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To cite this article: Ana María Chaux-Gutiérrez, Adriana Barbosa Santos, Diana Maria Granda-Restrepo & Maria Aparecida Mauro (2017) Foam mat drying of mango: Effect of processing parameters on the drying kinetic and product quality, *Drying Technology*, 35:5, 631-641, DOI: [10.1080/07373937.2016.1201486](https://doi.org/10.1080/07373937.2016.1201486)

To link to this article: <https://doi.org/10.1080/07373937.2016.1201486>



Accepted author version posted online: 01 Jul 2016.
Published online: 27 Feb 2017.



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Foam mat drying of mango: Effect of processing parameters on the drying kinetic and product quality

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ABSTRACT

This study investigated the foam mat drying process parameters (temperature and concentration of foaming agents, albumin, and an emulsifier blend) and evaluated their effects on drying kinetics, color, carotenoid retention, and solubility of the mango pulp powder. Fick's model was able to represent the foam mat drying kinetics. The foaming agents and high temperatures enhanced the carotenoid retention. This was explained by the greater effective water diffusion coefficients that allowed obtaining products with low moisture contents and water activities in short processing times of up to 3 h, with high carotenoid retention and color maintenance.

KEYWORDS

Albumin; carotenoid; color parameters; diffusion coefficients; emulsifier blend; experimental design

Introduction

The mango (*Mangifera indica* L) stands out among the exotic fruits produced and exported by Brazil, and is considered to be an agricultural product of great economic importance with a production of 1,163,000 thousand tons in 2013.^[1] The mango is also nutritionally attractive due to its β -carotene content, which contributes to the nutritional value since it is an antioxidant and vitamin A precursor. The mango is also a source of vitamin C and phenolic compounds.^[2] However, it is highly perishable and can deteriorate in short periods of time and hence its postharvest handling is an important factor in the production chain. Thus drying appears as an alternative to prolong the useful life of this product,^[3] drying being one of the oldest and most widely used methods to conserve fruits.^[4] However, conventional hot-air drying presents various disadvantages such as the need for long processing times at elevated temperatures, making the process energetically expensive, causing degradation of vitamins, antioxidant substances and dietetic fibers, and affecting some of the sensory properties such as color, taste, and texture. Thus new drying methods, such as foam mat drying, have been proposed, aimed at maintaining the nutritional characteristics of the product and decreasing energy consumption.^[5,6] Foam mat drying involves converting a liquid or semiliquid material into a stable foam by

beating it with the addition of foaming agents, which produce and stabilize the foam, followed by drying in thin layers with hot air at atmospheric pressure,^[7–9] microwave,^[10] or freeze drying^[11] and finally grinding the dried material to obtain a powder. This technique has been investigated for the production of fruit juice and/or pulp powders, such as mango,^[9,12,13] apple,^[14] Gac fruit (*Momordica cochinchinensis*) aril,^[15] muskmelon (*Cucumis melo*),^[16] sour cherry,^[17] papaya,^[8] pineapple,^[6] purple-cherry,^[18] and blackcurrant.^[19] It has also been applied to obtain cowpea flour,^[20] albumin powder,^[11] shrimp powder,^[21] and yacon juice powder.^[22] Various foaming agents have been tested, and in all cases the authors managed to obtain formulations and procedures resulting in products with good sensory quality and fast drying rates. For instance, Kadam et al.^[12] used milk as the foaming agent to optimize the production of mango pulp. Rajkumar et al.^[13] also investigated the production of mango pulp, performed a large-scale study concerning the expansion capacity and stability of different foaming agents, and the influence of the thickness of the layers and drying temperature on the mango powder characteristics. Rajkumar et al.^[9] also developed a continuous foam dryer, where they tested the most effective conditions selected in an earlier study, which were 10% albumin with 0.5% methyl cellulose to stabilize the foam,

1-mm-thick layers and a temperature of 60°C. Nevertheless, there is still much to be learnt concerning this technology, especially with respect to the modeling of the process, which would provide subsidies for the design and control of foam mat drying. Thus, with the objective of evaluating the influence of the foam mat drying process parameters on drying kinetics and the physical and nutritional properties of the mango pulp powder, this work investigated the effects of temperature, the EMB concentration, ALB concentration, and the EMB–ALB mixture on diffusion coefficients, color maintenance, carotenoid content, and retention, and the solubility of the mango pulp powder.

Materials and methods

Raw materials

Mangoes (*M. indica* L. cv. “Tommy Atkins”), cultivated in Petrolina, Pernambuco State (Brazil), were purchased in December 2013 at the São José do Rio Preto Supply Center (CEAGESP; São José do Rio Preto, São Paulo, Brazil), and maintained at room temperature until mature. Maturity was determined visually by observing a red-yellow color of the fruit skin and a firm consistency on touching. Once mature, the pulp was obtained and stored in a freezer at -18°C in high-density polyethylene bags. Commercial albumin powder (ALB) of the brand Naturovos (Salvador do Sul, RS, Brazil) was used and a commercial grade mixture of distilled fatty acid monoglycerides, sorbitan monostearate, and sorbitan monostearate polyoxyethylene (EMB) (Duas Rodas Industrial, Jaraguá do Sul, SC, Brazil).

Methods

Foam preparation

Before foam preparation, the frozen pulp was thawed at refrigeration temperature (5°C) for 24 h. For foam preparation, approximately 300 g of thawed pulp was added to the mixer bowl and quantities of ALB and EMB or their combinations added according to the experimental design shown in Table 1. The mixture was then beaten in a 3-speed RI 7110 domestic beater (Philips Walita, Brazil) for 5 min. The first minute was at medium speed, aimed at dissolving the foaming agents, and the remaining 4 min at high speed for better incorporation of the air in the emulsion.

Drying

The mango foams produced with the different emulsifiers were dried with air heated at two temperatures, 60 and 80°C , with an air speed of $1.0\text{ m}\cdot\text{s}^{-1}$ and layer thickness of 3 mm. The dryer used had a fixed bed with

Table 1. 2^3 Factorial experimental design with coded and noncoded factors applied to the foam mat drying of mango.

Trial	Factors		
	Temperature ($^{\circ}\text{C}$), x_1	EMB concentration ($\text{kg EMB}\cdot 100\text{ kg}^{-1}$ pulp), x_2	ALB concentration ($\text{kg ALB}\cdot 100\text{ kg}^{-1}$ pulp), x_3
1	60 (−1)	2 (1)	10 (1)
2	80 (1)	0 (−1)	0 (−1)
3	60 (−1)	2 (1)	0 (−1)
4	60 (−1)	2 (1)	0 (−1)
5	80 (1)	2 (1)	10 (1)
6	80 (1)	2 (1)	10 (1)
7	60 (−1)	0 (−1)	0 (−1)
8	80 (1)	0 (−1)	0 (−1)
9	60 (−1)	0 (−1)	10 (1)
10	60 (−1)	0 (−1)	0 (−1)
11	80 (1)	0 (−1)	10 (1)
12	80 (1)	2 (1)	0 (−1)
13	60 (−1)	0 (−1)	10 (1)
14	60 (−1)	2 (1)	10 (1)
15	80 (1)	0 (−1)	10 (1)
16	80 (1)	2 (1)	0 (−1)

ALB, mango powder with albumin ($10\text{ kg ALB}\cdot 100\text{ kg}^{-1}$ pulp); EMB, mango powder with emulsifier blend ($2\text{ kg EMB}\cdot 100\text{ kg}^{-1}$ pulp).

forced convection of the heated air using a centrifugal fan controlled by a frequency inverter (CWF10, WEG, Jaraguá do Sul, Brazil), which allows one to change the air speed. The air was heated by electric resistances and the temperature controlled using a microprocessor digital controller (N440, Novus, Porto Alegre, Brazil) with a J-type thermocouple. The relative humidity and air velocity were measured by a humidity sensor (DO9861T-R1m Delta Ohm, Caselle di Selvazzano, Itália) and the hot wire anemometer (HD403TS 1, Delta Ohm), respectively.

For each trial, the foams were filled into specially made $30\times 30\text{ cm}^2$ aluminum trays with 3-mm-high borders. The trays were previously weighed and identified, the maximum foam weight being 100 g. The trays containing the samples were weighed every 10 min during the first hour of drying and then every 15 min to constant weight. After each weighing, the tray was turned through 180° and placed in a new vertical position in the drying chamber. After reaching equilibrium, the dried foam block was removed with the help of a spatula for subsequent grinding. Curves were drawn using the data for water content on a dry basis as a function of drying time. The water content, color, and carotenoid contents were determined on the samples before and after the drying steps.

Drying kinetics

The drying mechanisms involved with foam drying could be compared with those attributed to porous material drying, which has been very well described in the literature.^[23] The solids that form the bubbles would be considered a skeleton with water saturating the wall-surfaces and occupying narrow spaces and capillaries. In

the initial stages of drying, water should migrate mainly by capillarity but shortly after by creeping along the walls. Also, as drying proceeds, liquid water bridges are formed in narrow spaces and water should migrate by successive evaporation–condensation between the water bridges.^[23] The vapor flow will predominate only at the last stage, when the drying takes place in all material, and an equilibrium state will be reached if the amount of water that vaporizes equals the amount that condenses.^[23]

For foam mat drying, it was considered that the drying process can be described by the falling-rate period, where the liquid diffusion is the principal flow mechanism. Thus, the drying kinetics was evaluated based on Fick's second law,^[24] presented below in its modified form in terms of the mass fractions on a dry weight basis, considering the concentration of the solids to be constant:

$$\frac{\partial X}{\partial t} = D_{\text{eff}} \nabla^2 X \quad (1)$$

where X is the mass fraction of water on a dry weight basis ($\text{kg} \cdot \text{kg}^{-1}$, db), D_{eff} is the effective water diffusion coefficient ($\text{m}^2 \cdot \text{s}^{-1}$), and t is the time (s).

To determine the diffusivity coefficient, the infinite plate geometry was assumed in the diffusion model, with only one surface exposed to the drying air. Moisture migration occurred in the direction of the thickness of the material. Thus considering that water migration only occurred in the direction z , that the moisture was uniformly distributed in the foam at the initial moment, and that external resistance to moisture transference was insignificant, Eq. (1) would be subjected to the following conditions:

$$t = 0, \text{ for the whole of } z, X = X_0 \quad (2)$$

$$t > 0, z = 0, \left. \frac{\partial X}{\partial z} \right|_{z=0} = 0 \quad (3)$$

$$t > 0, z = L, X = X_{\text{eq}} \quad (4)$$

where X_0 and X_{eq} represent the water content on a dry weight basis ($\text{kg} \cdot \text{kg}^{-1}$, db) at the initial moment ($t = 0$) and at equilibrium (eq).

The effective diffusion coefficient was treated as constant. Effects of the temperature gradient which could affect the phenomenon of water transference in the product were assumed negligible. Hence, these were encompassed by the effective diffusion coefficient that also absorbs the effects of shrinkage, porosity, and tortuosity. The analytical solutions are applicable to solids with simple, constant geometry throughout the process,^[24] although widely used in drying studies, even with highly deformable solids.

In order to determine the effective water diffusion coefficients according to Fick's second law, applied to an infinite plate and subject to the initial condition and to the boundary conditions given by Eqs. (2)–(4), the analytical solution of Eq. (1) integrated throughout the distance z was used^[24]:

$$MR = \frac{\bar{X} - X_{\text{eq}}}{X_0 - X_{\text{eq}}} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[-\frac{(2n+1)^2 \cdot \pi^2 \cdot D_{\text{eff}} \cdot t}{4L^2} \right] \quad (5)$$

where D_{eff} is the effective water diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$), moisture ratio (MR) is the nondimensional aspect of the water concentration, \bar{X} represents the mean water content on a dry weight basis ($\text{kg} \cdot \text{kg}^{-1}$ dry matter) in time t (s), X_{eq} and X_0 represent the water contents on a dry weight basis ($\text{kg} \cdot \text{kg}^{-1}$ dry matter) at equilibrium and at the initial moment, respectively, and L is the thickness of the plate exposed to the drying air at just one of its faces. The analytical solutions of Fick's law are applicable to solids with simple, constant geometry throughout the process,^[24] although widely used in drying studies, even with highly deformable solids. However, in the present study a simplified procedure that uses shrinkage consideration was applied. In an approximate way, the thickness of the plate L was considered as a linear function of the moisture content of the foam. The incorporation of thicknesses that vary as a function of moisture content in the integrated analytical solutions of the diffusion equation has proved to be a suitable method to decrease the influence of shrinkage on the effective diffusion coefficients determined by these equations. This diminished the discrepancies resulting from the consideration of the initial thickness as constant throughout the whole drying process, for highly deformable materials.^[25]

Color analyses

The colors of the foams and mango powders were determined using a ColorFlex model 45/0 spectrophotometer (Hunterlab, USA) with the D65 illuminant and observer at 10° . The 4.10 version universal software was used to determine the absolute values of L^* , a^* , and b^* . The chroma (C^*), which expresses the degree of intensity or saturation of the color (Eq. 6), and also the hue angle (h^*), which represents the tonality of the color (Eq. 7),^[26] were also calculated:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (6)$$

$$h^* = \text{arctg} \left(\frac{b^*}{a^*} \right) \quad (7)$$

Carotenoids and percent retention

The total carotenoid content was determined according to the methodology described by Rodriguez-Amaya and Kimura.^[27] The carotenoids were extracted using acetone from approximately 2 g of raw sample and 1 g of dry sample using the Turrattec model TE-102 equipment (Tecnal, Brazil). To facilitate the extraction, the raw samples remained in the acetone for 10 min, and the dry samples were previously rehydrated in distilled water for 20 min. The absorbance of the extracts was measured at the wavelength of maximum absorption (450 nm) using a model SP-220 UV-visible spectrophotometer (Biospectro, Brazil). All analyses were performed in duplicate. The retention of the carotenoids was calculated according to Murphy et al.^[28] (Eq. 8):

$$\text{Ret}(\%) = \frac{C_f \cdot M_f}{C_i \cdot M_i} \cdot 100 \quad (8)$$

where Ret is the percent total carotenoid retention, C_f is the final total carotenoid content of the samples, C_i is the initial total carotenoid content ($\mu\text{g } \beta\text{carotene} \cdot \text{g}^{-1}$ total), M_f is the final sample mass, and M_i is the initial sample mass (g).

Solubility

The solubility of the powders was determined according to Caparino et al.^[29] with some modifications. A quantity of 0.5 g of sample of powder was dispersed in 50 mL of distilled water and mixed at high speed ($\sim 13,000$ rpm) for 5 min using a TE-102 Turrattec equipment (Tecnal, Brazil). The dispersion was then centrifuged at $3,500 \times g$ for 5 min and a 12-ml aliquot of the supernatant transferred to a previously weighed Petridish and dried in an oven at 105°C (MA 033, Marconi, Brazil) to constant weight.

Experimental design

A 2^3 complete factorial design with two repetitions, giving a total of 16 treatments, was used to characterize the foam mat drying process and determine the factors influencing the responses of the color parameters (L^* , a^* , b^* , C^* , and h^*), carotenoid retention and powder solubility. Each treatment corresponded to a combination of the levels of the factors, that is: drying temperature x_1 , EMB concentration x_2 , and ALB concentration x_3 . All the factors were investigated at two levels, the codified maximum level being equal to +1 and the minimum to -1. Table 1 shows the codified values of the factors and the order the experiments were performed.

The regression model was fitted to describe each response variable, according to the general form of the

first-order model described by Montgomery^[30]:

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + \varepsilon_i \quad (9)$$

In Eq. (9), y identifies the response variable, where $i = 1, 2, 3, 4, 5, 6, 7$, or more specifically y_1 represents the lightness (L^*), y_2 the parameter a^* , y_3 the parameter b^* , y_4 the chroma (C^*), y_5 the hue angle (h^*), y_6 the percent carotenoid retention, y_7 the solubility, and y_8 the diffusion coefficient of water. $\beta_0, \beta_1, \beta_2, \beta_3, \beta_{12}, \beta_{13}, \beta_{23}, \beta_{123}$, are the model parameters (regression coefficient) whose values are to be determined, x_1 is a variable that represents the factor temperature, x_2 is a variable that represents the factor EMB concentration, and x_3 is a variable that represents the factor ALB concentration. Finally $x_1 x_2$, $x_1 x_3$, $x_2 x_3$ and $x_1 x_2 x_3$ represent the interactions and ε_i is the random error term.

Statistical analyses

Analyses of variance were performed to evaluate the influence of the response variables of interest, considering a significance level of 5%. The results were obtained using the Minitab 16[®] program. Fick's Law mathematical model was fitted to the experimental drying curves using the program Statistica 7.0. The coefficient of determination (R^2) and the chi-squared statistic χ^2 were used to evaluate the capacity of the mathematical model to represent drying, and the best fit was identified for high R^2 values and low χ^2 values.

Results and discussion

Effects of temperature and foaming agent concentration

The mango pulp used in all the trials was characterized with respect to its moisture content, carotenoid content, °Brix, pH, and color parameters (Table 2).

Table 3 shows the results of the responses evaluated during the mango pulp foam mat drying process, determining the color parameters L^* , a^* , b^* , C^* and h^* , carotenoid retention and powder solubility. Table 4 shows the results obtained in the significance tests associated with each term in the model fitted for the different response variables, and Table 5 shows the estimates for the regression coefficients for each term in the model.

Lightness (L^*) was significantly affected by the presence of the foaming agents and by the interaction between them (Table 4) but not by the temperature. As shown by coefficient β_2 (Table 5), an increase in

Table 2. Means and standard deviation for each physico-chemical characteristics of the mango pulp.

Parameter	Value
Moisture content (kg water · 100 kg ⁻¹ total)	85.66 ± 0.11
Soluble solids (°Brix)	13.81 ± 0.05
pH	4.01 ± 0.06
Carotenoids (µg g ⁻¹ total)	16.90 ± 0.43
<i>L</i> [*]	58.91 ± 0.08
<i>a</i> [*]	11.93 ± 0.35
Color parameters	
<i>b</i> [*]	71.78 ± 0.57
<i>C</i> [*]	59.33 ± 1.32
<i>h</i> [*]	80.57 ± 0.53

the EMB concentration resulted in a pronounced tendency for an increase in the value for lightness (*L*^{*}). Similar behavior was also shown by coefficient β₃ for an increase in the ALB concentration (Table 5). However, the interaction between these two factors resulted in a negative effect on lightness, although the coefficient, β₂₃, whose value in the module was lower than that of β₁ and of β₂, exerted a smaller weight on this response, such that the values for *L*^{*} were still very high when a mixture of the two agents was present (Table 3). The *L*^{*} value increasing was attributed to the incorporation of the air into the mango pulp during the foaming process, which increases with the addition of foaming agents.^[16] Other authors have also found high values for lightness in powders obtained by foam mat drying. Falade et al.^[20] obtained a value for *L*^{*} of 76.76 in cowpea powder containing glyceryl monostearate, whereas Karim and Wai^[31] obtained values of 78.4 for starfruit powder obtained from a mixture of the pulp with methylcellulose as the foaming agent. High values for lightness (70) were also reported by Chauhan and Patil^[32] who spray dried mango pulp with milk.

The parameter *a*^{*} was affected by the EMB concentration, the ALB concentration, and by the interactions between the temperature and EMB concentration and between the temperature and ALB concentration (Table 4). Although the rise in temperature caused a slight increase in this response, the effect of the foaming agents was negative and more intense than that of temperature (Table 5). From the experimental results, it is possible to conclude that the addition of foaming agents tends to reduce *a*^{*} value, indicating that they could reduce the nonenzymatic browning reactions.^[33] The parameter *b*^{*} is one of the most important characteristics in terms of mango color, since it indicates the intensity of the yellow color. During processing, *b*^{*} was significantly affected by the interaction between the agents EMB-ALB and by the ALB concentration (Table 4), although the temperature alone did not exert a significant effect on *b*^{*}. An increase in the concentration of EMB, ALB, or of both implied in a slight decrease in the parameter *b*^{*} in the dehydrated powder, even at a higher drying temperature (80°C), since this parameter was positively affected by the temperature only through the interaction factor β₁₂₃ (Table 5). Similar results were obtained by Gupta and Alam,^[34] which reported that the incorporation of egg albumen and methyl cellulose as foaming agents in grape concentrate decreased the parameters *a*^{*} and *b*^{*}.

The parameter *h*^{*}, which represents the tonality of the powders, was affected by the three variables involved in the process, negatively by temperature but positively by the EMB and ALB concentrations, and also by the interactions between the temperature and EMB concentration and between the temperature and ALB

Table 3. Descriptive statistics for the color parameters, carotene retention, solubility, and diffusion coefficients related to the 2³ factorial experimental design for mango powders.

Treatments (randomized trial)	Responses							<i>D</i> _{eff} × 10 ¹⁰ (m ² · s ⁻¹) [<i>R</i> ²]
	<i>L</i> [*]	<i>a</i> [*]	<i>b</i> [*]	<i>h</i> [*]	<i>C</i> [*]	Ret (%)	<i>S</i>	
60°C								
Pulp (7)	44.90 ± 1.27	6.52 ± 1.08	39.68 ± 3.81	80.70 ± 0.92	45.38 ± 1.18	36.53 ± 0.99	88.90 ± 2.43	2.41 [0.995]
Pulp (10)	45.30 ± 0.63	6.45 ± 0.21	42.86 ± 1.26	81.43 ± 0.40	45.76 ± 0.65	45.42 ± 5.09	86.23 ± 1.95	2.15 [0.995]
EMB (3)	82.47 ± 0.26	5.01 ± 0.20	52.25 ± 0.89	84.53 ± 0.12	52.48 ± 0.90	67.55 ± 0.03	91.03 ± 0.72	2.49 [0.987]
EMB (4)	83.95 ± 0.31	4.17 ± 0.05	47.21 ± 0.19	84.95 ± 0.05	47.39 ± 0.19	61.18 ± 5.00	90.52 ± 2.39	2.91 [0.992]
ALB (9)	79.65 ± 0.22	6.76 ± 0.26	43.76 ± 1.62	81.34 ± 0.06	44.27 ± 1.64	53.75 ± 0.73	88.39 ± 0.49	3.66 [0.998]
ALB (13)	77.98 ± 0.23	6.72 ± 0.11	45.43 ± 0.84	81.63 ± 0.04	45.92 ± 0.85	57.72 ± 10.78	84.32 ± 1.38	3.44 [0.997]
EMB-ALB (1)	84.76 ± 0.13	2.91 ± 0.09	36.32 ± 0.76	85.42 ± 0.06	36.43 ± 0.76	72.84 ± 6.91	82.79 ± 0.48	2.82 [0.998]
EMB-ALB (14)	83.05 ± 0.04	3.40 ± 0.07	40.19 ± 0.18	85.15 ± 0.08	40.33 ± 0.18	78.60 ± 2.41	88.07 ± 0.69	2.52 [0.996]
80°C								
Pulp (2)	44.61 ± 0.70	14.00 ± 1.74	46.77 ± 3.11	73.39 ± 0.96	46.78 ± 1.13	42.91 ± 4.42	85.07 ± 0.56	3.47 [0.994]
Pulp (8)	52.33 ± 0.33	11.19 ± 0.31	46.95 ± 1.11	76.59 ± 0.12	53.51 ± 0.29	50.25 ± 4.61	83.87 ± 0.20	3.05 [0.996]
EMB (12)	80.58 ± 0.36	6.65 ± 0.18	50.62 ± 0.44	82.51 ± 0.24	51.01 ± 0.42	59.91 ± 0.29	89.54 ± 0.62	5.17 [0.992]
EMB (16)	81.87 ± 0.43	5.65 ± 0.28	49.64 ± 1.93	83.51 ± 0.08	49.96 ± 1.95	61.01 ± 3.01	92.51 ± 0.97	5.49 [0.996]
ALB (11)	78.81 ± 0.24	6.76 ± 0.11	46.56 ± 1.57	81.73 ± 0.21	47.05 ± 1.57	83.94 ± 18.74	84.45 ± 1.10	5.17 [0.995]
ALB (15)	77.60 ± 0.43	6.61 ± 0.16	43.29 ± 0.99	81.26 ± 0.18	43.76 ± 0.99	94.45 ± 5.57	85.90 ± 0.55	4.96 [0.995]
EMB-ALB (5)	85.18 ± 0.16	2.48 ± 0.02	35.55 ± 0.20	86.01 ± 0.02	35.63 ± 0.20	81.24 ± 9.25	88.84 ± 0.47	6.12 [0.997]
EMB-ALB (6)	83.66 ± 0.26	3.54 ± 0.04	38.05 ± 0.61	84.68 ± 0.04	38.21 ± 0.61	75.88 ± 1.53	82.70 ± 2.26	5.34 [0.995]

Pulp, pure mango pulp; ALB, mango powder with albumin (10 kg ALB · 100 kg⁻¹ pulp); EMB, mango powder with emulsifier blend (2 kg EMB · 100 kg⁻¹ pulp); EMB-ALB, mango powder with albumin (10 kg ALB · 100 kg⁻¹ pulp) and emulsifier blend (2 kg EMB · 100 kg⁻¹ pulp).

Table 4. Results of the analysis of variance for the influence of the factors on the responses: color parameters, carotene retention, powder solubility, and effective diffusion coefficients.

Source of variation	Df	L^*		a^*		b^*		h^*		C^*		Ret (%)		S (%)		$D_{\text{eff}} \times 10^{10} \text{ (m}^2 \cdot \text{s}^{-1}\text{)}$	
		SQ	P-value	SQ	P-value	SQ	P-value	SQ	P-value	SQ	P-value	SQ	P-value	SQ	P-value	SQ	P-value
x_1	1	0.42	0.770	13.93	0.002	5.91	0.282	14.96	0.003	21.66	0.320	371.57	0.003	3.412	0.485	16.734	0.000
x_2	1	1,678.60	0.000	60.90	0.000	1.87	0.534	93.59	0.000	32.15	0.233	527.63	0.001	22.223	0.090	1.2854	0.004
x_3	1	1,133.44	0.000	26.17	0.000	137.13	0.001	24.06	0.001	0.21	0.918	1,908.95	0.000	30.881	0.590	2.9866	0.000
$x_1 x_2$	1	4.47	0.352	5.39	0.023	12.14	0.137	4.85	0.047	19.58	0.343	389.01	0.003	5.920	0.363	2.5544	0.001
$x_1 x_3$	1	0.55	0.738	15.51	0.001	12.61	0.131	15.49	0.003	55.15	0.129	289.90	0.006	1.004	0.702	0.2351	0.130
$x_2 x_3$	1	886.90	0.000	0.30	0.528	171.4	0.000	4.11	0.063	14.83	0.406	185.30	0.018	25.428	0.081	1.8312	0.002
$x_1 x_2 x_3$	1	10.51	0.168	4.97	0.028	2.88	0.445	4.63	0.051	0.28	0.906	118.82	0.046	0.837	0.726	0.0026	0.863
Pure error	8	36.52		5.49		35.62		7.04		154.31		170.07		50.940		0.6590	
R^2		0.99		0.95		0.91		0.96		0.48		0.96		0.64		0.97	
Adjusted R^2		0.98		0.92		0.82		0.92		0.03		0.92		0.32			0.95

df, degrees of freedom.

concentration (Table 4). This signified that an increase in concentration of the foaming agents tended to increase h^* , making the powders more yellow rather than more orange, even with decreases in the values for b^* and a^* , since the parameter h^* results from a combination of the two (Eq. 7). For its part, the temperature affected this parameter negatively, which was more evident in the pulp without additives, whose yellow tonality became more orange at 80°C due to the decrease in the value of h^* (Table 3).

On the other hand, the parameter chroma was not significantly affected by the factors analyzed (Table 4). An analysis of how the color is perceived in terms of °hue and chroma is of great importance, since they indicate the tonality of the mango powders and how bright its color is after drying under the different process conditions. From the results obtained (Table 3), it can be seen that the values found for °hue in the powders prepared with additives were always close to 80°, indicating a yellowy-orange tone. In addition, the values for chroma presented values between 36 and 50 units, indicating less saturation and consequently a less intense color. Caparino et al.^[29] reported data for spray-dried mango powders with added maltodextrin, showing values for °hue around 80 and for chroma around 40, close to the values obtained in the present study, signifying that the different additives produced powders of similar color. However it must be mentioned that the powders with added EMB always

presented more vivid colors than those with added ALB-EMB.

Percent total carotenoid retention

With respect to the percent total carotenoid retention, this response was significantly affected by all the factors, including the interactions (Table 4). The most significant effect was due to the ALB concentration, which caused increased retention with increasing concentration. Similarly increments in the EMB concentration, in the temperature and in the temperature-ALB concentration interaction, all exerted positive effects on retention, while the temperature-EMB concentration and ALB concentration-EMB concentration interactions presented negative effects on this response. On comparing the product obtained from the pulp dried without additives with those dried with foaming agents, the latter presented retentions equal or higher than 53%, showing that their addition improved carotenoid retention. These results suggest that the addition of ALB, EMB, or EMB-ALB provides some protection against degradation of the carotenoids, resulting in higher retention than without the foaming agents. The greatest percent retention of 88.9% was obtained with ALB at 80°C. High carotenoid retention was reported by Pott et al.^[35] on drying mango slices for short periods of 3.5 h, obtaining retentions of *trans*- β -carotene in the range from 70% to 93%. In general, better percent

Table 5. Regression coefficients for the fitted model according to Eq. (9) for the responses to the mango powder parameters: Responses for the color parameters, carotenoid retention, and coefficient of diffusion.

	L^*	a^*	b^*	h^*	Ret (%)	$D_{\text{eff}} \times 10^{10} \text{ (m}^2 \cdot \text{s}^{-1}\text{)}$
β_0	72.918	6.177	44.068	82.1772	63.882	3.8234
β_1	0.162*	0.933	0.608*	-0.9669	4.819	1.0227
β_2	10.270	-1.951	-0.343	2.4186	5.743	0.2834
β_3	8.417	-1.279	-2.928	1.2264	10.923	0.4320
β_{12}	-0.528*	-0.581	-0.871*	0.5503	-4.931	0.3996
β_{13}	-0.185*	-0.985	-0.888*	0.9838	4.257	0.1212*
β_{23}	-7.445	0.137*	-3.274	-0.5069*	-3.403	-0.3383
β_{123}	0.811	0.557	0.424	-0.5380	-2.725	-0.0128*

*Nonsignificant term.

carotenoid retentions were obtained at the higher temperature in the present study. This was due to the fact that at the higher temperature, the lipoxygenases, responsible for the enzymatic degradation of the carotenoids, showed a minimal rate of activity.^[36] In addition, all the drying times were short, which could have contributed to the maintenance of these compounds due to the rapid decrease in moisture content and reduced time of exposure to oxygen. Sramek et al.^[37] when drying tomato paste foamed with whey protein isolate or egg white, found that β -carotene content did not show significant differences for drying temperatures between 50 and 70°C, being that its minimum retention was 81%. The relation between the drying time and carotenoid retention has been described by Auisakchaiyoung and Rojanakorn^[15] for dried Gac fruit (*M. cochinchinensis*) aril. The authors found the greatest degradation of β -carotene for the lengthy dryings, which, in turn, were dependent on the foam thickness and the drying temperature.

Solubility

The solubility of the mango powders was not significantly affected by the ALB concentration, EMB concentration (Table 4), which could be attributed to the influence of the sugars on the solubility (S), since their amounts are the highest in comparison to the total solutes of the powders. Even though the solubility was not significantly affected by the foam agents, it can be observed that the EMB powders were more soluble than those obtained with ALB or EMB-ALB (Table 3). These differences could have been due to the nature of the emulsifiers used, since they have the capacity to improve the solubility due to the lipophilic-hydrophilic balance of the molecule.^[38] Also, the drying temperature did not significantly affect the solubility (Table 4). This behavior has also been reported by Mishra et al.^[39] for the solubility of amla (*Embllica officinalis*) juice powder and by Franco et al.^[22] for the yacon juice powder. The solubility of the present powders was similar to

that of powders obtained by Caparino et al.^[29] by freeze-drying Philippine mangoes of the variety "Carabao" (89.70 kg 100 kg⁻¹), but lower than the values obtained for the same mango variety using a rotary drum and a spray drier (the latter with the addition of maltodextrin), which presented values of 94.38 and 95.31 kg 100 kg⁻¹, respectively. Conversely, in the present study, the solubility values were higher than those reported by Wilson et al.^[40] for mango juice powder obtained by foam mat drying using albumin as foaming agent, whose values were between 51.83 and 66.65 kg · 100 kg⁻¹.

Drying kinetics

The foams produced with EMB, ALB, and EMB-ALB and the fresh pulp presented mean initial water contents of 85.67 ± 0.22 kg · 100 kg⁻¹ total mass, 78.61 ± 0.25 kg · 100 kg⁻¹, 78.70 ± 0.23 kg · 100 kg⁻¹, and 85.87 ± 0.57 kg · 100 kg⁻¹, respectively, values which were reduced by drying to moisture contents in the range from 3.33 to 1.52 kg · 100 kg⁻¹ in powders containing additives, and from 8.44 to 6.55 kg · 100 kg⁻¹ in the powder without additives (Table 2). The water content differences between the powders obtained from foamed and nonfoamed mango pulp were related to the foam structure, which increases the evaporation surface, improving the process of moisture removal from the product.^[16,41,42] Hence, the powders containing foaming agents demonstrated the potential of this technology, since these low moistures should confer stability and the properties required for fruit pulp powders. Similar moisture content values were found for foam mat-dried products, such as pineapple pulp powder^[6] (3–3.5 kg · 100 kg⁻¹ total mass), muskmelon pulp powder^[16] (2.69–2.2 kg · 100 kg⁻¹ total mass), and mango pulp powder with egg white^[43] (1.12–3.05 kg · 100 kg⁻¹ total mass). As shown in Table 6, the water contents of the ALB and EMB-ALB powders showed differences according to the temperature used (80 or 60°C), whereas the EMB powders showed similar moisture contents for the two temperatures.

Table 6. Water content and water activity (measured at 25°C) of the mango powders obtained in the different treatments.

Formulation	Drying temperature (°C)	Relative humidity RH (%)	Water content (kg · 100 kg ⁻¹ total mass)	a_w (at 25°C)
Pulp	60	9.24 ± 0.47	8.44 ± 0.32 ^a	0.46 ± 0.04 ^a
	80	5.29 ± 0.23	6.55 ± 0.69 ^b	0.38 ± 0.03 ^b
ALB	60	10.69 ± 0.50	2.95 ± 0.97 ^c	0.27 ± 0.01 ^c
	80	5.15 ± 0.20	1.55 ± 0.17 ^d	0.15 ± 0.02 ^d
EMB	60	9.74 ± 0.44	3.33 ± 0.34 ^c	0.21 ± 0.01 ^e
	80	5.59 ± 0.19	2.87 ± 0.25 ^c	0.20 ± 0.01 ^e
EMB-ALB	60	9.48 ± 0.41	3.43 ± 0.23 ^c	0.27 ± 0.03 ^c
	80	4.90 ± 0.16	1.32 ± 0.20 ^d	0.13 ± 0.02 ^d

Means with the same letter in the same column indicate no significant difference by the Tukey test ($P < 0.05$). Pulp, pure mango pulp; ALB, mango powder with albumin (10 kg 100 kg⁻¹ pulp); EMB, mango powder with emulsifier blend (2 kg · 100 kg⁻¹ pulp); EMB-ALB, mango powder with albumin (10 kg 100 kg⁻¹ pulp) and emulsifier blend (2 kg 100 kg⁻¹ pulp). Means of two experimental trials ± standard deviation.

The water activities of the mango powders with ALB, EMB, and EMB-ALB were between 0.27 and 0.13, whose values are sufficiently low to prevent growth of microorganisms. In addition, one must mention that low a_w values contribute to pigment and/or color stability, since in the a_w range between 0.1 and 0.4, auto-oxidation reactions are minimal due to inactivation of the lipoxygenases.^[44] It should be noted that the powders with ALB and EMB-ALB showed low values for water activity, in the range between 0.15 and 0.13, when dried at 80°C. Similar values of a_w were reported for the powders obtained from yacon juice foamed with albumin and dried at 50, 60, and 70°C,^[22] Gac fruit foamed with methylcellulose and dried at 60, 70, and 80°C^[15] and shrimp powder foamed with xanthan gum and dried at 45, 60, 75, and 90°C.^[21]

Figure 1a shows the moisture content of the foams as a function of time, representing the drying kinetics at 60°C of the mango pulp foams containing EMB, ALB, EMB-ALB, and without the addition of foaming agents. An evaluation of the drying times at 60°C showed that the foams prepared with EMB and EMB-ALB exhibited

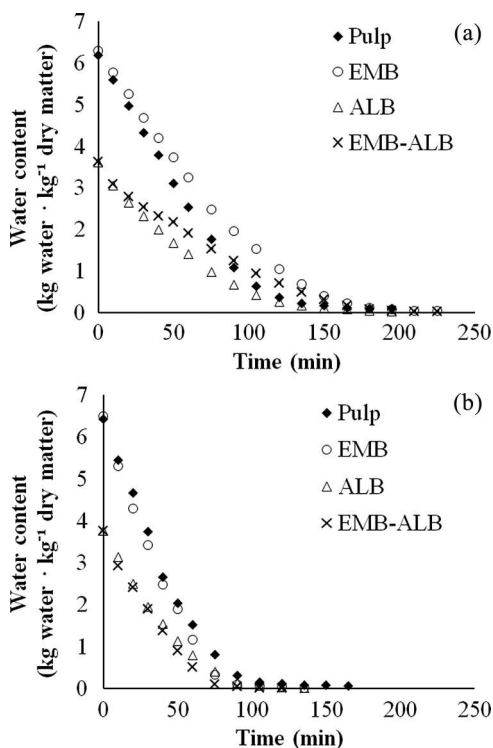


Figure 1. Drying kinetics of the pure mango pulp, and of the foams with EMB (2 kg 100 kg⁻¹ pulp), with ALB (10 kg 100 kg⁻¹ pulp), and with EMB (2 kg 100 kg⁻¹ pulp) plus ALB (10 kg 100 kg⁻¹ pulp) at 60°C (a) and 80°C (b). Note: ALB, mango powder with albumin (10 kg 100 kg⁻¹ pulp); EMB, mango powder with emulsifier blend (2 kg · 100 kg⁻¹ pulp); EMB-ALB, mango powder with albumin (10 kg 100 kg⁻¹ pulp) and emulsifier blend (2 kg 100 kg⁻¹ pulp).

a tendency for longer drying times than the foams produced with ALB or the fresh pulp. At 60°C, the foam with ALB reached low moisture contents quicker than the other foams and also than the pulp without additives. At 80°C, the differences between the drying times required to reach lower moisture contents were less pronounced (Fig. 1b), although the equilibrium moisture contents showed differences due to the water sorption properties of the different components and to their proportions in the foam compositions. Table 6 shows that the mango pulp without the addition of any additive retained the largest amount of moisture, this being associated with the elevated sugar content in relation to the total dry matter when compared to formulations with foaming agents, since the water interact more with the sugars^[45] than with the proteins.^[46] When dried at 60°C, the equilibrium moisture content reached for the pulp was 8.44 ± 0.32 kg water · 100 kg⁻¹ total mass (Table 6), significantly different from the equilibrium moisture content attained with EMB, with a value of 3.33 ± 0.22 kg water · 100 kg⁻¹ total mass. However the drying of the pulp without additives showed greater drying rates than the foams with EMB (Fig. 1a). Since the drying rate of the pulp was higher at the start of drying, this suggests the formation of hardened crusts on the surface of the dehydrated pulp at 60°C, making the loss of further water difficult in the later stages of drying.

However, one must consider that if, on one hand, migration of the water inside the foam to the surface is facilitated by the porous structure, on the other hand, the emulsifier agents have the role of retaining water. Consequently, the drying curves are the result of these two factors, which exert opposite effects on the drying rates. It is possible that at 60°C the effect of water retention by the emulsifiers was more pronounced than the effect of porosity, justifying the greater drying rate of the pulp.

The behavior of the drying curve at 80°C shows a tendency for a greater moisture loss than that obtained at 60°C, which may be explained by an increase in molecular mobility thereby improving the removal of water from the foams and consequently reducing the drying times.^[17] On comparing the EMB foams with the fresh pulp, it can be seen that at this high temperature, the curves showed similar moisture loss behaviors, the drying rate of the foam with EMB being slightly superior to that of the pulp, indicating an increase in the efficiency of the foam mat. Once again, the equilibrium moisture content reached by the fresh pulp was high, equal to 6.55 ± 0.69 kg water · 100 kg⁻¹ total mass (Table 5), significantly higher than that obtained for the EMB foam, which was 2.87 ± 0.25 kg water · 100 kg⁻¹

total mass. This could be explained by the greater water retention due to the greater proportion of sugars in the total dry mass of the fruit pulp powder. With respect to the emulsifier agents, the drying kinetics at 60 and 80°C always showed superior drying rates for the foams with EMB than for the foams with ALB or EMB–ALB. This could be a result of the lower density obtained in the EMB foams, which improved the migration velocity of the water inside the product.

During foam mat drying, it was considered that the movement of moisture into nonfoamed and foamed mango pulp was by liquid diffusion. Thus, the drying kinetics was described according to Fick's law of diffusion^[22] and the curves are represented in Fig. 1. The effective diffusion coefficients are shown in Table 3 with their corresponding coefficients of determination R^2 (above 0.98).

Other authors have modeled the drying kinetics of foams using the diffusion equation, for example, Thuwapanichayanan et al.^[47] for banana foam and Djaeni et al.^[48] for carrageenan foam. The effective diffusion coefficients for the water in the fresh mango pulp and mango foams were calculated as from the analytical solution of Fick's equation (Eq. 5). This was fitted to the experimental data of two trials using the Statistica 7.0 software, with seven terms, a number which enables one to obtain convergence of the diffusivity values. Figures 2 and 3 compare the experimental data with the results calculated according to Eq. (5), for drying at 60 and 80°C, respectively. The D_{eff} was affected by the temperature, concentrations of EMB and ALB, and also by the interactions between the temperature and EMB concentration and between the concentrations of

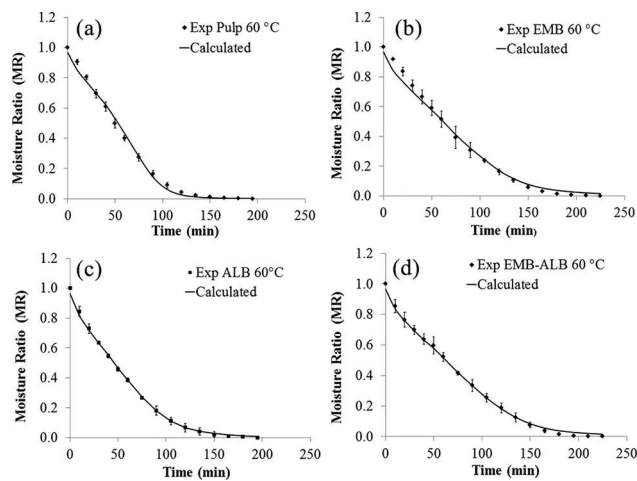


Figure 2. Ratios of the experimental to the predicted moisture contents at 60°C for (a) mango pulp, (b) foam with EMB, (c) foam with ALB, and (d) foam with EMB–ALB. The bars represent the standard deviation.

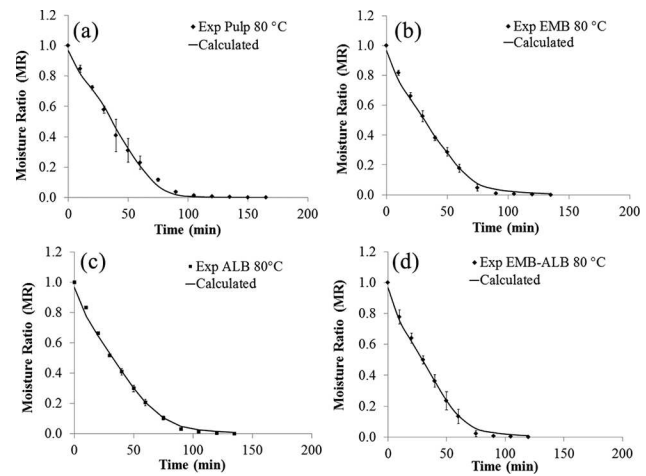


Figure 3. Ratios of the experimental to the predicted moisture contents at 80°C for (a) mango pulp, (b) foam with EMB, (c) foam with ALB, and (d) foam with EMB–ALB. The bars represent the standard deviation.

EMB and ALB (Table 4). Temperature was the highest and positive effect on the water diffusivity (Table 5). The change in temperature from 60 to 80°C caused an increase in the diffusion coefficients for both the foams and pulp, especially for the EMB foams, where the diffusivity value doubled in relation to that obtained at 60°C (Table 3).

An increase in foaming agent concentration caused an increase in D_{eff} in relation to that of the mango pulp, a result that was to be expected because the formation of a porous structure improved the capacity for the exit of water from the food.^[16,31,33] The porous structure of the ALB foam was achieved due to interactions with bubble walls (lamella) by electrostatic or hydrophobic forces, hydrogen bonds or covalent linkages.^[5] Meanwhile, EMB was adsorbed on the air–water interface, reducing the free energy, that consequently diminished interfacial surface tension.^[49]

However, as shown in Table 5, the negative effect of the interaction between the concentrations of EMB and ALB tended to decrease the value of D_{eff} . It was more evident at the lower temperature, because the effects of the temperature were less pronounced on the diffusivity, as shown in Table 3 and also by the fitted model for the responses, which can be calculated through the substitution of the coefficients (Table 5) and codified variables in Eq. (9).

The diffusion coefficients obtained in the present study were much lower than those reported by Wilson et al.^[43] and Rajkumar et al.^[13] for the foam mat drying of mango pulp with albumin, where the values reported for the diffusion coefficients were around $1.53 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ for process temperatures of 65°C and

$2.63 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ at 85°C . For the drying of shrimp foam, Azizpour et al.^[50] found values of $3.51 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ at 85°C . The authors calculated the diffusivity based on the analytical solution of the diffusion equation for plates, but only used the first term of the series, which is usually adequate for numbers greater than 0.2, because the series converges quickly for this condition. The same simplification was tested in the present study and resulted in high values for diffusivity, also to the order of $10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$, proving that this approximation would be inadequate for the drying of these foams.

Conclusion

Foam mat drying was shown to be a viable method to obtain mango powders and maintain their physical and nutritional properties. The foaming agents of albumin and the emulsifier blend significantly affected the color parameters of the dehydrated pulp, resulting in a lighter color than the product without the additives and maintaining a yellow tonality, results similar to those of powders produced by traditional methods such as spray drying. Albumin and the emulsifier blend also exerted positive effects on the retention of total carotenoids during the drying of the foams, always resulting in greater retention than in the powders obtained from pulps without additives, the maximum value being obtained at 80°C with $10 \text{ kg ALB} \cdot 100 \text{ kg}^{-1}$ pulp (88.9% retention). The temperature also positively affected retention, this result being attributed to the shorter drying time. The solubility was not affected by the temperature or by the concentration of the foaming agents. High values were obtained for the water diffusion coefficient (D_{eff}), allowing for low moisture contents and water activities to be attained in short drying times. The diffusivity was estimated based on Fick's law, and taking shrinkage into consideration allowed for very efficient fits to the model, showing it to be adequate to represent the foam mat drying process.

Funding

The authors are grateful to the State of São Paulo Research Foundation (FAPESP) for the scholarship (process 2012/21428-6) and financing (process 2014/11514-8).

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