Foaming properties of custard apple pulp and mathematical modelling of foam mat drying

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Abstract Foaming of custard apple pulp was carried out using foaming agent and stabilizer for drying of pulp in thin layers. The effect of parameters was studied and optimization was performed using response surface methodology. The concentration of egg albumen (0–20%, w/w) as foaming agent with methyl cellulose (0.0–0.50%, w/w) as stabilizer were added for whipping time (5–25 min). The foam properties were influenced by concentration of foaming agent and whipping time. The desirable foaming properties (high foam expansion, lower foam density and high foam stability) was observed at 15% of egg albumen, 0.37% of methyl cellulose for a whipping time of 17.32 min. Dehydration of optimized foamed pulp was completed within 100–140 min for 60–75 °C temperatures at 2 mm thickness of pulp. Average effective diffusivities remained $2.01\text{--}9.67 \times 10^{-08} \text{ m}^2/\text{s}$ and activation energy was 29.99 kJ/mol.

Keywords Foaming parameters · Foam mat drying · Mathematical modelling · Effective diffusivity · Activation energy

Introduction

Custard apple (*Annona squamosa* L.) is one of the delicious fruits, which is being enjoyed in many ways. The attractiveness of the fruit is due to its quilted appearance, mild

aroma, pleasant flavour and sweet taste. Luscious taste and nutritive value makes it popular dessert fruit (Pawar and Hashmi 2010). It weighs about 326 g and has white coloured tender flesh with considerable amount of sugar, ascorbic acid, magnesium, potassium and dietary fiber (Khodifad et al. 2018). The calorific value is almost double to the popular fruits like apple, orange and peach (Kumar et al. 2015). The fruit shows climacteric nature due to increased ethylene production during ripening stage with a typical climacteric peak of 104.23 mg CO₂ per kg of fruit per hour in ambient conditions on second day (Mallikarjuna et al. 2012). Modified atmospheric storage also has limitation of storing not more than 12 days even at 10 °C (Silva et al. 2012). Therefore, it is being used in the preparation of stable value-added products like jam, toffee, ready to serve beverage and squash during the season (Singh et al. 2006; Muniz et al. 2008; Shalini et al. 2010; Patil et al. 2011).

The higher moisture content of custard apple is the major reason for faster rotting and spoilage, which makes it inedible and rendering huge wastage. Drying of fruits is one of the traditional storage practices, which transforms perishable fruits into stable form by removal of water and reduction in water activity (Roberts et al. 2008). This makes it available throughout the year for preparing the value added products for human consumption. It is widely used for being simpler in practice, having lower processing cost and economical in all aspects. The dried products can also be stored for longer duration even at normal temperatures.

Simultaneous occurrence of heat and mass transfer process during the drying makes it difficult to analyze the process easily (Yilbas et al. 2003). Reduction of moisture through drying up to the least possible level of 1–5% restrict unintentional enzymatic reactions and detrimental

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microbial spoilage (Sangamithra et al. 2015), which also confers advantages of reduction in volumes of handling, storing and transporting the material (Fumagalli and Silveira 2005). Drying of fruit juices/pulps is preferred in trays, drums and belts through conductive heat transfer (Hertzendorf et al. 1970), however, significant change in colour and poor rehydration quality are major concern. Application of freeze drying in seasonal fruits is also limited due to higher cost involved even though it produces excellent product in terms of quality or sensory attributes (Sangamithra et al. 2015).

Foam mat drying is a proven technology and is gaining higher momentum due to its simplicity and rapid removal of water from fruit pulps. Rapid drying rates, superior nutritional and reconstitution attributes are major advantages of foam mat drying over conventional drying (Kundra and Ratti 2006). It also has capability to dry sticky, heat sensitive, sugary and viscous products without significant change in quality (Morgan et al. 1961). The method always remains significantly cheaper than vacuum, spray and freeze drying method (Kadam et al. 2010).

The foam mat drying has been successfully applied to many fruits and foods like mango, banana, guava, apple, sapota, bael fruit and papaya (Kandasamy et al. 2012). However, application of foam mat drying of custard apple is not reported, therefore, the investigation was carried out to optimize process parameters for foam mat drying and dehydration characteristics of foamed custard apple pulp.

Materials and methods

Selection of fruits, foaming agents and whipping time

The custard apple fruits used were obtained from local market of Godhra, Gujarat, India. The fruits were kept at room temperature till desired peel colour was attained. Ripened fruits were pulped manually by removing peels and seeds. The concentration of egg albumen (0, 5, 10, 15 and 20%, w/w) with concentration of methyl cellulose (0.0, 0.125, 0.25, 0.375 and 0.50%, w/w) and whipping time (5, 10, 15, 20 and 25 min) were selected and three variable (five levels of each variable) central composite rotatable experimental design was prepared for the study (Table 1) using Design Expert software (Version: 8.0.7.1, M/s Stat-Ease Inc., Minneapolis, USA).

Foaming experiment

Foaming of custard apple pulp

The custard apple pulp was converted into foams for more expansion, high stability and low density with the use of

foaming agents. The air was incorporated using a laboratory scale foaming device. The foaming device was developed using a transparent cylindrical plastic vessel for keeping the pulp and air pump (M/s Sobo, Model: SB-988, China) with 3 air nozzles at flow rate 4 l/min per nozzle to blow the air through the pulp. A portable hand blender (M/s Priya Gold, India) in the vessel was used for proper mixing.

Samples (200 g) were weighed and kept in the foaming device. The distilled water (400 ml) was added based on the preliminary experimentation followed by the addition of predetermined quantity of foaming agents (Table 1). Controlled rate of compressed air flow rate 0.03 m³/min was introduced and blender was started. After predetermined time, the air flow and rotation of whipping blade were stopped simultaneously.

Foaming properties

Foam expansion Foam expansion was calculated from the volume of custard apple pulp before and after whipping using following formula reported by Durian (1995)

$$\text{Foam expansion (\%)} = \left[\frac{\text{Final volume of foam (cm}^3\text{)} - \text{Initial volume of pulp (cm}^3\text{)}}{\text{Initial volume of pulp (cm}^3\text{)}} \right] \times 100 \quad (1)$$

Foam density The density of foamed custard apple pulp was calculated in terms of mass by volume (g/cm³) reported by Falade et al. (2003)

$$\text{Foam density} = \text{Density of pulp (g/cm}^3\text{)} \times \frac{\text{Initial volume of pulp (cm}^3\text{)}}{\text{Final volume of pulp (cm}^3\text{)}} \quad (2)$$

Foam stability A graduated transparent beaker was used for determination of foam stability. The foams were kept poured in the beaker and allowed to settle for 3 h. Foam stability was determined by using following formula:

$$\text{Foam stability (\%)} = \frac{\text{Volume of foams at 180 min}}{\text{Initial volume of foam including the liquid volume without foaming}} \times 100 \quad (3)$$

Statistical analysis of responses The responses (foam expansion, density and stability) for different combinations are related to the coded variables (x_i , $i = 1, 2$, and 3) by a second degree polynomial equation

Table 1 Foaming properties with different combinations of treatments

ER	EA (% w/w)		MC (% w/w)		WT (min)		FE (%)	FD (g/cc)	FS (%)
	C	UC	C	UC	C	UC			
1	– 1	5.00	– 1	0.125	– 1	10.00	109.84	0.42	78.13
2	1	15.00	– 1	0.125	– 1	10.00	78.13	0.47	87.72
3	– 1	5.00	1	0.375	– 1	10.00	109.68	0.42	84.62
4	1	15.00	1	0.375	– 1	10.00	112.50	0.42	98.31
5	– 1	5.00	– 1	0.125	1	20.00	29.03	0.68	92.50
6	1	15.00	– 1	0.125	1	20.00	70.97	0.53	98.11
7	– 1	5.00	1	0.375	1	20.00	70.00	0.53	98.04
8	1	15.00	1	0.375	1	20.00	112.50	0.42	100.00
9	– 1.68	1.59	0	0.250	0	15.00	103.33	0.43	72.13
10	1.68	18.41	0	0.250	0	15.00	115.63	0.41	95.65
11	0	10.00	– 1.68	0.040	0	15.00	122.58	0.40	95.65
12	0	10.00	1.68	0.460	0	15.00	119.35	0.42	94.12
13	0	10.00	0	0.250	– 1.68	6.59	106.45	0.44	90.63
14	0	10.00	0	0.250	1.68	23.41	29.07	0.68	95.00
15	0	10.00	0	0.250	0	15.00	87.10	0.46	98.28
16	0	10.00	0	0.250	0	15.00	74.19	0.51	94.44
17	0	10.00	0	0.250	0	15.00	61.29	0.54	100.00
18	0	10.00	0	0.250	0	15.00	90.32	0.47	96.61
19	0	10.00	0	0.250	0	15.00	87.10	0.48	96.55
20	0	10.00	0	0.250	0	15.00	61.29	0.56	100.00

ER experimental runs, EA concentration of egg albumen, MC concentration of methyl cellulose, WT whipping time, FE foam expansion, FD foam density, FS foam stability, C Coded, UC Uncoded

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \varepsilon \dots \quad (4)$$

The coefficients of the polynomial are represented by β_0 (constant), β_1 , β_2 , β_3 (linear effects); β_{12} , β_{13} , β_{23} (interaction effects); β_{11} , β_{22} , β_{33} (quadratic effects); and ε (random error). Data were fitted in the Eq. (4) and statistical significance were tested using Design Expert Software (8.0.7.1). The regression model was evaluated by R^2 , Adjusted R^2 , Adequate Precision and Fisher's F test (Table 2). Three dimensional plotting and numerical optimization of processing parameters for higher foam expansion were also carried out. The optimized samples using the mentioned criteria were subjected to drying of foams.

Foam mat drying and modelling

Hot air tray dryer (M/s Nova instruments Pvt. Ltd., Ahmadabad, India) was used to dry the optimized foamed material. The foamed custard apple pulp was equally spread in 2 mm thickness on the tray (0.81×0.40 m) made of stainless steel. The pulp was dried at 60, 65, 70 and 75 °C temperatures with $0.03 \text{ m}^3/\text{min}$ air flow rate.

Decrease in amount of water was recorded at every 10 min interval until attaining constant mass of sample.

Drying rate, moisture content and moisture ratio (MR) were also calculated. Twelve drying models mentioned in Table 3 for thin layer were fitted between simplified moisture ratio of instantaneous moisture content and initial moisture content (M/Mo) with drying time (t) considering equivalent moisture content as negligible for long drying periods. The coefficient of determination (R^2), Chi square (χ^2) and root mean square error were calculated for mathematical models evaluation. The regression analysis was carried out using OriginPro 9.4 software (Origin Lab, Massachusetts).

Effective diffusivity The diffusivity was estimated using Fick's second law of diffusion by plotting logarithmic of moisture ratio (MR) with time (t) using the following equation (Tutuncu and Labuza 1996):

$$\ln \text{MR} = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}}}{4 L_0^2} \quad (5)$$

where D_{eff} represents effective diffusivity (m^2/s) and L_0 is half of drying thickness (m).

Table 2 Regression coefficients of second order polynomial and their significance for foam expansion, foam density and foam stability

S. no.	Coefficients	Foam expansion (%)			Foam density (g/cc)			Foam stability (%)		
		Coeff. Value	F	P	Coeff. value	F	P	Coeff. value	F	P
1	x_1	5.58 ^{ns}	1.59	0.2356	− 0.018 ^{ns}	2.11	0.1772	5.16***	22.15	0.0008
2	x_2	8.15*	3.39	0.0952	− 0.021 ^{ns}	2.94	0.1174	1.61 ^{ns}	2.15	0.1736
3	x_3	− 18.88***	18.22	0.0016	0.060***	25.08	0.0005	3.46**	9.97	0.0102
4	$x_1 x_2$	4.39 ^{ns}	0.58	0.4653	− 0.002 ^{ns}	0.02	0.8926	0.06 ^{ns}	0	0.9699
5	$x_1 x_3$	14.17**	6.01	0.0342	− 0.038**	5.76	0.0373	− 1.96 ^{ns}	1.88	0.2001
6	$x_2 x_3$	6.04 ^{ns}	1.09	0.3209	− 0.025 ^{ns}	2.44	0.1491	− 1.21 ^{ns}	0.71	0.4191
7	x_1^2	8.53*	3.93	0.0757	− 0.023*	3.88	0.0773	− 4.42***	17.21	0.002
8	x_2^2	12.59**	8.56	0.0152	− 0.029**	5.99	0.0344	− 0.54 ^{ns}	0.25	0.625
9	x_3^2	− 6.22 ^{ns}	2.09	0.1789	0.025*	4.51	0.0598	− 1.27 ^{ns}	1.42	0.2611
10	R^2	0.82			0.84			0.85		
11	Adjusted R^2	0.66			0.70			0.71		
12	Adequate precision	8.54			9.14			8.18		
13	F value	5.11			5.98			6.08		

x_1 —concentration of egg albumen, x_2 —concentration of methyl cellulose, x_3 —whipping time

ns not significant

Significant at *10%, **5%, ***1%

Activation energy Arrhenius type relationship was used to describe effect of temperature on effective diffusivity (Akgun and Doymaz 2005):

$$D_{eff} = D_0 \exp \left(-\frac{E_a}{RT} \right) \quad (6)$$

where E_a , D_0 , R and T represents activation energy (kJ/mol), Arrhenius equation factor (m^2/s), gas constant (kJ/mol K), temperature (K) respectively.

Results and discussion

The custard apples used for the study were 63.45 ± 3.22 mm in length, 57.29 ± 3.08 mm in mean diameter and had 97.72 ± 16.33 cm³ volume, 251.14 ± 29.24 g mass, $43.89 \pm 6.37\%$ pulp recovery and 0.72 g/cm³ bulk density.

Analysis of responses for foaming properties

Variations of responses (foam expansion, density and stability) of foaming with independent variables (egg albumen, methyl cellulose and whipping time) are shown in Table 1. A complete second order model (Eq. 4) was tested for its adequacy to correlate the variation of response with independent variables. Three dimension response surfaces were also plotted to visualize the variation of response with

processing variables (Fig. 1) using Design Expert software (Version: 8.0.7.1, M/s Stat-Ease Inc., Minneapolis, USA).

Foam expansion

Foam expansion of custard apple pulp ranged from 29.03 to 122.58% with an average value of 87.52%. The maximum expansion at coded point (0, − 1.68, 0) was about 4.22 times more than the minimum expansion at coded point of − 1, − 1, 1 (Table 1). It can be observed from Table 2 that model is significant due to model F value of 5.11 ($P < 0.05$). R^2 and adjusted R^2 values of the model are 0.82 and 0.66 respectively. The adequate precision value of 8.54 indicates that the model can be used to predict foam expansion within the range studied (Montgomery 2001). Following model represents the variation of foam expansion:

$$\begin{aligned} \text{Foam expansion} = & +77.34 + 5.58x_1 + 8.15x_2 - 18.88x_3 \\ & + 4.39x_1x_2 + 14.17x_1x_3 \\ & + 6.04x_2x_3 + 8.53x_1^2 + 12.59x_2^2 \\ & - 6.22x_3^2 \end{aligned} \quad (7)$$

The linear terms for methyl cellulose concentration and whipping time are significant

(Table 2) and coefficients of whipping time (x_3) in Eq. (7) is negative, but those of methyl cellulose concentration (x_2) is positive, indicating increase in foam

Table 3 Statistical results obtained from thin-layer drying models

S. no.	Model name and expression	Temperature (°C)	Constants						R ²	X ²	RMSE
			1st	2nd	3rd	4th	5th	6th			
1	Lewis	60	k = 0.0208						0.9333	0.0089	0.0909
2	MR = exp(−kt)	65	k = 0.0237						0.9527	0.0058	0.0737
3		70	k = 0.0329						0.9593	0.0053	0.0694
4		75	k = 0.0385						0.9597	0.0054	0.0697
5	Page	60	k = 0.0008	n = 1.7774				Average	0.9512	0.0063	0.0759
6	MR = exp(−kt ⁿ)	65	k = 0.0023	n = 1.5848					0.9956	0.0006	0.0225
7		70	k = 0.0036	n = 1.6107					0.9931	0.0009	0.0272
8		75	k = 0.0039	n = 1.6669					0.9977	0.0003	0.0158
9	Henderson and Pabis	60	k = 0.0229	a = 1.1219				Average	0.9964	0.0005	0.0186
10	MR = a exp(−kt)	65	k = 0.0255	a = 1.0912					0.9440	0.0074	0.0803
11		70	k = 0.0351	a = 0.0602					0.9580	0.0052	0.0670
12		75	k = 0.0410	a = 1.0819					0.9630	0.0048	0.0631
13	Logarithmic	60	k = 0.0146	a = 0.0858				Average	0.9569	0.0056	0.0685
14	MR = a exp(−kt) + c	65	k = 0.0184	a = 1.2044	c = −0.2415				0.9734	0.0035	0.0531
15		70	k = 0.0274	a = 1.1670	c = −0.1502				0.9778	0.0027	0.0467
16		75	k = 0.0335	a = 1.1499	c = −0.1086				0.9767	0.0030	0.0475
17	Two term	60	a = −227.4580	b = 228.4323	c = −0.0867			Average	0.9751	0.0032	0.0498
18	MR = a exp(−k ₀ t) + b exp(−k ₁ t)	65	a = −201.3920	b = 202.3686	k ₀ = 0.0456	k ₁ = 0.0454			0.9857	0.0019	0.0373
19		70	a = −211.7680	b = 212.7584	k ₀ = 0.0483	k ₁ = 0.0480			0.9867	0.0016	0.0347
20		75	a = −226.630	b = 227.6341	k ₀ = 0.0687	k ₁ = 0.0687			0.9932	0.0009	0.0243
21	Wang and Singh	60	a = −0.0149	b = 0.0001	k ₀ = 0.0837	k ₁ = 0.0833		Average	0.9905	0.0012	0.0284
22	MR = 1 + at + bt ²	65	a = −0.0169	b = 0.0001					0.9829	0.0023	0.0443
23		70	a = −0.0229	b = 0.0001					0.9925	0.0009	0.0283
24		75	a = −0.0265	b = 0.0002					0.9932	0.0009	0.0243
									0.9864	0.0018	0.0385

Table 3 continued

S. no.	Model name and expression	Temperature (°C)	Constants					R ²	X ²	RMSE
			1st	2nd	3rd	4th	5th			
25	Approximation diffusion	60	a = 2.1092	k = 0.0333				0.9887	0.0015	0.0338
26	MR = $a \exp(-kt) + (1 - a) \exp(-ka)$	65	a = 2.0061	k = 0.0360				0.9839	0.0021	0.0430
27		70	a = 2.0590	k = 0.0513				0.9858	0.0018	0.0389
28		75	a = 2.1291	k = 0.0621				0.9926	0.0010	0.0283
29	Verma	60	a = 188.8290	g = 0.0452	k = 0.0449			0.9895	0.0014	0.0329
30	MR = $a \exp(-kt) + (1 - a) \exp(-gt)$	65	a = 196.7800	g = 0.0478	k = 0.0476			0.9874	0.0016	0.0352
31		70	a = 210.3990	k = 0.0681	g = 0.0685			0.9938	0.0008	0.0244
32		75	a = 173.8890	k = 0.0831	g = 0.0837			0.9968	0.0004	0.0176
33	Hii, Law and Cloue	60	a = 0.2057	k = 0.0005	n = 1.87787	c = 0.7597	g = 0.0006	0.9911	0.0011	0.0288
34	MR = $a \exp(-kt^n) + c \exp(-gt^n)$	65	a = 0.1794	k = 0.0015	n = 1.68395	c = 0.7815	g = 0.0015	0.9959	0.0005	0.0190
35		70	a = 0.2164	k = 0.0031	n = 1.64984	c = 0.7663	g = 0.0031	0.9929	0.0009	0.0242
36		75	a = 0.2544	k = 0.0037	n = 1.68133	c = 0.7584	g = 0.0037	0.9971	0.0004	0.0147
37	Modified Page	60	k = 0.0193	n = 1.7774				0.9990	0.0001	0.0086
38	MR = $\exp(-(kt)^n)$	65	k = 0.0220	n = 1.5849				0.9962	0.0005	0.0166
39		70	k = 0.0306	n = 1.6107				0.9956	0.0006	0.0225
40		75	k = 0.0359	n = 1.6669				0.9931	0.0009	0.0272
41	Diffusion approach	60	a = 224.2520	k = 0.04493	b = 1.0050			0.9977	0.0003	0.0158
42	MR = $a \exp(-kt) + (1 - a) \exp(-kbt)$	65	a = 157.4550	k = 0.04752	b = 1.0062			0.9993	0.0001	0.0088
43		70	a = 210.0190	k = 0.06811	b = 1.0050			0.9964	0.0005	0.0186
44		75	a = 227.0313	k = 0.08317	b = 1.0050			0.9864	0.0018	0.0379
								0.9874	0.0016	0.0352
								0.9938	0.0008	0.0244
								0.9968	0.0004	0.0176
								0.9911	0.0011	0.0288

Table 3 continued

S. no.	Model name and expression	Temperature (°C)	Constants						R ²	X ²	RMSE
			1st	2nd	3rd	4th	5th	6th			
45	Modified Henderson and Pabis	60	a = – 0.2966	k = 645295.88	b = 0.8895	c = 0.4071	g = 0.0261	h = 0.0261	0.9486	0.0068	0.0640
46	MR = a exp(– kt) + b exp(– gt) + c exp(– ht)	65	a = – 0.2431	k = 341701.99	b = 0.8959	c = 0.3472	g = 0.0286	h = 0.0287	0.9588	0.0051	0.0551
47		70	a = – 0.3361	k = 227376.70	b = 0.9125	c = 0.4236	g = 0.0421	h = 0.0421	0.9725	0.0036	0.0421
48		75	a = – 0.4382	k = 219475.46	b = 0.9697	c = 0.4685	g = 0.0522	h = 0.0522	0.9821	0.0024	0.0329
								Average	0.9655	0.0045	0.0485

expansion with the increase in methyl cellulose and reduction in whipping time ($P < 0.05$). The square terms for egg albumen (x_1^2) and methyl cellulose (x_2^2) are also significant, indicating non linear variation in foam expansion due to change in egg albumen and methyl cellulose proportion ($P < 0.10$). The interaction terms of egg albumen concentration and whipping time ($x_1 x_3$) is also significant, indicating the influence of combined effect on foam expansion. Reduction in foam expansion with reduction in whipping time can be observed from Fig. 1a. It may be due to shorter whipping time of egg albumen proteins, which could be more rapidly adsorbed at the air–liquid interface and more rapidly denatured than other proteins.

Foam density

The minimum foam density (0.40 g/cc) of custard apple pulp at coded point (0, – 1.68, 0) was about 0.59 times less than maximum foam density (0.68 g/cc) at coded point (– 1, – 1, 1 and 0, 0, 1.68) and average value of foam density was 0.49 g/cc (Table 1). The F, R², adjusted R² and adequate precision values for Eq. (8) were 5.98, 0.84, 0.70 and 9.14 respectively (Table 2), indicating model is significant ($P < 0.05$).

$$\begin{aligned}
 \text{Foam density} = & +0.50 - 0.018x_1 - 0.021x_2 \\
 & + 0.060x_3 - 0.002x_1x_2 - 0.038x_1x_3 \\
 & - 0.025x_2x_3 - 0.023x_1^2 - 0.029x_2^2 \\
 & + 0.025x_3^2
 \end{aligned} \quad (8)$$

The linear term for whipping time is significant (Table 2) and coefficient of x_3 is positive, indicates increase in whipping time produces more dense foams ($P < 0.01$). Square terms of egg albumen (x_1^2), methyl cellulose (x_2^2) and whipping time (x_3^2) were also significant, indicates non linear variation in density due to process parameters. Similar combined effect of egg albumen concentration and whipping time ($x_1 x_3$) was also observed ($P < 0.05$).

All the coefficients of bulk density were opposite to the coefficients of foam expansion, as expected. Since coefficient of x_1x_3 is negative, this may be due to negative significant variation of whipping time. It was observed from Fig. 1b that foam density increased with increase in whipping time due to more mechanical deformation and greater bubble wall rupture during extended whipping.

Fig. 1 Variation in responses for foaming properties with different parameters; **a** foam expansion, **b** foam density, **c** foam stability

Foam stability

Foam of custard apple foams with 100% stability was obtained at coded point (1, 1, 1 and 0, 0, 0) remained 1.39 times more than the minimum value of foam stability at coded point (−1.68, 0, 0) and average value of foam stability was 93.32 (Table 1). The F , R^2 , adjusted R^2 and adequate precision values for Eq. (9) were 6.08, 0.85, 0.71 and 8.18 respectively (Table 2), indicating model is significant ($P < 0.05$).

$$\begin{aligned} \text{Foam stability} = & +97.58 + 5.16x_1 + 1.61x_2 + 3.46x_3 \\ & + 0.06x_1x_2 - 1.96x_1x_3 \\ & - 1.21x_2x_3 - 4.42x_1^2 - 0.54x_2^2 \\ & - 1.27x_3^2 \end{aligned} \quad (9)$$

It can be observed that coefficient of x_1 and x_3 are positive and significant ($P < 0.05$), indicating higher foam stability with the increase in egg albumen concentration and whipping. Non linear variation due to egg albumen concentration (x_1^2) was also significant ($P < 0.01$). The increase in foam stability with the increase in whipping time can be observed from Fig. 1c. Foam stability increased with increase concentration of egg albumen initially followed by decrease in foam stability. This may be due to presence of protein in egg albumen, which behaved as a good stabilizer due to ability of reducing surface energy level between bubbles during continuously creation of foams.

Compromised optimum condition

The desirable responses were selected for maximum foam expansion and foam stability, and minimum foam density for creation of stable foams during drying operations keeping equal weights or importance and by constraining independent variables within the experimental range. The optimized process parameters were obtained using Design Expert software at 15% egg albumen, 0.37% methyl cellulose with 17.32 min whipping time.

Drying characteristics

Foam mat drying of custard apple pulp was carried out using optimized level of egg albumen (15%) and methyl cellulose (0.37%) with 17.32 min whipping time at foam thickness 2 mm and drying at 60 °C, 65 °C, 70 °C and 75 °C temperature in laboratory scale tray dryer. The drying of foamed custard apple pulp from 5.722 g to about 0.010 g water/g dry matter. Rapid reduction of moisture with increase in temperature was observed due to faster

conversion of water into vapours. Variation of moisture for foamed custard apple pulp with drying time at the 60–75 °C temperatures are shown in Fig. 2a. It took 140, 130, 110 and 100 min to reach the final moisture content at 60 °C, 65 °C, 70 °C and 75 °C respectively. Moisture content decreased faster in the starting and become sluggish afterwards for all the drying processes. Time elapsed for drying the pulp was short at higher temperatures. Similar findings were also reported by Kandasamy et al. (2012) for papaya. Similar decrease in moisture ratio is also evident with the progression of drying. First half moisture (moisture ratio = 0.5) was removed in 24–44 min, which is about one-third of the total drying time (Fig. 2b). Slower diffusion in the remaining drying period resulted in longer duration for removal of remaining half moisture. The maximum drying rates for drying foamed custard apple pulp were 0.0773–0.1520 g water/g dry matter/min for 60, 65, 70 and 75 °C respectively. The reduced moisture content and rate of moisture migration from inner surface to outer surface with the progression of drying remained the reason for slower drying rates with time (Fig. 2c). Similar results were also reported by Rajkumar et al. (2007) for alphonso mango pulp.

Fitting of mathematical models

Moisture ratio (MR) values were calculated from moisture content data observed during the drying experiment and fitted to the 12 models (Table 3). Drying model coefficients and comparison criteria for model selection are also listed in Table 3. The average R^2 value of Hii et al. (2009) model was higher (0.9962), and corresponding χ^2 (0.0005) and RMSE (0.0166) values were lesser than other models, indicating better fitting of model in comparison to other models. The residual of experimental and predicted moisture ratios for the Hii, Law and Cloke model varied from −0.04 to 0.04 values for the model for each drying curve. A linear variation at 45° angle of predicted data with experimental data exhibits realistic agreement of model for describing drying behaviour foamed custard apple (Fig. 3).

Effective diffusivity

The internal mass transfer resistance governed the drying process. The values of effective diffusivity (D_{eff}) were calculated using Eq. (5). The average values of effective diffusivities of foamed custard apple pulp were 2.01×10^{-08} , 4.90×10^{-08} , 7.81×10^{-08} and 9.67×10^{-08} m²/s at temperatures of 60, 65, 70 and 75 °C respectively. More thermal energy in material dried at higher temperatures due to increase in the activity of water molecule is evident and might have led to higher effective diffusivity. The effective diffusivities increased with

Fig. 2 Variation of **a** moisture content, **b** moisture ratio and **c** drying rate with respect to drying time of foamed custard apple

temperature of drying air in all the samples due to more diffusion of moisture at higher temperature by increasing the activity of water molecules. Kumar et al. (2012) also reported similar dependence of effective diffusivities on temperature.

Activation energy

Activation energy was obtained by plotting natural logarithm of effective diffusivity (D_{eff}) against reciprocal of absolute temperature ($1/T$) in Arrhenius type liner relationship. The activation energy was 29.99 kJ/mol, which remained in line with the general range of 12.7–110 kJ/mol for food materials.

Conclusion

The foaming behaviour of custard apple pulp was optimized with use of response surface methodology. The optimum conditions obtained were 15% egg albumen, 0.37% methyl cellulose and 17.32 min of whipping time. The developed foams were successfully dried in tray dryer which provides advantages of rapid drying at lower drying temperature. The drying time varied from 140 to 100 min for 60–75 °C respectively with 2 mm drying thickness. The Hii, Law and Cloke models is recommended for describing the drying behaviour of foamed custard apple pulp in thin layers. The average values of effective diffusivities and activation energy of foamed custard apple pulp were $2.01\text{--}9.67 \times 10^{-08} \text{ m}^2/\text{s}$ and 29.99 kJ/mol respectively.

Fig. 3 Predicted moisture ratio with respect to experimental moisture ratio at 2 mm drying thickness with different temperature

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