Mathematical modelling and standardization of technology for the production of bael fruit powder

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In this study, pulp from ripe bael fruits was dried in the open sun, solar, greenhouse and hot air (50°C, 60°C, 70°C and 80°C) at three levels of thickness (2, 4 and 6 mm). Maximum antioxidant activity of 107.62 and 108.09 mg/100 g, total phenol content of 41.95 and 43.79 mg/100 g and overall acceptability scores (8.33 and 8.11) were found in bael powder dried using natural (greenhouse) and mechanical (50°C) drying methods respectively, with 2 mm of pulp thickness. The Page model was found to be the best fitted for drying bael pulp.

Keywords: Antioxidant activity, bael pulp, mathematical modelling, thin layer drying, total phenol content.

AEGLE marmelos, belonging to the family Rutaceae, is commonly known as bael in the indigenous system of medicine in India[1]. Bael is a deciduous sacred tree having useful medicinal properties, especially cooling and laxative properties[2]. The pulp of the bael fruit is a natural source of essential antioxidants and bioactive compounds. Various parts of the bael plant are used in gastrointestinal-related problems such as diarrhoea, dysentery and diabetes. Bael is well-known to have antibacterial, antifungal, anticancer, pyretic and analgesic activities and relieves constipation. Several phytochemicals have been isolated and recognized from various parts of bael, including alkaloids, phenols, glycoside coumarins, steroids, tannins and carotenoids[3].

Drying is the process of removal of moisture which supports the microbial activity. It improves shelf life compared to liquid products and reduces the cost of transportation. Small farmers cannot afford to dry their agricultural products in a commercial dryer as it is expensive with high maintenance costs. So, a farmer-friendly option is to adopt advanced greenhouse and solar drying technologies compared to traditional drying (open-sun drying, OSD). Although researchers have worked on drying bael fruit pulp using a tray dryer, hot-air cabinet dryer and freeze dryer, there are no comparative studies to determine the suitability of different dryers for drying bael fruit pulp. Assessment of drying kinetics as a function of drying conditions can help in the simulation for predicting suitable drying conditions.

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Materials and methodology

Pulp extraction

Bael fruits (*A. marmelos*) of Rajasthani local variety were procured from ICAR-Directorate of Medicinal and Aromatic Plants Research, Boriavi farm, Anand, Gujarat, India. They were sorted to discard the diseased, damaged and broken fruits. The fruits were washed thoroughly under tap water and used for further experiments. The bael pulp with seeds and fibre was added with equal amounts of water, mixed and heated for 1 min at 80°C (refs 4, 5). A brush-type pulp extractor/pulper (Khera Laboratory Instruments, New Delhi) was used to extract bael fruit pulp with a 3 mm size sieve made up of 22 gauge stainless steel.

Drying methods

The pulp was distributed evenly in the trays at three thickness levels (2 (T1), 4 (T2) and 6 (T3) mm). The trays were placed in an open environment for direct exposure of bael fruit pulp to sunlight for OSD (*D*1). Cabinet-type solar dryer (SD, *D*2; Sardar Patel Renewable Energy Research Institute (SPRERI), Anand) and a gable roof-type greenhouse dryer (GHD, *D*3) of span 4.5 m × 3.0 m (College of Food Processing Technology and Bioenergy, Anand Agricultural University (AAU), Anand) were used for drying of bael pulp using the natural drying method.

For mechanical drying, a laboratory hot-air tray dryer (Narang Scientific Works Pvt Ltd, New Delhi) was used. It was fitted with a manually controlled digital thermostat, PT-100 thermocouple, a blower driven by a 0.5 HP motor and electric finned heaters of 3 × 1 kW. The tray dryer was adjusted to selected temperatures (50°C (*D*4), 60°C (*D*5), 70°C (*D*6) and 80°C (*D*7)). The dried bael pulp was ground using a laboratory mixer-grinder to make the powder.

Standardization

Standardization of drying parameters was done in two ways – natural drying method and mechanical drying method. It was based on the total phenol content, total antioxidant content and sensory attributes (score) of the bael fruit powder. The critical difference (CD) and coefficient of variation (CV) values were determined using factorial CRD software developed by the Department of Statistics, BA College of Agriculture, AAU. Total phenol was determined by Folin–Ciocalteu method[6]. Total antioxidant content was determined using the FRAP method[7]. The sensory evaluation of bael fruit powder was done using a nine-point hedonic scale[8].

Modelling of thin-layer drying curves

The development of a model is necessary to study the drying characteristics of bael pulp. The experimental drying data of bael pulp using different drying methods or temperatures and thickness of the pulp were fitted into three thin-layer drying models (Page, two-term and Newton models).

(I) Page model[9]

$$\mathrm{MR} = \exp(-kt^n). \quad (1)$$

(II) Two-term model[10]

$$\mathrm{MR} = a\exp(-kt) + b\exp(-gt). \quad (2)$$

(III) Newton model[11]

$$\mathrm{MR} = \exp(-kt). \quad (3)$$

Here MR is the moisture ratio, t the time (min) and k, n, a, b, g are the empirical constants and coefficients in the drying models.

The root mean square error (RMSE) and χ^2 values were calculated as follows

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{Exp},i} - \mathrm{MR}_{\mathrm{Pre},i})^2}{(N-Z)}, \quad (4)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{Pre},i} - \mathrm{MR}_{\mathrm{Exp},i})^2}, \quad (5)$$

where $\mathrm{MR}_{\mathrm{Exp},i}$ is the ith experimentally observed moisture ratio, $\mathrm{MR}_{\mathrm{Pre},i}$ the predicted moisture ratio, N the number of observations and Z is the number of constants of each respective model.

A model is considered to be the best if the average R^2 value is high, and average χ^2 and RMSE values are low.

Results and discussion

Drying characteristics

The extracted pulp with 576.58% (dry basis; db) moisture content was dried using various natural as well as mechanical drying methods or temperatures for three levels of thickness of pulp. Figure 1 shows the time required to achieve the final moisture content (10–13% db) for all the drying methods. Initially, the drying rate was higher, and it decreased gradually with time for all the drying methods (Table 1).

The drying time required to achieve final moisture content of bael fruit pulp in greenhouse drying was less than OSD and solar drying, because the products placed in trays received solar radiation through plastic film material, and moisture was removed by natural and forced convection. A similar result was observed for the drying of chilli and banana in another study[12]. The drying rate was much higher in greenhouse drying compared to OSD for date fruit[13].

In tray drying, the drying time was reduced with an increase in temperature for all levels of thickness of bael fruit pulp. This was due to increased vapour pressure in the samples with increased temperature from 50°C to 80°C. As a result, moisture was removed comparatively faster. Similar outcomes were observed for drying bael fruit pulp[5] and stone apple slices[14].

Standardization of drying parameters

Table 2 shows the effect of various drying methods and levels of thickness on total phenol content, total antioxidant content and sensory attributes in terms of colour, flavour and overall acceptability.

For standardization of drying parameters for natural drying, all five parameters, namely total phenol content, total antioxidant content and sensory attributes in terms of colour, flavour and overall acceptability, were considered. It was found that the $D3T1$ combination (greenhouse drying method with 2 mm thickness of bael fruit pulp) gave better results than the other combinations because this sample gave the highest total antioxidant and total phenol content. Also, the highest colour and overall acceptability (OA) values were also obtained. Hence, the combination $D3T1$ was considered the standardized drying parameter for natural drying.

For mechanical drying, parameters such as total phenol content, total antioxidant content and sensory attributes in terms of colour, flavour and overall acceptability were considered. The $D4T1$ combination (50°C drying temperature with 2 mm thickness of pulp) was found to be the best among all combinations because the sample gave the highest total antioxidant and total phenol contents. Also, it had the highest colour, flavour and overall acceptability value. Hence, the combination $D4T1$ was considered as the drying parameter for mechanical drying method.

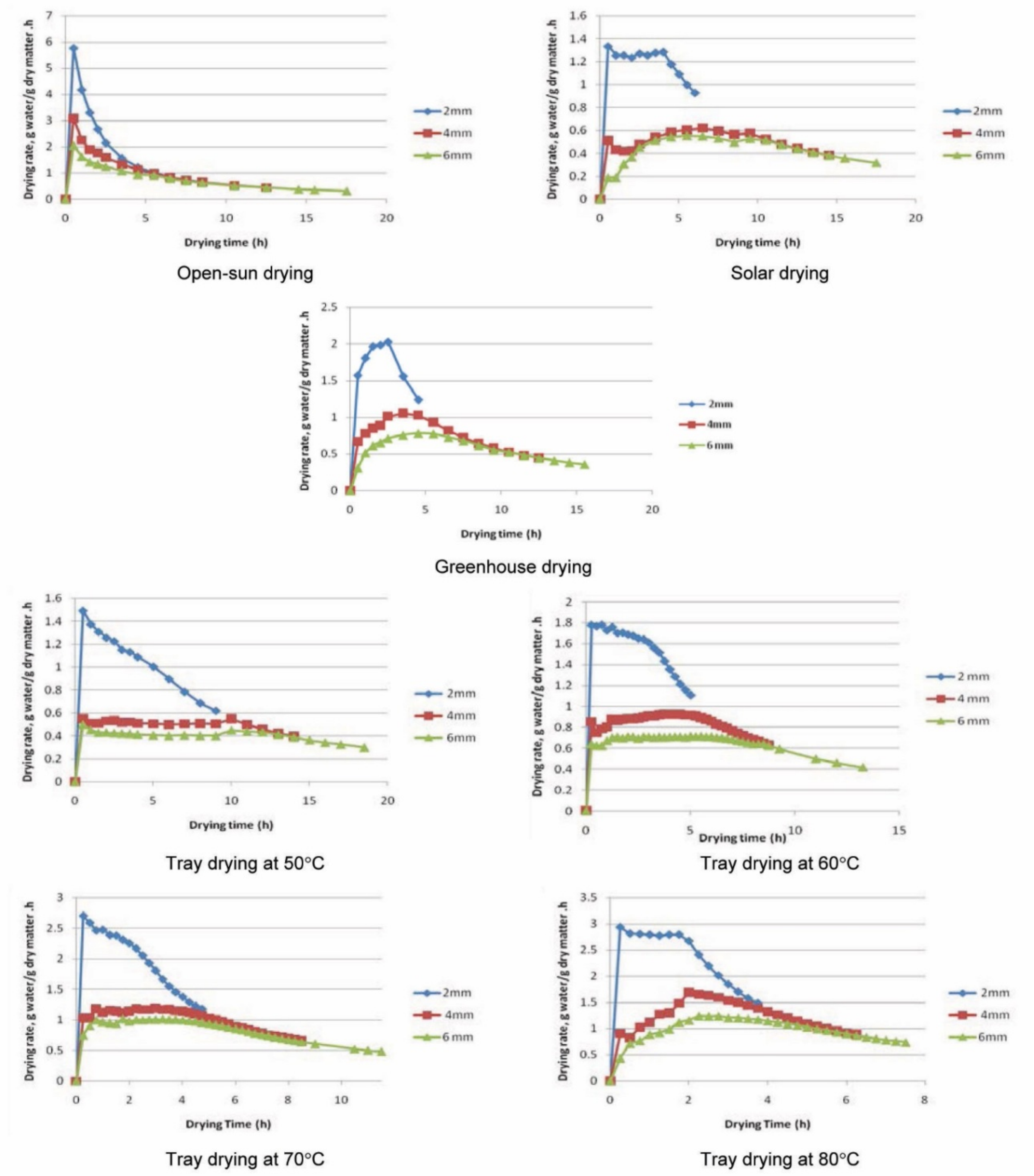

Figure 1. Drying rate versus drying time curves of bael fruit pulp for various drying methods.

Table 1. Time required for drying of bael fruit pulp using various drying methods and for different level of thicknesses of the pulp

		Drying time (h)		
		Thickness		
Drying method	Temperature (°C)	2 mm	4 mm	6 mm
Open-sun drying	–	6.5	12.5	17.5
Solar drying	–	6	14.5	17.5
Greenhouse drying	–	4.5	12.5	15.5
Tray drying	50	9	14	18.5
	60	5.75	8.75	13.25
	70	4.75	8.5	11.5
	80	3.75	6.25	7.5

Table 2. Effect of drying methods and thickness on TPC, TAA and sensory attributes

Parameters	Drying methods	Name of drying methods (*D*)	Pulp thickness (*T*) (mm) 2	4	6	CD *D*	*T*	*DT*	CV%
TPC	Natural drying	*D*1-OSD	26.65	25.53	18.45	0.769	0.769	NS	0.75
		*D*2-SD	23.04	22.94	20.66				
		*D*3-GHD	41.95	28.99	28.62				
	Mechanical drying	*D*4-50°C	43.79	36.15	23.22	2.249	1.948	3.896	7.03
		*D*5-60°C	35.80	30.24	18.92				
		*D*6-70°C	38.91	31.05	28.79				
		*D*7-80°C	41.00	39.16	27.35				
TAA	Natural drying	*D*1-OSD	106.19	104.76	103.34	0.769	0.769	NS	0.75
		*D*2-SD	101.91	101.91	100.00				
		*D*3-GHD	107.62	105.24	103.34				
	Mechanical drying	*D*4-50°C	108.09	106.19	103.81	0.803	0.695	1.390	0.79
		*D*5-60°C	106.19	102.38	100.95				
		*D*6-70°C	104.76	103.81	103.34				
		*D*7-80°C	108.09	106.66	105.24				
Colour (sensory)	Natural drying	*D*1-OSD	7.17	6.25	6.58	NS	0.751	NS	16.01
		*D*2-SD	7.92	7.08	6.50				
		*D*3-GHD	7.92	7.00	6.42				
	Mechanical drying	*D*4-50°C	7.83	7.92	6.58	NS	0.485	NS	11.74
		*D*5-60°C	8.00	6.92	6.33				
		*D*6-70°C	7.92	7.00	6.92				
		*D*7-80°C	7.50	6.67	6.33				
Flavour (sensory)	Natural drying	*D*1-OSD	6.83	6.83	6.75	NS	NS	NS	9.72
		*D*2-SD	7.58	6.92	6.67				
		*D*3-GHD	7.75	7.17	7.08				
	Mechanical drying	*D*4-50°C	7.50	7.17	6.58	NS	0.502	NS	12.49
		*D*5-60°C	7.58	6.67	6.54				
		*D*6-70°C	7.75	6.92	6.96				
		*D*7-80°C	7.00	6.50	6.33				
OAA (sensory)	Natural drying	*D*1-OSD	7.00	6.50	6.42	NS	0.543	NS	11.50
		*D*2-SD	7.58	7.00	7.00				
		*D*3-GHD	7.75	7.08	6.83				
	Mechanical drying	*D*4-50°C	7.58	7.42	6.42	NS	0.472	NS	11.77
		*D*5-60°C	7.75	6.75	6.29				
		*D*6-70°C	7.67	6.83	6.79				
		*D*7-80°C	7.17	6.50	6.17				

TPC, Total phenol content; TAA, Total antioxidant activity; OAA, Overall acceptability; OSD, Open-sun drying; SD, Solar drying; GHD, Greenhouse drying; CD, Critical difference; CV, Co-efficient of variance.

Fitting of drying models

Based on moisture loss data, the drying rate and moisture ratio were calculated. The coefficient of determination (R^2) was determined using SPSS-15. The three drying models (Page model, two-term model and Newton model) were compared according to their coefficient of determination, RMSE and chi-square values to determine the best-fit model for drying bael fruit pulp for different levels of thickness of pulp (Table 3).

The values of R^2, χ^2 and RMSE of all the models ranged from 0.924 to 1, 4.4E-05 to 0.011 and 6.61E-03 to 0.102, with an average value of 0.951 to 0.995, 5.21E-04 to 2.7E-03 and 8.39E-03 to 2.06E-02 respectively.

The moisture ratio data of bael fruit pulp dried using different drying methods or temperatures and for different levels of thickness of pulp were fitted into three drying models (Table 3). It was observed that the Page model had the highest average R^2 and lowest average RMSE and χ^2 values compared to the other two models. Table 4 shows the values of constants of the best-fitted drying model (Page model). The Page model was the best-fitting for drying bael fruit pulp with various drying methods or temperatures and levels of pulp thickness, with average values of R^2, RMSE and χ^2 being 0.995, 5.21E-04 and 8.39E-03 respectively. This model was found to be the best for drying whole and sliced turmeric rhizomes in a solar conduction dryer[15] and freeze-dried aloe vera fillets[16].

Suitability of the model

The accuracy of the established model for thin-layer drying of bael fruit pulp was evaluated by comparing the predicted moisture ratio of the Page model and the experimental moisture ratio. Figure 2 shows the performance of the model for all the drying methods/temperatures and levels of thickness of bael fruit pulp. The predicted moisture ratio data of

Table 3. Statistical parameters for different drying models using various drying methods and different levels of thickness of bael fruit pulp

Drying methods_ thicknesses	Two-term model			Page model			Newton model		
	R^2	Chi-square	RMSE	R^2	Chi-square	RMSE	R^2	Chi-square	RMSE
OSD_2 mm	0.999	8.44E-04	0.023	0.999	8.92E-05	0.008	0.999	8.27E-05	0.009
OSD_4 mm	0.997	4.00E-04	0.017	0.996	4.33E-04	0.019	0.996	4.01E-04	0.019
OSD_6 mm	0.997	3.94E-04	0.017	0.996	4.34E-04	0.019	0.996	4.82E-04	0.021
SD_2 mm	0.945	9.51E-03	0.081	0.99	1.34E-03	0.034	0.932	8.72E-03	0.090
SD_4 mm	0.98	3.71E-03	0.054	0.996	6.06E-04	0.023	0.929	1.10E-02	0.102
SD_6 mm	0.982	3.34E-03	0.052	0.996	7.26E-04	0.026	0.935	9.96E-03	0.097
GHD_2 mm	0.977	5.80E-03	0.054	0.987	2.20E-03	0.041	0.945	7.78E-03	0.083
GHD_4 mm	0.966	6.36E-03	0.070	0.999	1.58E-04	0.012	0.951	7.30E-03	0.083
GHD_6 mm	0.973	4.74E-03	0.061	0.999	9.22E-05	0.009	0.957	6.41E-03	0.078
TD50_2 mm	0.981	2.83E-03	0.045	0.995	5.75E-04	0.022	0.977	2.65E-03	0.050
TD50_4 mm	0.985	2.32E-03	0.043	0.983	2.45E-03	0.047	0.924	1.01E-02	0.098
TD50_6 mm	0.982	2.89E-03	0.049	0.985	2.17E-03	0.045	0.928	9.92E-03	0.097
TD60_2 mm	0.987	1.79E-03	0.039	0.996	5.15E-04	0.022	0.951	5.68E-03	0.074
TD60_4 mm	0.953	5.91E-03	0.073	0.996	5.25E-04	0.022	0.932	7.83E-03	0.087
TD60_6 mm	0.957	5.02E-03	0.067	0.993	7.44E-04	0.027	0.938	6.66E-03	0.081
TD70_2 mm	0.988	1.51E-03	0.035	0.996	4.63E-04	0.020	0.969	3.36E-03	0.056
TD70_4 mm	0.986	1.68E-03	0.039	0.997	3.10E-04	0.017	0.951	5.35E-03	0.072
TD70_6 mm	0.987	1.46E-03	0.036	0.998	2.12E-04	0.014	0.956	4.74E-03	0.068
TD80_2 mm	0.972	4.48E-03	0.058	0.993	9.07E-04	0.028	0.935	8.40E-03	0.089
TD80_4 mm	0.974	3.79E-03	0.057	0.999	1.98E-04	0.014	0.924	9.66E-03	0.096
TD80_6 mm	0.986	1.91E-03	0.041	1	4.67E-05	0.007	0.937	7.58E-03	0.085
Average	0.979	1.81E-03	0.014	0.995	5.21E-04	0.008	0.951	2.70E-03	0.021

TD50, Tray drying at 50°C; TD60, Tray drying at 60°C; TD70, Tray drying at 70°C; TD80, Tray drying at 80°C.

Table 4. Constants of the best-fitted drying model of bael fruit pulp

Drying method	Temperature (°C)	Thickness (mm)	Constants of Page model MR = exp($-kt^n$)		Coefficient of determination (R^2)	Chi-square (χ^2)	RMSE
			k	n			
Sun drying	–	2	0.023	1.019	0.999	8.92E-05	8.45E-03
		4	0.009	0.991	0.996	4.33E-04	1.93E-02
		6	0.004	1.059	0.996	4.34E-04	1.96E-02
Solar drying	–	2	0.000	1.685	0.990	1.34E-03	3.37E-02
		4	2.564E-5	1.818	0.996	6.06E-04	2.32E-02
		6	3.201E-5	1.748	0.996	7.26E-04	2.56E-02
Greenhouse drying	–	2	0.001	1.616	0.987	2.20E-03	4.06E-02
		4	0.000	1.741	0.999	1.58E-04	1.18E-02
		6	0.000	1.635	0.999	9.22E-05	9.08E-03
Tray drying	50	2	0.001	1.320	0.995	5.75E-04	2.22E-02
		4	6.360E-5	1.630	0.983	2.45E-03	4.68E-02
		6	3.826E-5	1.658	0.985	2.17E-03	4.45E-02
	60	2	0.001	1.572	0.996	5.15E-04	2.17E-02
		4	0.000	1.682	0.996	5.25E-04	2.23E-02
		6	0.000	1.599	0.993	7.44E-04	2.66E-02
	70	2	0.002	1.435	0.996	4.63E-04	2.04E-02
		4	0.000	1.579	0.997	3.10E-04	1.71E-02
		6	0.000	1.533	0.998	2.12E-04	1.42E-02
	80	2	0.000	1.799	0.993	9.07E-04	2.82E-02
		4	0.000	1.889	0.999	1.98E-04	1.35E-02
		6	0.000	1.701	1.000	4.67E-05	6.61E-03

bael pulp drying followed a straight line with an angle of 45°, which indicates the suitability of the Page model for describing the drying of bael fruit pulp. A similar approach for selecting a model for thin-layer drying has also been reported for carrot pomace[17] and bael fruit pulp[5,18].

Conclusion

In this study, the bael fruit pulp was dried using various drying methods and for different levels of pulp thickness. The drying rate decreased gradually with time for various

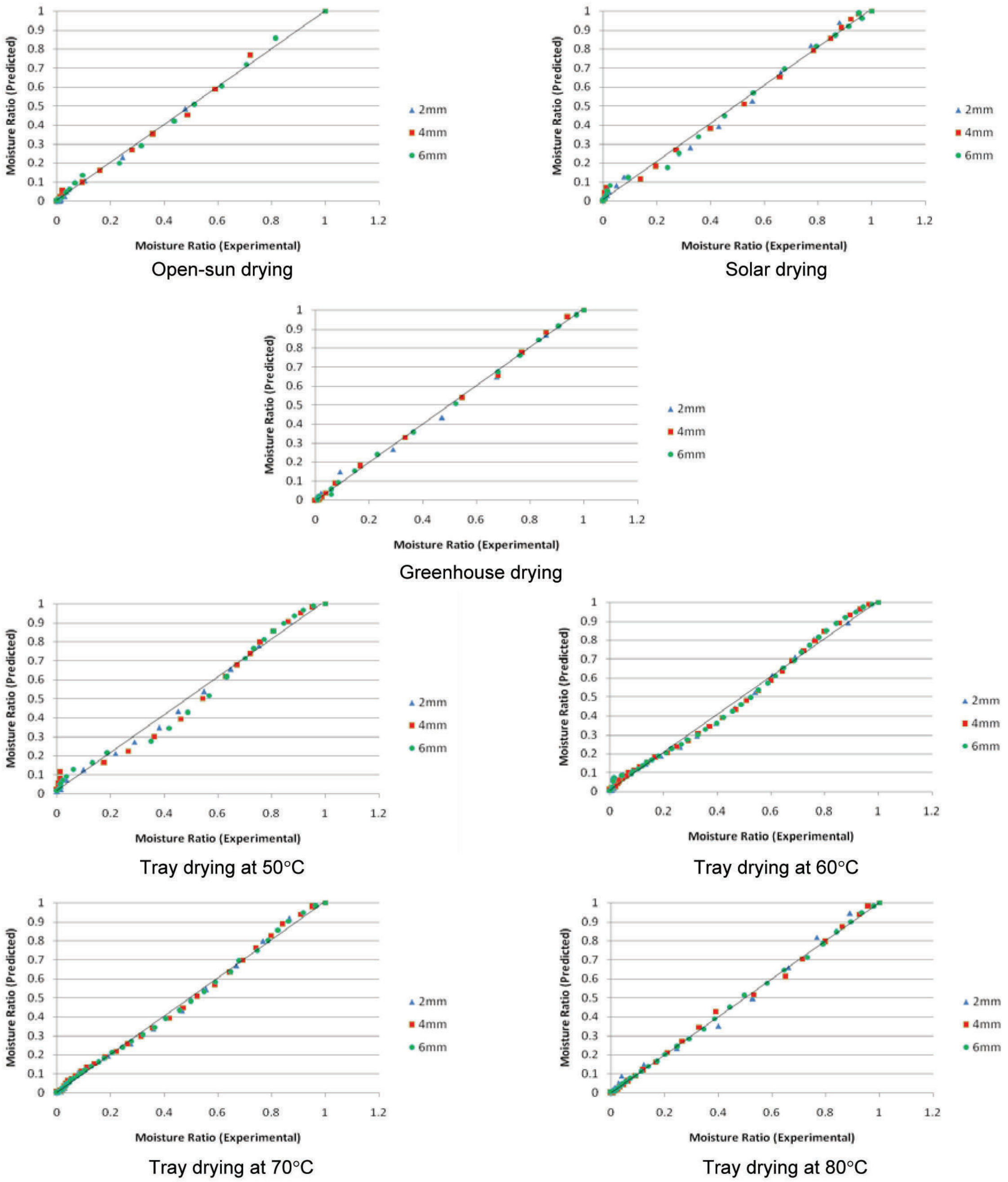

Figure 2. Experimental versus predicted moisture ratio (Page model: MR = exp($-kt^n$)).

drying methods and thickness of pulp. The maximum total phenol content of 41.95 mg/100 g was found in bael powder dried using the natural drying method, i.e. greenhouse drying with 2 mm pulp thickness. While in mechanical drying at 50°C and 2 mm pulp thickness, it was 43.79 mg/100 g. Maximum antioxidant activity of 107.62 mg/100 g was found in bael powder dried using a natural drying method with 2 mm thickness of bael pulp. While at 50°C and 80°C with 2 mm thickness of bael pulp, the maximum antioxidant activity of 108.09 mg/100 g was observed for mechanical drying. Maximum overall acceptability score was found in bael powder with 2 mm thick pulp in both the drying methods, i.e. natural and mechanical. The Page model was found to be the best fitted for drying bael fruit pulp using different drying methods or temperatures and levels of pulp thickness, with average values of R^2, RMSE and χ^2 being 0.995, 5.21E-04 and 8.39E-03 respectively.

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