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Characterization and mathematical modelling of drying behaviour of wood apple (*Limonia Acidissima*) pulp

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The present study was undertaken to investigate drying characteristics and the effect of drying conditions on quality parameters of wood apple pulp in hot air oven drier and solar drier and to describe the suitable drying process through mathematical modelling. The wood apple pulp was dried in hot air oven at 50°C, 60°C, 70°C and 80°C and also in solar drier. The experimental moisture ratio during drying was fitted to the most widely investigated mathematical models. The yield of wood apple powder was ranged between 28 to 48%. Though the drying time was lengthier (8 hours) in solar drying, the overall drying rate, dehydration ratio, moisture ratio, fruit powder yield, bulk density, porosity, swelling power and retention of nutrients were found to be greater than hot air oven drying at various temperatures. Authors approximation model could adequately describe hot air oven drying behaviour at 50°C, 60°C and 70°C; Page, Modified Page and Modified Page Equation models together could describe the hot air oven drying behaviour at 80°C equally and adequately; and Two-term Exponential model could adequately describe solar drying behaviour.

Keywords: Wood apple; drying characteristics; hot air oven drier; solar drier; mathematical models; nutritional composition.

Introduction

The wood apple (*Limonia acidissima*), is the only species of its genus, in the family Rutaceae. The wood apple is native and common in India, Srilanka, China and Indonesia, where it is cultivated along roads and edges of fields and occasionally in orchards[1]. In addition to the fresh use as a fruit, value - added products especially wood apple jam, jelly and ready to serve drinks are becoming popular in Srilanka[2]. The fresh extracted pulp was included in the preparation of jelly and oven dried powder of wood apple pulp was used in the jeera lune powder. Drying process is the most common form of food preservation and extends the shelf-life of food. Open sun drying is a well-known food preservation technique that is still the most common method used to preserve agricultural product in most tropical and subtropical countries[3]. The description and prediction of the drying kinetics of a given material, under given process conditions, is still a weakness in the modelling of drying process. Recently many authors have undertaken studies revealing mathematical modelling and kinetics of the foodstuff drying process e.g. red chilli[4], apple[5], amaranth grain[6], mulberry[7], okra[8] and tomato[9]. Realizing the importance of fruit as a cheaper, highly nutritious and because of perishable nature and seasonally available, the present study was planned to investigate drying characteristics of wood apple in hot air oven drier and solar drier, to fit the experimental data to mathematical models for describing the suitable drying process and to study the effect of drying conditions on physical, functional and nutritional characteristics.

Materials and Methods

Preparation of fruit powder

The mature wood apple variety (*Limonia acidissima*) indigenous in India was procured from local market at Salem district. The pulp with seed was scooped out and spread on heat stable polythene sheet which placed over aluminium tray. It was dried by hot air oven and newly designed solar drier (Fig.1), powdered in a mixer grinder and packed in an airtight container. The drying process in hot air oven was studied at temperatures of 50°C, 60°C, 70°C and 80°C.

Drying characteristics

The drying rate of the sample was measured by determining the moisture content at one hour interval

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until the drying gets completed. The end of the drying was noted by the concordant value in moisture content[10]. The overall drying rate[11], changes in weight in g%, moisture in g %[12], dehydration ratio[13], percent moisture loss[14] and drying time in hours was noted as drying characteristics.

Mathematical modelling of drying curves

The experimental moisture ratio of wood apple pulp during drying in hot air oven and solar drier were fitted to the most widely investigated theoretical mathematical models (Table 1).

The effective diffusion coefficients were typically determined by plotting experimental data in terms of *ln* (M_t/M_0) versus time. The purpose of the fitting was to find out the best suited model for describing the drying curve of wood apple pulp. The coefficient of determination (R^2) is the primary criterion for selecting the best model[15,16]. In addition to R^2, Root Mean Square Error (RMSE) was calculated to evaluate the fitting of a model to experimental data. The highest values of R^2 and the lowest values of RMSE were used to determine the best fit[17,18,15,19].

Fig.1 - Newly designed solar drier

Characterisation of fruit powder

The wood apple fruit pulp powder prepared by hot air oven method of drying at various temperatures and solar drying method were determined for its physical properties such as bulk density in g/ml[20], true density in g/ml[21], porosity in %[22], hygroscopicity[23] and bulk volume[24]; functional properties such as water absorption capacity in g/g[25] and swelling power in ml/g at 50ºC, 60ºC, 70ºC and 80ºC and nutritional properties like total carbohydrate (g%) (Anthrone method), protein (g%) (Kjeldhal method), crude fiber (Acid – Alkali digestion method)[26], moisture content (g%) (Hot air oven method), ash (g%)[13].

Results and Discussion

Drying characteristics

The linear reduction in weight of the pulp was noted. In all drying conditions, the final moisture content was found to be less than 10% (solar dying – 6.47%, hot air oven drying at 50ºC - 6.12%, at 60ºC – 8%, at 70ºC – 7.75%, at 80ºC – 7.8%). The percentage moisture loss of wood apple pulp was reached to maximum of 97% at 7 hours of drying in solar drier and 4 hours of drying in hot air oven at 80°C. An increase in drying air temperature resulted in a decrease in the drying time[18]. The moisture ratio

Table 1 - Results of analysis on the modelling of moisture ratio and drying time

Model Name	Adjusted R^2					RMSE				
	Solar Drying	50°C	60°C	70°C	80°C	Solar Drying	50°C	60°C	70°C	80°C
Newton	0.9733	0.9713	0.8670	0.8450	0.8708	0.05873	0.05826	0.13330	0.15710	0.1552
Page	0.9978	0.9882	0.9765	0.9843	0.9446	0.01696	0.03744	0.05605	0.05007	0.1015
Henderson and Pabis	0.976	0.9716	0.8637	0.8432	0.8367	0.05563	0.05804	0.1349	0.1581	0.1744
Logarithmic	0.9879	0.9707	0.9108	0.9040	0.8890	0.03959	0.05894	0.1091	0.1237	0.1438
Two-term	0.9795	0.9526	0.8374	0.8390	NaN	0.05145	0.07492	0.1474	0.1602	NaN
Wang and Singh	0.9934	0.9834	0.9251	0.9155	0.9253	0.0291	0.04435	0.1000	0.1160	0.1179
Two-term exponential	0.9981	0.9904	0.9739	0.9148	0.9128	0.0156	0.03369	0.05898	0.1165	0.1275
Modified page	0.9978	0.9882	0.9765	0.9843	0.9446	0.01696	0.03744	0.05605	0.05007	0.1015
Verma	0.9867	0.9675	0.8901	0.9826	0.8785	0.04149	0.06201	0.1211	0.05268	0.1504
Diffusion approximation	0.9867	0.9686	0.8787	0.863	0.8845	0.04148	0.06102	0.1273	0.1477	0.1466
Modified page equation	0.9978	0.9882	0.9765	0.9843	0.9446	0.01696	0.03744	0.05605	0.05007	0.1015
Authors approximation	0.9928	0.9963	0.9905	0.9992	0.9429	0.0304	0.02103	0.03558	0.01119	0.1031

was almost equilibrated to zero on solar drying and hot air oven drying at 80ºC.The dehydration ratio was significantly ($p<0.01$) greater in solar drying conditions. While increasing the drying air temperature in hot air oven drying, the overall drying rate and the moisture ratio was increased significantly at $p<0.01$. Similar results have been reported for kiwifruit[27]; pineapple[28], banana[29], different crops[30] and mulberry fruits[7]. The drying rate of apple slices was increased with increasing drying air temperature and reached its maximum values at 80°C[31]. Similar observation was noted in the present study in which the maximum drying rate of 14.56 was noted in hot air oven drying at 80°C.

Fruit powder yield

The number of wood apple per kg was 9 which depend on the size of the fruit. The average weight of one fruit was 140 g and the pulp weighs about 68.8 g. One kg of fruit along with seed yielded 630 g of pulp. The yield of wood apple pulp powder was ranged between 28 to 40%. The maximum fruit powder yield (significant at $p<0.01$) was noted in hot air oven drying at 70^0 C, 80^0 C and solar drying.

Mathematical modelling of moisture ratio and drying time

Since the Authors approximation model gave the lowest RMSE (0.02103) value and the highest adjusted R^2 value (0.9963) in hot air oven drying at 50°C, 60°C, 70°C; Page, Modified Page and Modified Page equation models in hot air oven drying at 80°C; and two term exponential model in solar drying (Table 1 and 2), these models were chosen to represent drying behaviour of wood apple pulp in respective drying conditions. The predicted data generally banded around the straight line and good conformity of experimental data with predicted moisture ratio of these selected models was noted (Fig. 2). The expression of selected model can be used to estimate the moisture ratio of wood apple pulp at any time during hot air oven drying at 50°C with a good accuracy.

Table 2 – Coefficients and its constants on modelling of moisture ratio and drying time

Model Name	Coefficients and Constants				
	Solar Drying	50°C	60°C	70°C	80°C
Newton	k = 0.3412	k = 0.3317	k = 0.2698	k =0.2965	k = 0.4877
Page	k = 0.2107	k = 0.2316	k=0.0784	k = 0.06477	k = 0.1798
	n = 1.396	n = 1.321	n = 2.093	n =2.402	n = 2.213
Henderson and Pabis	a = 1.066	a = 1.052	a =1.107	a = 1.131	a = 1.065
	k = 0.3616	k = 0.3496	k =0.304	k = 0.3382	k = 0.5153
Logarithmic	a =1.193	a = 1.165	a = 24.74	a = 13.27	a = 3.465
	c = -0.1539	c = -0.1283	c =-23.68	c = -12.19	c = -2.442
	k = 0.2643	k = 0.2767	k =0.007831	k = 0.01621	k = 0.09133
Two-term	a = -15.52	a =1.929	a =17.6	a = 18.37	a = 1.203
	b = 16.59	b = -0.8775	b =-16.5	b = -17.25	b = 0.1843
	k_1 = 0.2341	k_1 = 0.3498	k_1 = 0.08832	k_1 = 0.07097	exp = 0.8298
	k_2 = 0.2408	k_2 = 0.3501	k_2 = 0.07814	k_2 = 0.05967	k_1 = 0.1824
					k_2 = 0.5389
Wang and Singh	a = -0.2518	a = -0.2732	a = -0.1522	a = -0.1585	a = -0.2985
	a = -0.2518	b = 0.02101	b = -0.005498	b = -0.006903	b = 0.009964
Two-term exponential	a = 1.983	a = 1.932	a = 2.308	a = 5.296	a = 2.254
	k = 0.526	k = 0.5141	k = 0.5343	k = -0.009411	k =0.8449
Modified page	k = 0.2107	k = 0.3304	k = 0.0784	k = 0.32	k = 0.1798
	n = 1.396	n =1.321	n = 2.093	n = 2.402	n = 2.213
Verma	a = -5.46	a = -5.603	a = -13.45	a = -16.28	a = -19.95
	g = 0.1616	g = 0.1966	g = 0.02215	g = 0.832	g = 1.122
	k = 0.1398	k =0.178	k = 0.009974	k = 0.9161	k = 1.195
				k = 0.9161	
Diffusion	a = 8.004	a = 7.287	a = 23.39	a = 39.23	a = 22.08
approximation	b = 0.8921	b = 0.8914	b =0.8377	b =0.8933	b = 0.8341
	k = 0.16	k = 0.1713	k = 0.04336	k = 0.04233	k = 0.07144
Modified page equation	k = 0.2107	k = 0.2316	k = 0.07843	k = 0.06477	k = 0.1798
	n = 1.396	n = 1.321	n = 2.093	n = 2.402	n = 2.213
Authors approximation	a = 0.0004549	a = 0.005535	a = 0.02186	a = 0.02657	a = 0.03573
	b = 0.01108	b = -0.02622	b = -0.1623	b =-0.1975	b = -0.1975
	c = -0.2389	c = -0.1827	c = 0.1002	c = 0.1483	c= -0.02854

a, b,c are dimensionless coefficients and k, k_1, k_2 and n are the drying constants

Characterization of wood apple pulp powder

Physical properties

The maximum bulk volume and hygroscopicity was noted in hot oven dried sample at 50°C and 60°C respectively (Table 3). The hot air oven dried samples at 50°C and 70°C was significantly ($p<0.01$) less dense than other samples. The true density and porosity of solar dried wood apple powder was significantly ($p<0.001$) higher than the other drying conditions. The low true density and porosity is a desirable quality for reconstitution of dried food materials. According to the result on true density and porosity, the wood apple pulp powder prepared by drying in hot air oven at 50°C could have good reconstitution quality than powder prepared by other drying conditions[32].

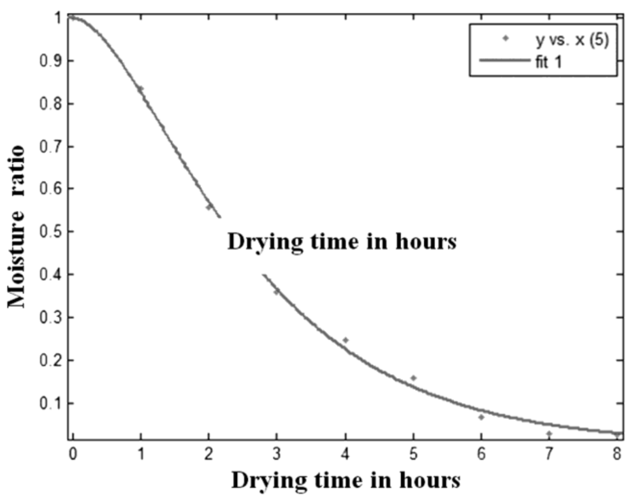

Fig.2 - Modelling graph on comparing experimental and predicted value (Two term exponential)

Functional properties

The water absorption capacity of solar dried sample was significantly ($p<0.01$) lower than powder prepared by other drying conditions (Table 3). This reflects on lower reconstitution capacity of the powder. The swelling power of the wood apple pulp powder was significantly ($p<0.001$) influenced by temperature at which the swelling power determined. The drying temperature and drying conditions did not have significant influence on swelling power.

Nutritional composition

The drying air temperature showed inverse influence on moisture content and direct significant influence on crude fibre content and total carbohydrate content. As per the edible fruit composition reported[33], it was understood that drying revealed a concentration effect on nutritional composition and the maximum retention of all nutrients expect ascorbic acid were noted significantly ($p<0.01$) in solar dried sample (Table 3).

Conclusion

Author approximation model for drying of wood apple pulp in hot air oven at 50°C, 60°C and 70°C; Page model or Modified Page model or Modified Page equation for drying in hot air oven at 80°C; and Two Term Exponential model for drying in solar drier were represented as best mathematical models for predicting drying behaviour of wood apple pulp. The drying time was greatly influenced by drying air temperature. Though the drying time was lengthier in solar drying, the overall drying rate, dehydration ratio,

Table 3 – Properties of wood apple pulp powder

Properties	Hot air oven				Solar
	50°C	60°C	70°C	80°C	drying
Carbohydrate (g %)	60.00±0.140[a]	62.00±0.280[b]	66.40±0.140[c]	66.60±0.160[c]	70.25±0.07[d]
Protein (g %)	11.21±0.040[a]	10.54±0.050[b]	10.82±0.050[b]	11.29±0.014[a]	12.39±0.04[c]
Crude fibre (g %)	03.13±0.210[a]	03.23±0.070[b]	03.40±0.060[c]	03.70±0.030[d]	04.10±0.02[e]
Ash (g %)	05.20±0.007[a]	05.11±0.007[b]	04.88±0.009[c]	04.70±0.002[d]	05.23±0.01[a]
Moisture (g%)	13.30±0.000[a]	11.50±0.050[b]	10.37±0.030[c]	08.92±0.000[d]	14.35±0.03[e]
Bulk density (g/ml)	00.59±0.009[a]	00.62±0.004[b]	00.590±0.002[a]	00.640±0.002[c]	00.620±0.001[b]
True density (g/ml)	01.49±0.040[a]	01.60±0.040[b]	01.910±0.020[c]	01.900±0.020[c]	01.950±0.020[c]
Porosity (%)	59.45±0.060[a]	59.95±0.030[a]	68.430±0.020[b]	66.540±0.020[c]	70.600±0.070[d]
Hygroscopicity (%)	01.45±0.002[a]	01.58±0.010[b]	01.552±0.001[c]	01.475±0.003[a]	01.557±0.001[c]
Bulk volume (ml/g)	01.68±0.020[a]	01.605±0.007[b]	01.660±0.010[a]	01.550±0.007[c]	01.610±0.010[b]
Swelling power(ml/g) at 30°C	0.45±0.070[a]	0.50±0.000[a]	0.50±0.000[a]	0.55±0.007[a]	0.70±0.040[b]
Swelling power(ml/g)at 60°C	1.9±0.14[a]	2.6±0.14[b]	2.5±0.14[b]	2.6±0.14[b]	1.9±0.14[a]
Swelling power(ml/g) at 90°C	3.45±0.07[a]	3.85±0.07[a]	3.75±0.07[a]	3.55±0.07[a]	3.55±0.07[a]
Water absorption capacity (g/g)	1.62±0.002[a]	1.88±0.022[b]	2.23±0.002[c]	2.30±0.000[c]	1.44±0.000[d]

Values are the average of two determinants. Values denoted by each alphabets (a, b, c, d, e) are significantly different at $p<0.05$, similar alphabets indicate no significant difference.

moisture ratio, fruit powder yield, bulk density, porosity, swelling power and retention of nutrients was found to be greater than hot air oven drying at different temperatures.

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