids from pineapple into the osmotic

medium (Figure 3a). Its extent was slightly increased due to application of high pressure (Figure 3b). The pressure pretreatment was found to result in rise in diffusivity for moisture infusion and solid loss from 0.12×10^{-9} m²/s to 0.55×10^{-9} m²/s and from 0.26×10^{-9} m²/s to 0.40×10^{-9} m²/s, respectively.
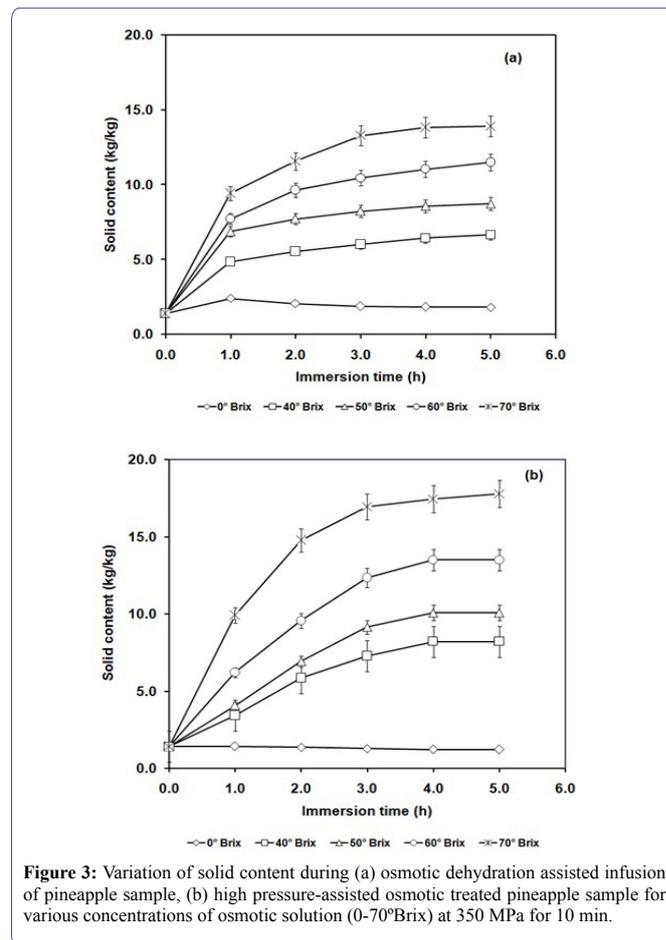

Figure 3: Variation of solid content during (a) osmotic dehydration assisted infusion of pineapple sample, (b) high pressure-assisted osmotic treated pineapple sample for various concentrations of osmotic solution (0-70ºBrix) at 350 MPa for 10 min.

The pineapple slices subjected to 40 to 70ºBrix osmotic solution containing water soluble curcuminoids resulted in the reversal of direction of mass transfer. The diffusion of water took place from pineapple slices to osmotic solution and solids were diffused from osmotic solution to the pineapple because of higher osmotic pressure of osmotic solutions (Figures 2a, 3a). Further, high pressure treatment resulted in increased moisture and solute mass transfers (Figures 2b, 3b). For instance, for 70ºBrix concentration of surrounding solution, the application of high pressure (350 MPa) increased the moisture diffusion coefficient from 1.17×10^{-9} m²/s to 1.68×10^{-09} m²/s and solid diffusion coefficient were increased from 1.42×10^{-9} m²/s to 1.75×10^{-09} m²/s (Table 1).

As far as the infusion of curcuminoids is concerned, the increase in concentration of osmotic solution from 0 to 70ºBrix resulted in decrease in diffusion coefficient for curcuminoids diffusion from 0.86×10^{-09} to 0.31×10^{-09} m²/s (Figure 4a, Table 1). Further, the application of high pressure resulted in instant increase in curcuminoids content up to 22.30±0.31 mg/100g. The diffusion coefficient value for curcuminoids diffusion for 0ºBrix surrounding solution was found to increase from 0.86×10^{-09} to 1.53×10^{-09} m²/s (Figure 4, Table 1).

Further, increase in concentration of osmotic solution from 40 to 70ºBrix of high pressure treated pineapple resulted in decrease in the curcuminoids after instant increase to 22.30±0.17 mg/100g and the corresponding diffusion coefficient values were decreased from 1.42 to 0.64 × 10^{-09} m²/s (Figure 4, Table 1). The values in the parenthesis indicate a reversal in direction of mass transfer with corresponding increase in the surrounding solution concentration (Table 1). However, the curcuminoids contents were always higher in pressure treated pineapple as compared to control sample.
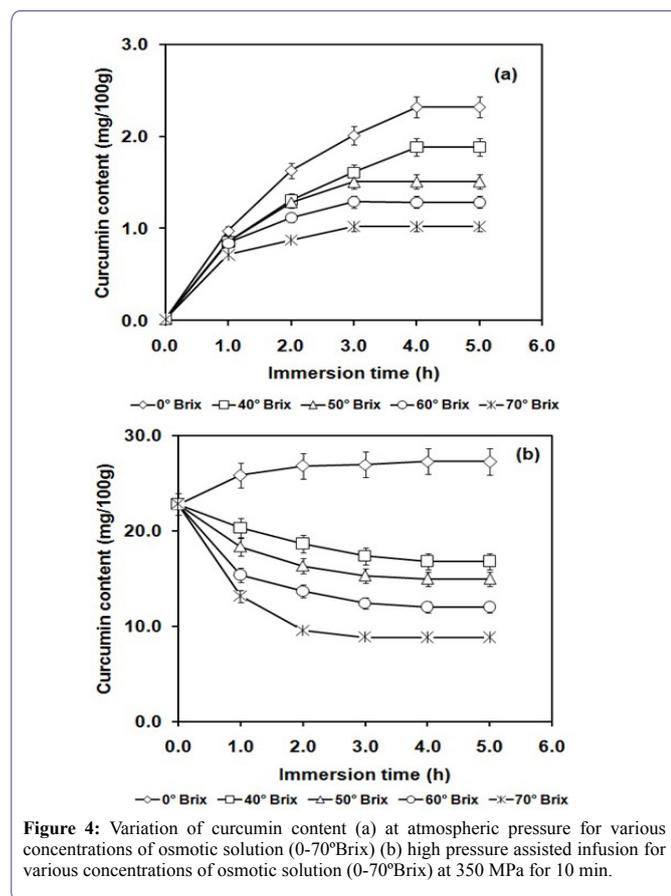

Figure 4: Variation of curcumin content (a) at atmospheric pressure for various concentrations of osmotic solution (0-70ºBrix) (b) high pressure assisted infusion for various concentrations of osmotic solution (0-70ºBrix) at 350 MPa for 10 min.

When water was used the surrounding solution, the total grape phenolic compounds impregnated in model food system was almost found to be twice as compared to osmotic solution (sucrose 50 g/100g) [4,5]. The optimum condition for infusion was found when the surrounding medium had minimum concentration. Similarly, George et al., [15] also showed that the infusion of anthocyanin under high hydrostatic pressure (250 MPa/10 min) was nearly 3 folds higher as compared to ambient conditions (0.1 MPa) when pure water (0°Brix) was used as osmotic solution.

Impact of high pressure treatment on curcuminoids infusion, antioxidant activity and texture

The curcuminoids content and antioxidant activity of fresh pineapple and the samples subjected to 0ºBrix with or without pressure treatment after 5.0 h of immersion are shown in figure 5a, which indicated that the treatment with surrounding solution containing pure water (0°Brix) resulted in 2.19±0.23 mg/100g of curcuminoids content

that was further enhanced to 27.32±0.27 mg/100g by the application of the pressure treatment. The antioxidant activity of the pineapple samples was also higher wherever the curcuminoids content was higher indicating infused curcuminoids in pineapple sample led to the enhancement of antioxidant activity. Lin et al., [49] also demonstrated that minimum concentration of the surrounding medium resulted in higher fortification of Vitamin E content in fresh pears. The higher infusion of curcuminoids was found to be related with the minimum compressive force (Figure 5b). The decrease in compressive force with on subjecting to high pressure may be related to the permeabilisation of cells leading to reduced mass transfer resistance thereby resulting in higher infusion. In case of pineapple slices high pressure treatment results in decrease in compressive force [26]. These results clearly indicate that the high pressure pretreatment is one of the potential methods to enhance the infusion of bioactive compounds.
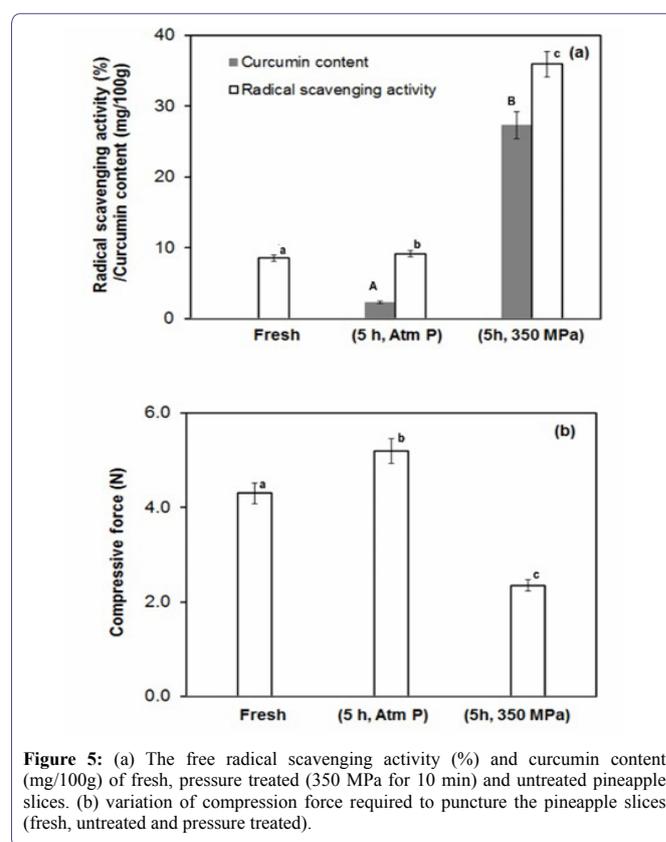

Figure 5: (a) The free radical scavenging activity (%) and curcumin content (mg/100g) of fresh, pressure treated (350 MPa for 10 min) and untreated pineapple slices. (b) variation of compression force required to puncture the pineapple slices (fresh, untreated and pressure treated).

Conclusion

High pressure pretreatment of pineapple slices exhibited an increase in the infused curcuminoids as compared to ambient condition (0.1 MPa), besides enhancing the mass transfer rates of moisture and solid leading to the decrease in process time. Highest incorporation of curcuminoids infusion in pineapple slices was achieved in case when the concentration of osmotic solution was minimum i.e., 0ºBrix. In addition, the present work confirmed the possibility of high pressure treatment for the development of foods with enhanced infusion of bioactive compounds. The study may be useful in optimizing process parameters depending on the extent of infusion of bioactive compounds required for the product development.

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Parameters	Mass Transfer Coefficient (Kew, Kes or Kec × 10⁻⁹ m²/s)					Diffusion Coefficient (Dew, Des or Dec × 10⁻⁹ m²/s)					Equilibrium Content (x∞w, x∞s kg/kg; or x∞c mg/100g)				
	0%	40%	50%	60%	70%	0%	40%	50%	60%	70%	0%	40%	50%	60%	70%
Curcuminoids															
Without HPP	0.87[a]	(0.72)[b]	(0.65)[c]	(0.32)[d]	(0.23)[e]	0.86[a]	(0.69)[b]	(0.62)[c]	(0.43)[d]	(0.31)[e]	2.92[a]	(2.20)[b]	(1.71)[c]	(0.97)[d]	(0.66)[e]
With HPP	1.86[f]	(0.95)[g]	(0.82)[h]	(0.49)[i]	(0.42)[j]	1.53[f]	(1.42)[g]	(0.82)[h]	(0.68)[i]	(0.64)[j]	24.64[f]	(15.42)[g]	(14.80)[h]	(12.25)[i]	(9.37)[j]
Moisture															
Without HPP	(0.92)[a]	0.97[a]	1.15[b]	1.17[b]	1.23[c]	0.12[a]	0.48[b]	0.97[c]	1.16[d]	1.17[d]	0.95[a]	(0.80)[b]	(0.72)[c]	(0.66)[d]	(0.58)[e]
With HPP	(1.07)[d]	1.09[e]	1.30[f]	1.35[g]	1.57[h]	0.55[e]	1.02[f]	1.11[g]	1.52[h]	1.68[i]	0.96[a]	(0.75)[f]	(0.62)[g]	(0.52)[h]	(0.45)[i]
Solids															
Without HPP	(1.12)[a]	1.17[a]	1.29[b]	1.39[c]	1.47[d]	0.26[a]	1.04[b]	1.18[c]	1.34[d]	1.42[e]	2.20[a]	5.61[b]	7.33[c]	10.53[d]	12.45[e]
With HPP	(1.00)[e]	1.29[f]	1.39[g]	1.44[h]	1.72[i]	0.40[f]	1.14[g]	1.55[h]	1.60[i]	1.75[j]	1.24[f]	6.99[g]	11.67[h]	15.89[i]	16.45[j]

Table 1: Diffusion coefficient for moisture, solid and curcuminoids content during osmotic dehydration with and without application of high pressure (350 MPa/10 min).

The values of diffusion coefficients in the parenthesis indicate the absorption of water from surrounding solution to the pineapple slices. The corresponding values for solids indicate the loss of solids from pineapple slices to the surrounding medium. The values without parenthesis indicate the vice versa. The groups containing different letters in the same row (with respect to treatment) and same column (with respect to concentration) are found to be statistically significant at $p \leq 0.05$. The statistical significance between groups were determined using a one-way Analysis of Variance (ANOVA) followed by Turkey-Kramer test, with $p \leq 0.05$ indicating significance, using MS-Excel.

Acknowledgement

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