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Full Length Research Paper

Modeling of convective drying of safed musli (*Chlorophytum borivilinum*)

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The drying kinetics of Safed musli (*Chlorophytum borivilinum*) in terms of moisture content, moisture ratio, drying time and drying rate was investigated. A laboratory model dehumidified air dryer and a hot air dryer (Tray dryer) were employed to study the drying behavior at 30, 35, 40 and 45°C. Safed musli drying primarily occurred in falling rate period. The drying data were fitted to seven thin layer drying models and the two-term model satisfactorily described the drying behavior of safed musli roots with highest coefficient of determination (R^2) and lowest chi-square (χ^2), root mean square error (RMSE) and mean bias error (MBE) values except at 30°C in dehumidified air dryer where logarithmic model was found as the best model having the highest R^2 and lowest χ^2, RMSE and MBE values. Effective moisture diffusivity (D_{eff}) of safed musli was found to increase with the increase in drying air temperature and it ranged from 2.23010 × 10^{-7} to 4.43057 × 10^{-7} m^2/s. The results of the study are very useful for commercial scale drying of safed musli to optimize drying process and to achieve superior quality of dried product.

Key words: Drying, dehumidified air dryer, tray dryer, safed musli, modeling.

INTRODUCTION

'Safed musli' is an endangered medicinal plant of Liliaceae family belonging to genus Chlorophytum. The name Chlorophytum is derived from the Greek word choloros meaning green and phyton-plant (Rochford and Grover, 1961). The genus Chlorophytumis is represented by about 175 valid taxa of rhizomatous herbs distributed predominantly in the tropical parts of the world (Hooker, 1894). Of the genus, Chlorophytum, 13 species are reported to occur in India (Sheriff and Chennaveeriah, 1972) of which, eight are endemic (Nair, 1974). It is the most important species of genus Chlorophytum, popularly known as Safed musli. It is distributed in Dangs forest (Gujarat), Sinhagad near Mahi, Aravali hills, Malghat Chikhaldara and Satpuda hills near by Akola (Ganorkar et al., 2004).

Safed musli root powder is used in combination with other herbal material in the preparation of several tonics intended for different ailments. The fleshy roots contained 63.0 to 84.5% moisture that is, dry matter, in the range of 15.5 and 37.0% only. The major chemical constituents are carbohydrates (42%), proteins (8%), fiber (3 to 4%) and Saponins (2 to 17%). The tuber are rich in minerals and the dried tubers contains sodium 0.04 mg/g, K 0.80 mg/g, Ca 6.6 mg/g, Mg 1.9 mg/g, P 3.2 mg/g, Zn 0.002 mg/g and Cu 0.148 mg/g (Manikpuri and Jain, 2010). It is considered as wonder drug in Indian system of medicines due to its aphrodisiac and natural sex tonic properties. Its action is on the central nervous system like the Ginseng. It is known as the Indian Ginseng (Singhania, 2003) because of its great therapeutic importance. Safed musli

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tubers are the major constituents of more than 100 ayurvedic preparations (Oudhia, 2000). In the traditional diet of nursing mothers (after confinement), its powder is added in the preparation of '*laddoo*s' (sweet prepared in ball form) to be taken as an energizing food. Efforts are on in countries like the USA and England to make chips/flakes with the tubers, to use it as a nutritious item in breakfast. Traditionally, tubers are used in the treatment of rheumatism and the leaves as vegetable in various culinary preparations. Dried root powder increases the lactation amongst the feeding mothers and lactating cows (Singhania, 2003; Elizabeth, 2001; Singh and Chauhan, 2003).

High temperature drying deteriorates the material structure and can render it unsuitable for further use. Heat pump dryers operating under closed loop conditions have the potential to dry these crops, independent of ambient conditions. Under high ambient moist air conditions, it may not even be possible to dry the material by conventional means. The principle advantages of heat pump dehumidified dryers (HPD) emerge from ability of heat pumps to recover energy from exhaust, as well as their ability to control the drying air temperature and humidity (Mujumdar et al., 2002). HPDs have the potential to operate more efficiently and at lower temperatures than conventional dryers (Filho and Stormmen, 1996).

In HPD, both sensible and latent heat can be recovered from the dryer exhaust air, improving the overall thermal performance. Continuous dryers, where the material is fed and discharged at a uniform rate, are also configured with heat pumps. Adapa et al. (2002) presented a simplified model for the performance of a low temperature heat pump dryer for specialty crops. Mathematical models for heat pumps and thin layer dryers were combined to obtain a re-circulating heat pump dryer model. Strommen and Kramer (1994) stated that heat pump dryers produce a higher quality product compared to traditional oil fired dryers. A number of studies for drying of fruits and vegetables have been reported by various workers. To analyze the drying behavior of a food product, it is quite essential to study the drying kinetics of the food. The thin layer drying is widely used for fruits and vegetables to prolong their shelf life.

Among the wide range of models, thin layer drying models have found widest application because of their ease of use. They do not require evaluation of many models' parameters, as is common in more complex representations.

Thin layer drying equations describe drying phenomena in a unified manner regardless of controlling mechanism. The equations are used to estimate drying time of several products and generalize drying curves (Karathanos and Belessiotis, 1999). Thin layer drying models for agricultural products correlates moisture content of the material at any given point in time (after product's exposure to a constant relative humidity and temperature condition) and drying parameters (Midilli et al., 2002; Togrul and Pehliavan, 2002). Dried product quality entirely depends on different unit operations involved in drying process. Drying process should be undertaken in closed equipment to improve the quality of the product (Ertekin and Yaldiz, 2004). Limited information is available on drying kinetics of safed musli roots. The present work ascertains the effect of dehumidified air dryer conditions on safed musli roots and evaluates different thin layer drying model.

Theoretical considerations

The moisture content of safed musli roots during thin-layer drying were expressed in terms of moisture ratios (MR) and calculated from the following equation (Midilli, 2001; Erenturk et al., 2004).

$$MR = \frac{(M - M_e)}{(M_o - M_e)} \qquad (1)$$

Where MR is moisture ratio (dimensionless), M is moisture content at time t% (db), M_o is initial moisture content (%) (db), and M_e is equilibrium moisture content (%) (db). For determining the moisture content, the samples were placed in a hot air oven at 100°C and for 18 h (Ranganna, 1986). The equilibrium moisture content was determined by static method (Asae, 1996). The samples were weighted before and after drying and their moisture content was determined using Equation 2.

$$M_c = \frac{W_w - W_d}{W_d} \qquad (2)$$

Where Mc is moisture content (%) (db), W_w is weight of sample (g) and W_d is dry matter weight (g). Seven thin layer-drying equations were tested (Table 1) to select the best model for describing the drying curve equation of safed musli. Non-linear regression analysis was performed for the drying data by using STATISTICA. The models were tested on the basis of coefficient of determination (R^2) (Ozdemir and Devres, 1999; Yaldiz et al., 2001; Erenturk et al., 2004), chi-square (χ^2), and mean bias error (MBE) and root mean square error (RMSE). R^2 value should be higher for quality fit, whereas χ^2, MBE and RMSE values should be lower (Togrul and Pehlivan, 2002; Demir et al., 2004; Erenturk et al., 2004; Goyal et al., 2007). The above mentioned parameters can be calculated as follows:

$$\chi^2 = \sum_{i=1}^{N} \frac{(MR_{exp,i} - MR_{pre,i})^2}{N - n} \qquad (3)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2\right]^{\frac{1}{2}} \qquad (4)$$

Table 1. Alternative mathematical models available in the literature.

S/N	Name of the model	Model equation	Reference
1	Lewis	MR = Exp(-k×t)	Lewis (1921)
2	Henderson and Pabis	MR = a×Exp(-k×t)	Henderson and Pabis (1961)
3	Logarithmic	MR = a×Exp(-k×t)+c	Doymaz (2004a)
4	Two- term	MR = a×Exp(-k×t)+b×Exp(-n×t)	Gunhan et al. (2004)
5	Two–term exponential	MR = a×Exp(-k×t)+(1-a)×Exp(-k×a×t)	Gunhan et al. (2004)
6	Wang and sing	MR = 1+(a×t)+(b×(t×2))	Ertekin and Yaldiz (2004)
7	Diffusion approach	MR = a×Exp(-k×t)+(1-a)×Exp(-k×b×t)	Togrul and Pehlivan (2003)

a, b, c, k and n = model coefficients, t = drying time (min).

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right) \quad (5)$$

Where, MR_{pre} = moisture ratio of predicted data; MR_{exp} = moisture ratio of experimental data; N = number of observations; n = number of model constants.

In the equations described in Table 1, k, n, a, b, and c are the model coefficients. Non-linear regression method was utilized to fit the data to the selected drying models. For evaluating the goodness of fit, three statistical indicators were used in addition to R^2. The model having the highest R^2 and the lowest RMSE, χ^2 and MBE was thus determined as the best model.

Moisture diffusivity

Fick's diffusion equation for particles with slab geometry was used for calculation of effective moisture diffusivity. The safed musli were dried after washing, the samples were considered with slab geometry (Doymaz, 2006). The equation is expressed as (Crank, 1975)

$$MR = \frac{8}{\pi^2} exp\left(\frac{-\pi^2 t D_{eff}}{4L^2}\right) \quad (6)$$

Then, equation 6 can be rewritten as:

$$D_{eff} = \frac{Ln\frac{8}{\pi^2} - LnMR}{\left(\frac{t\pi^2}{4L^2}\right)} \quad (7)$$

A plot of ln(MR) versus time for each temperature will give a straight line whose slope (k_o), presented in Equation (7), allows the estimation of the corresponding value of the diffusion coefficient.

$$k_0 = \left(\frac{-\pi^2 D_{eff}}{4L^2}\right) \quad (8)$$

METHODOLOGY

The experiments were conducted at the Department of Agricultural Process Engineering, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola to study the thin layer drying behavior of safed musli roots using dehumidified air dryer and hot air dryer. Safed musli samples were dried at 30, 35, 40 and 45°C in dehumidified air dryer and at 35, 40 and 45°C in hot air dryer. The temperature of drying air was measured by mercury thermometer, and relative humidity was measured by single probe digital RH meter. Samples were replicated thrice in each case of drying. The weight loss data were noted during drying of safed musli at an interval of 30 min.

Sample preparation

Fresh harvested safed musli roots were procured directly from farmer's field. The discolored, diseased or damaged safed musli were sorted out. These samples were washed properly in running water to remove the adhering impurities and spread the sample on a plastic filter tray to drain out the excess water and flow chart of drying procedure is shown in Figure 1. Surface moisture of the sample was removed by centrifuge machine at 300 rpm for 3 min. A sample mass of 200 g was used for the study.

Dehumidified air dryer

Lab model dehumidified air dryer was used for the drying experiment. The dryer consists of compressor, evaporator, condenser, drying chamber and thermostat. The condenser and evaporator coils provide the required heating and cooling/dehumidification operation for the process air in the dryer. In order to maintain low relative humidity condition and prevent air exchange with outside, an external condenser has been employed to remove excess heat. The size of the drying chamber was 73 × 51 × 56 cm. The aluminum wire mesh trays of size (50 × 48 cm) were kept one above the other. The relative humidities maintained in the dehumidified air dryer at different temperatures of 30, 35, 40, and 45°C were 19, 22, 35 and 42%, respectively.

Tray dryer

Tray dryer is most suitable when large quantities of products are to be dried within a short time. Tray dryer consists of drying chamber, blower, heaters and thermostat switch. The drying chamber of size 1500 × 1000 × 400 mm having 12 aluminum trays was used. Trays were kept one above the other with the clearance of 30 mm in between to permit air circulation. The relative humidities maintained in the hot air dryer at different temperatures of 35, 4 0, and 45°C

Table 2. Physical dimensions of safed musli (mm).

Sample	Thickness	Length
1	0.50	52
2	0.45	81
3	0.55	101
4	0.57	71
5	0.56	65
6	0.48	112
7	0.42	120
8	0.52	132
9	0.51	145
10	0.53	112
Mean	0.51	99.1
Standard Deviation	0.0495	30.55

were 35, 40 and 52%, respectively.

Physical properties

Thickness and length of safed musli were measured by using vernier caliper having a least count of 0.01 cm. The average length of safed musli roots was used to calculate moisture diffusivity. Water activity of dried safed musli roots was 0.26 ± 0.02, measured by Aqua Lab manufactured by Dicagon Devices Inc., USA (Model CX2).

Statistical analysis

Modeling of convective thin layer drying of safed musli was done by using ‘STATISTICA 11.0’.

RESULT AND DISCUSSION

Physical dimensions of safed musli

The physical dimensions of safed musli are shown in Table 2. The average thickness of safed musli was 0.51 mm and average length was 99.1 mm. The thickness of the safed musli roots was more or less constant, but length varied from 52 to 145 mm. The average length was used to determine moisture diffusivity of safed musli roots.

Drying characteristics of safed musli

Moisture content of fresh safed musli was found to be 400.85% (db) and dried up to 8% (db). It took 960 min at 45°C whereas it took 1,440 min at 30°C. It was observed that drying of safed musli occurred primarily in falling rate period and no constant rate period was observed in dehumidified air dryer (Figure 2) and in hot air dryer (Figure 3) at all drying temperatures. Moisture depletion per hour was higher at initial stages and then started to decrease with drying time. Drying in falling rate period indicated that initial mass transfer occurred by diffusion. Similar results have been reported for the drying studies (Yaldiz and Ertekin, 2001; Akpinar, 2006; Doymaz et al., 2006).

Curve fitting of drying data

The moisture content data at the different drying air temperatures were converted to moisture ratio, and same were fitted for the mentioned thin layer drying models (Table 1). The coefficient of correlation and results of statistical analyses are shown in Tables 3 and 4. The Wang and Singh model was eliminated for having R^2 values lower than 0.9. Although, the other models showed R^2 values greater than 0.90 at all temperatures, the two-term model showed the best fit having highest R^2 and lowest χ^2, MBE and RMSE. Thus, the two term model with highest R^2 value of 0.998 adequately represented thin layer behavior of safed musli roots in dehumidified air dryer and hot air dryer. Similar findings were reported for hot air drying of apricots (Togrul and Pehlivan, 2002; Doymaz, 2004), rosehip (Erenturk et al., 2004) mint leaves in tunnel dryer (Kadam et al., 2011) and Plum (Goyal et al., 2007). Table 5 shows the results of fitting the Two-term model to data obtained from experimental treatments.

The two-term model was not fitted for temperature 30°C in dehumidified air dryer as R^2 value was lower. Thus, the logarithmic model with highest R^2 value of 0.9982 and lowest χ^2 value of 0.114×10^{-3} adequately represented thin layer drying behavior of safed musli roots dehumidified air dryer. The coefficients of logarithmic equation fitted to drying data are shown in Table 6. Experimentally determined and predicted moisture ratio values were fitted to two-term model at all temperatures, and all drying methods are shown in Figure 4 and experimentally determined and predicted moisture ratio values were fitted to logarithmic model at 30°C in dehumidified air dryer as shown in Figure 5.

Moisture diffusivity

Moisture diffusivity of safed musli increased with the increase in drying air temperature. Moisture diffusivity (D_{eff}) varied from 2.23010×10^{-7} to 4.43057×10^{-7} m^2/s for temperature range from 30 to 45°C. Table 7 also shows the linear relationship between ln(MR) and time, with R^2 values. The relationship between ln(MR) and time are shown in Figure 6 for drying of safed musli at 40°C, and similar trends were observed for other drying air temperatures.

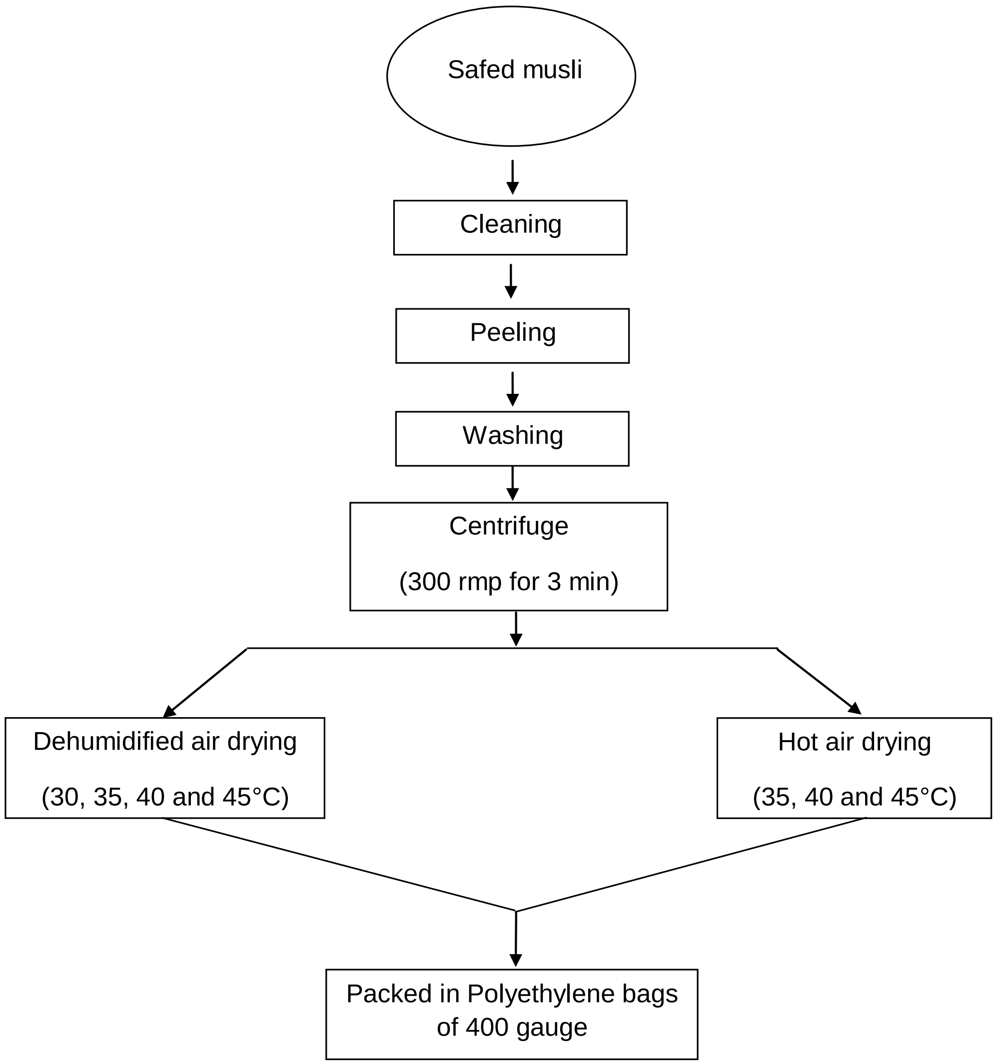

Figure 1. Experimental layout for drying of safed musli

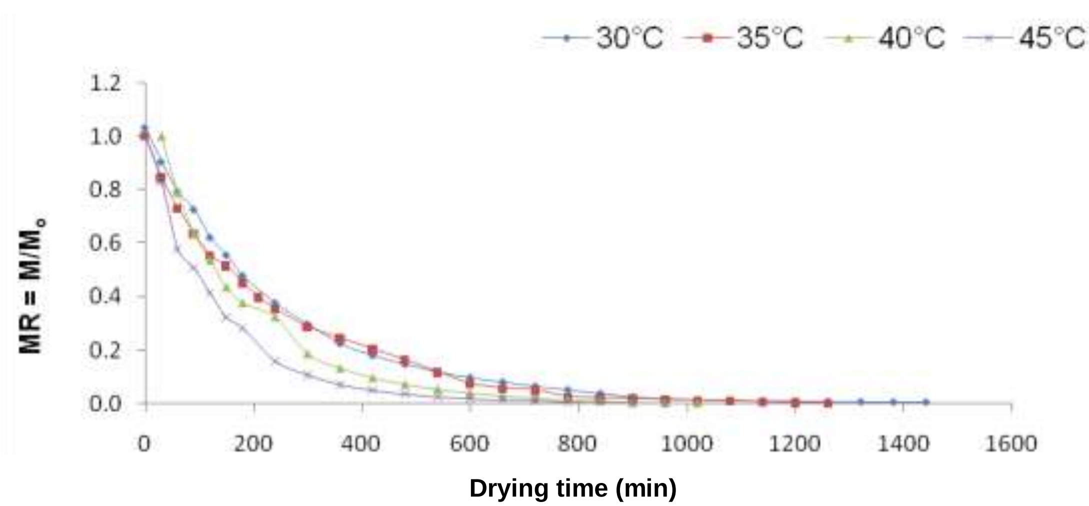

Figure 2. MR of dehumified air dried safd musli.

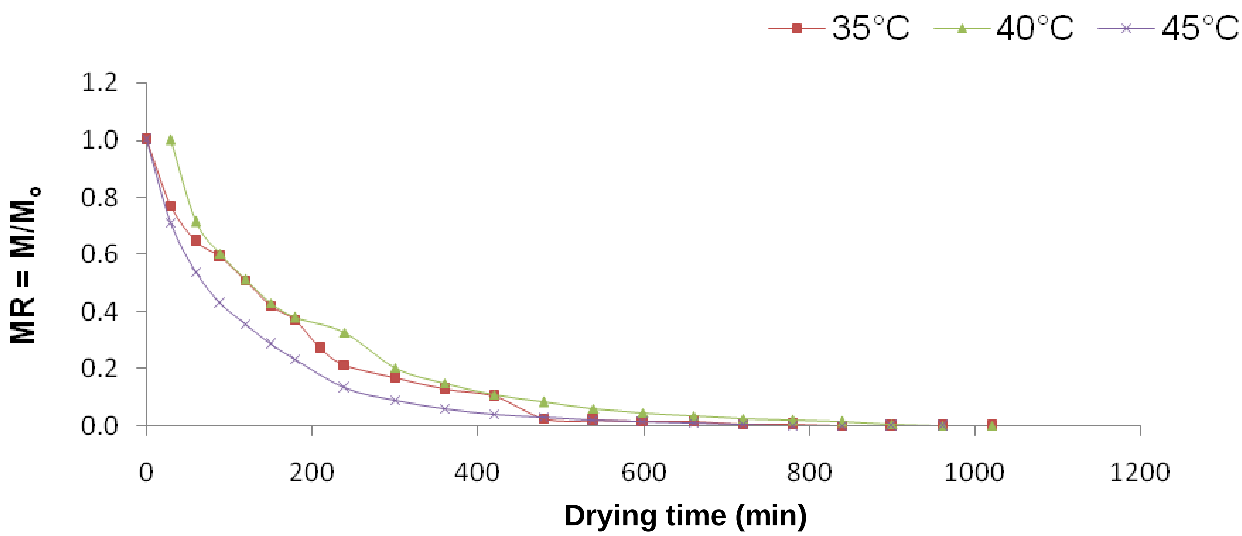

Figure 3. MRof hot dried safed musli.

Table 3. Fitting results of the experimental data of the dehumidified air drying safed musli roots to the thin layer models.

Temperature (°C)	Name of model	R^2	$c^2 \times 10^{-3}$	MBE × 10^{-2}	RMSE × 10^{-1}
	Newton	0.9982	0.115	-0.0070	0.1063
	Henderson and Pabis	0.9982	0.114	0.0050	0.1044
30	Logarithmic	0.9983	0.114	0.0000	0.1044
	Two–term exponential	0.9981	0.124	0.018	0.1088
	Wang and sing	0.8278	11.146	2.65	1.0335
	Newton	0.9962	0.243	0.2000	0.1523
	Henderson and Pabis	0.9973	0.179	0.1540	0.1306
	Logarithmic	0.9959	0.241	0.0000	0.1497
35	Two- term	0.9980	0.136	0.1556	0.1094
	Two –term exponential	0.9939	0.353	0.0700	0.2640
	Wang and sing	0.7634	13.833	3.2470	1.1478
	Diffusion approach	0.9978	0.132	0.1607	0.1107
	Newton	0.9929	0.399	-0.4018	0.19704
	Henderson and Pabis	0.9948	0.303	-0.4390	0.1970
	Logarithmic	0.9956	0.260	0.0000	0.1530
40	Two- term	0.9980	0.194	-0.2500	0.1318
	Two –term exponential	0.9973	0.158	-0.1598	0.1220
	Wang and sing	0.7282	15.820	3.390	0.12242
	Diffusion approach	0.9973	0.161	-0.1506	0.1218
	Newton	0.9964	0.227	-0.297	0.1484
	Henderson and Pabis	0.9964	0.235	-0.3004	0.1483
	Logarithmic	0.9967	0.221	0.0000	0.1414
45	Two- term	0.9969	0.251	-0.293	0.1483
	Two –term exponential	0.9964	0.235	-0.286	0.1484
	Wang and sing	0.7659	15.276	3.12	1.197
	Diffusion approach	0.9964	0.243	-0.2978	0.1484

Table 4. Fitting results of the experimental data of the hot air drying of safed musli roots to the thin layer models.

Temperature (°C)	Name of model	R^2	$\chi^2 \times 10^{-3}$	MBE × 10^{-2}	RMSE × 10^{-1}
35	Newton	0.9939	0.243	0.0700	0.1832
	Henderson and Pabis	0.9959	0.179	0.0128	0.1497
	Logarithmic	0.9959	0.241	0.0000	0.1496
	Two- term	0.9978	0.136	0.1590	0.1107
	Two–term exponential	0.9975	0.353	0.1676	0.1170
	Wang and sing	0.7635	13.833	3.247	1.1478
	Diffusion approach	0.9978	0.132	0.1607	0.4009
40	Newton	0.9846	0.575	-0.3737	0.234
	Henderson and Pabis	0.9931	0.376	-0.4361	0.1888
	Logarithmic	0.9939	0.340	0.0000	0.1770
	Two- term	0.9978	0.124	-0.1643	0.1054
	Two –term exponential	0.9967	0.178	-0.1519	0.1280
	Wang and sing	0.6663	18.354	3.768	1.3186
	Diffusion approach	0.9891	0.608	-0.3836	0.2366
45	Newton	0.9942	0.322	-0.3770	0.1760
	Henderson and Pabis	0.9958	0.240	-0.4330	0.1500
	Logarithmic	0.9965	0.206	0.0000	0.1367
	Two- term	0.9987	0.076	-0.1906	0.0817
	Two –term exponential	0.9988	0.065	-0.1411	0.0782
	Wang and sing	0.6371	20.646	3.915	1.3912
	Diffusion approach	0.9416	0.344	-0.3770	0.1765

Table 5. Coefficient of the two-term model fitted to drying data at 35°C, 40°C and 45°C.

Temperature (°C)	Drying method	a × 10^{-2}	k	b ×10^{-2}	n × 10^{-2}	R^2	$\chi^2 \times 10^{-3}$	MBE × 10^{-2}	RMSE × 10^{-1}
35	DAD	5.63	0.9	94.36	0.41	0.99	0.136	0.1556	0.1094
	HAD	8.88	0.9	91.1	0.51	0.99	0.136	0.1593	0.1107
40	DAD	9.37	0.9	90.63	0.56	0.99	0.194	-0.25	0.1318
	HAD	13.93	0.9	86.06	0.058	0.99	0.124	-0.1643	0.1054
45	DAD	0.35	0.9	99.63	0.75	0.99	0.251	-0.293	0.1483
	HAD	11.59	0.9	88.4	0.77	0.99	0.076	-0.1906	0.0817

DAD: Dehumidified air dryer, HAD: Hot air dryer.

seven drying models, the Two-term equation showed the best fit drying of safed musli roots at 35, 40 and 45°C in dehumidified air dryer and tray dryer. The two-term model was not suitable at 30°C in dehumidified air dryer as R^2 value was low. The logarithmic model with highest R^2 value of 0.99 and lowest χ^2 value of 0.114 × 10^{-3} adequately represented thin layer behavior of safed musli dehumidified air dryer. Effective moisture diffusivity (D_{eff}) of safed musli found to increase with the increase in drying air temperature and it ranged from 2.23010 × 10^{-7} to 4.43057 × 10^{-7} m^2/s. These models are suitable to estimate the moisture content during drying, in order to determine drying time. It is also applicable for designing of relevant dryer for this type of medicinal plant.

Table 6. Coefficient of the logarithmic model fitted to drying data at 30°C.

Temperature (°C)	Drying method	a × 10^{-2}	k	c × 10^{-2}	R^2	χ^2 × 10^{-3}	MBE × 10^{-2}	RMSE × 10^{-1}
30	DAD	1.0090	0.0045	-0.0119	0.9982	0.114	0.00	0.1044

DAD: Dehumidified air dryer

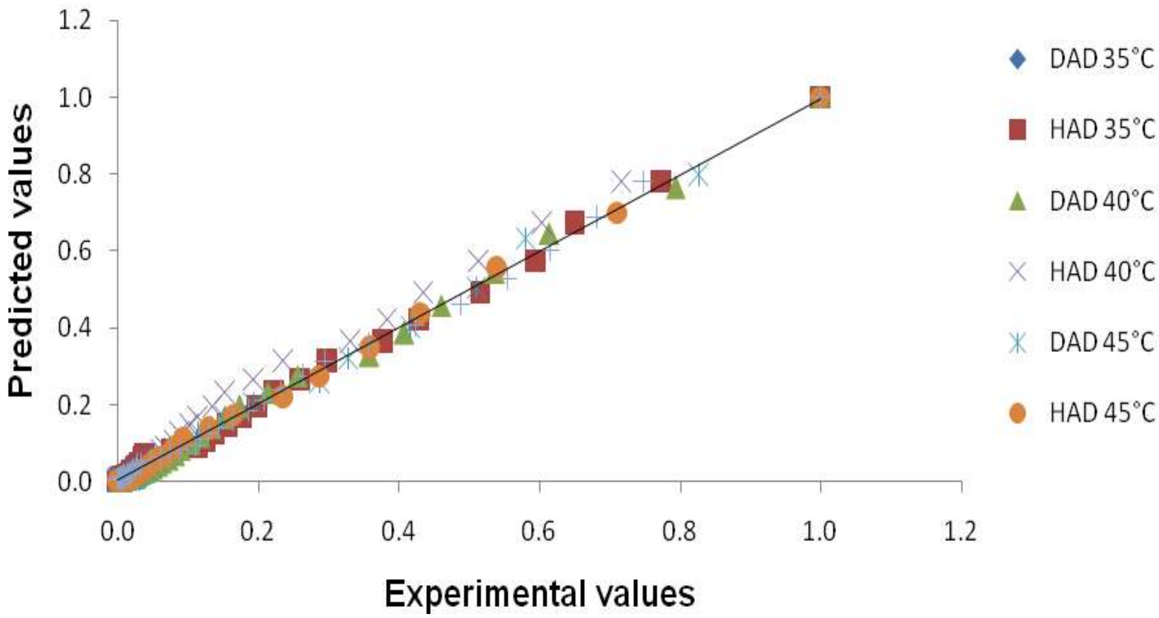

Figure 4. MR of experimental versus predicted values of two-term model.

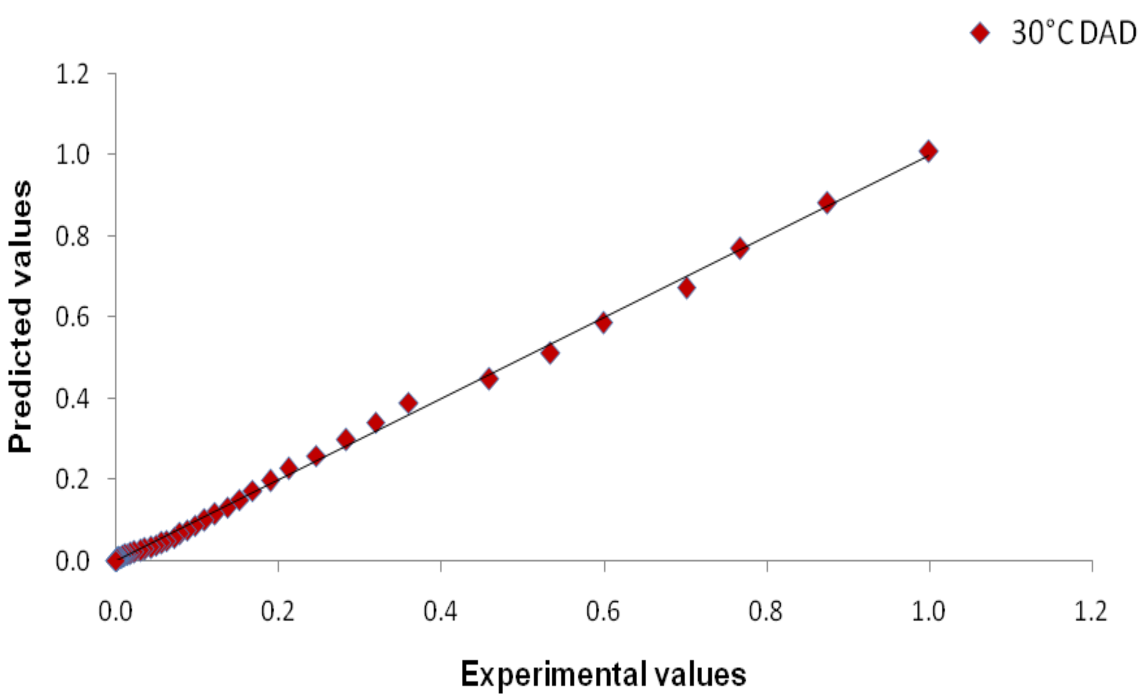

Figure 5. MR of experimental versus predicted values of logarithmic model.

Table 7. Moisture diffusivity and its linear equation for safed musli at different drying temperatures.

Dryer type	Drying temperature (°C)	Equation	k_o	D_{eff} (m^2/s)	R^2
Dehumidified air dryer	30	y = -0.005x+0.312	-0.005	2.2757×10^{-7}	0.961
	35	y = -0.005x+0.245	-0.005	2.2301×10^{-7}	0.976
	40	y = -0.005x+0.052	-0.005	3.0563×10^{-7}	0.961
	45	y = -0.008x+0.515	-0.008	3.7441×10^{-7}	0.834
Hot air dryer	35	y = -0.006x+0.238	-0.006	3.2329×10^{-7}	0.986
	40	y = -0.005x-0.115	-0.005	3.3014×10^{-7}	0.990
	45	y = -0.008x+0.219	-0.008	4.4306×10^{-7}	0.861

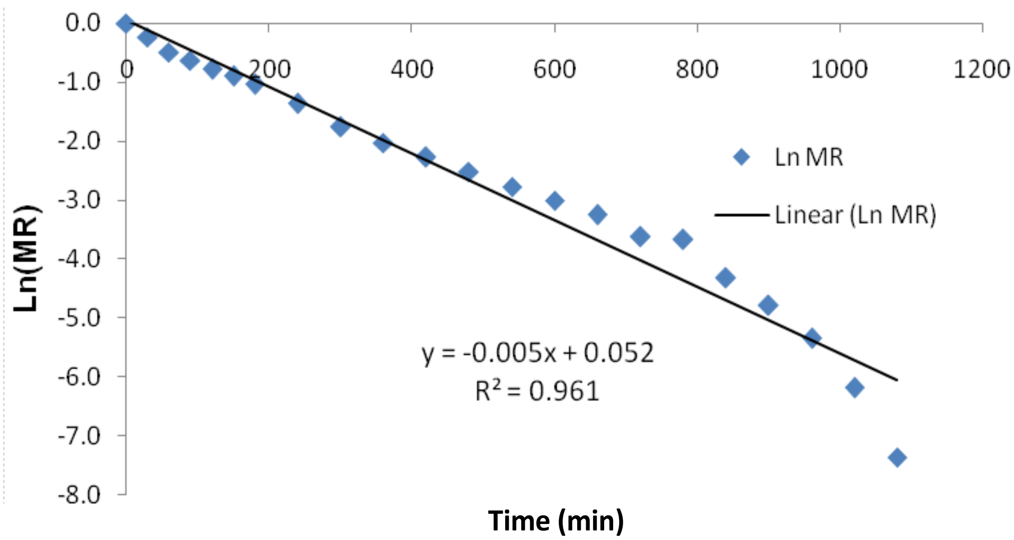

Figure 6. Ln(MR) at 40°C during at dehumidified air dryer

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