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Heat pump drying of safed musli (*Chlorophytum borivilianum*) roots

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ABSTRACT : Thin layer drying experiments under controlled conditions were conducted for safed musli roots in heat pump dryer at 30, 35, 40 and 45°C and hot air dryer at 35, 40 and 45°C with relative humidity's ranging from 19 to 55%. The two-term model showed goodness of fit for drying of safed musli root at 35, 40 and 45°C in HPD and HAD where as logarithmic model showed goodness of fit at 30°C in HPD. The effective moisture diffusivity was observed to increase with the increase in drying air temperature and ranged from 2.23010 x 10^{-7} to 4.43057 x 10^{-7} m^2/s. The SMER value of heat pump dried product (1.44 kg/h) was more as compared to hot air dryer (1.2 kg/h) at 45°C due to lower relative humidity of the drying air in the heat pump dryer. The retention of total carbohydrate content and protein content was observed to be more in heat pump dried samples with higher rehydration ratio and sensory scores. Keeping in a view, the energy consumption and quality attributes of dehydrated products, it is proposed to dry safed musli roots which was KMS treated with at 30°C in heat pump dryer.

KEY WORDS : Drying, Heat pump dryer, Tray dryer, Safed musli, Modeling

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Safed musli (*Chlorophytum borivilianum*) is an endangered medicinal plant of Liliaceae family belonging to genus *Chlorophytum*. Safed musli root powder is used in combination with other herbal material in the preparation of several tonics intended for different ailments. Safed musli roots dried traditionally by sun drying The fleshy roots contained 63.0 to 84.5 per cent moisture *i.e.* dry matter in the range of 15.5 and 37.0 per cent only. The major chemical constituents are carbohydrates (42%), proteins (8%), fibre (3-4%) and saponins (2-17%). The tubers are rich in minerals and the dried tubers contains sodium 0.04mg/g, K 0.80mg/g, Ca 6.6mg/g, Mg 1.9mg/g P 3.2mg/g, Zn 0.002mg/g and Cu 0.148mg/g (Manikpuri *et al.*, 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 because of great therapeutic importance (Singhania, 2003). Safed musli tubers are the major constituents of more than 100 ayurvedic preparations (Oudhia, 2000).

Heat pump drying has a great potential for energy savings due to its high energy efficiency in comparison to conventional air drying and heat pump dryers have been widely used in industries such as timber and food drying since the 1970s (Chau *et al.*, 2002). In general, a lot of energy is consumed to evaporate the water from the wet materials. Thus, it is important to enhance the energy efficiency in the industrial dryer. A heat pump dryer is often considered as an alternative to save the energy used in the dryer. 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).Heat pump dryers (HPD) have the potential to operate more efficiently, and at lower temperatures than conventional dryers (Filho and Stormmen, 1996).

Temperature and humidity are important factors in the drying process. Thus, their values should be optimized to obtain the maximum efficiency and drying performance. The process is generally measured by the moisture extraction rate

(MER) and specific moisture extraction rate (SMER). The SMER is a factor related to the drying cost. The SMER is typically in the range of 0.5–1.0 kg/kWh for the conventional hot air dryer and about 3 kg/kWh for the heat pump dryer (Kudra and Mujumdar, 2002).However, it has been reported that the SMER is less than 1–2 kg/kWh during the actual operation of the heat pump dryer (Adapa *et al.*, 2002; Oktay, 2003 and Chua and Chua, 2005).Limited information is available on drying kinetics of safed musli roots. The present work ascertains effect of dehumidified air dryer conditions on safed musli roots and evaluates different thin layer drying model.

METHODOLOGY

A laboratory model heat pump dryer (HPD) with special features of variable drying air temperatures was fabricated. The developed dryer consists of a dehumidifier unit (evaporator, compressor, condenser, and expansion device) and drying chamber. Fresh safedmusli roots were procured from the farmers field, sorted and washed properly for experimental use. The roots were separate out from seeds of safed musli. These were then peeled by steel knives. Then peeled roots were centrifuge (300 rpm) for 3 minute to remove surface moisture from roots. The safed musli roots samples were treated with 1% potassium aluminum sulphate (T_2), 1% KMS (T_3) and control (T_1) before drying. Thin-layer drying experiments under controlled conditions were conducted for safed musli roots in a dehumidified air dryer at 30, 35, 40, 45°C and in hot air dryer at 35, 40, 45°C.After attaining desired drying air temperature, samples were loaded onto the drying trays at single root thickness**.** A sample of about 200 ± 2g was placed as a thin layer in a small aluminum wire mesh tray (50 x 48cm) and placed at the center of the same drying tray. The aluminum tray was removed from the dryer and weighed regularly at 30 min intervals.

Table A : Alternative mathematical models available in the literature

Sr. No.	Name of the model	Model equation
1.	Lewis	MR = Exp(-k*t)
2.	Henderson and Pabis	MR = a*Exp(-k*t)
3.	Logarithmic	MR = a*Exp(-k*t) +c
4.	Two- term	MR = a*Exp(-k*t) + b*Exp(-n*t)
5.	Two–term exponential	MR = a*Exp(-k*t) + (1-a)*Exp (-k*a*t)
6.	Wang and sing	MR = 1+ (a*t) + (b*(t**2))
7.	Diffusion approach	MR = a*Exp(-k*t) + (1-a)*Exp (-k*b*t)

When the weight of the sample became constant, the experiment was stopped and the final moisture content of dried sample was determined by hot air oven method. All the experiments were carried out at 1.8 ± 0.2 m/s air velocity. The drying rates were computed from the experimental data and drying characteristic curves were plotted. Seven thin layer drying models were tested (Table A) to select the best model for describing the drying curve equation of safed musli. The quality parameters such as carbohydrate, protein and rehydration ratio of the dehydrated product were determined using standard experimental procedures. Sensory evaluation was carried out by a panel of 10 judges for different attributes, *viz.*, colour, texture, flavour, and overall acceptability on the basis of 9-point hedonic scale.

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 and Erenturk *et al.*, 2004).

$$\mathbf{MR} = \frac{(\mathbf{M} - \mathbf{M_e})}{(\mathbf{M} - \mathbf{M_e})} \tag{1}$$

In which MR is moisture ratio (dimensionless), M is moisture content at time t (d.b.%), M_0 is initial moisture content (d.b.%), and M_e is equilibrium moisture content (d.b.%). For determining the moisture content, the samples were placed in a hot air oven at 100^0 C and for 18 hours (Raganna, 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.

$$\mathbf{M_c} = \frac{\mathbf{W_w} - \mathbf{W_d}}{\mathbf{W_d}} \tag{2}$$

In which Mc is moisture content (d.b.%), Ww is weight of sample (g) and Wd is dry matter weight (g). Seven thin layer-drying equations were tested (Table A) 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 co-efficient of determination (R^2) (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 (Goyal *et al.*, 2007).The above mentioned parameters can be calculated as follows :

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

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

$$\mathbf{MBE} = \frac{1}{N}\sum_{i=1}^{N}(\mathbf{MR_{exp,i}} - \mathbf{MR_{exp,i}}) \tag{5}$$

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, k, n, a, b, and c are the model co-efficients. 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 root mean squares Error (RMSE), χ^2 and mean bias error (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 of slab geometry (Doymaz, 2006).The equation is expressed as (Crank, 1975).

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

Then equation (6) can be rewritten as:

$$D_{eff} = \frac{\mathrm{Ln}\frac{8}{\pi^2} - \mathrm{LnMR}}{\left(\frac{t\pi^2}{4L_2}\right)} \quad (7)$$

The slope (k_o) is calculated by plotting ln(MR) versus time according to equation (7) to determine the effective diffusivity for different temperatures.

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

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'.

Physical dimensions of safed musli:

The average thickness of safed musli was 0.51 mm and average length was 99.1 mm. The thickness of the safed musli roots were more or less constant, but length varied from 52 to 145 mm. The average length was used to determine moisture diffusivity of safed musli.

■ RESULTS AND DISCUSSION

The experimental findings obtained from the present study have been discussed in following heads:

Moisture content vs. drying time:

Variation in moisture content with time during drying of safed musli roots at drying air temperatures of 30, 35, 40 and 45°C in HPD and 35, 40, 45°C in HAD is shown in Fig. 1 and 2. From the plot of moisture content against drying time, it is clearly evident that drying time decreased with increase in drying air temperature from 30 to 45°C. Moisture content of safed musli roots was observed to be reduced exponentially with drying time. These curves followed the general trend of drying curves as reported for many food materials. As the temperature increased, the drying curve exhibited a steeper slope, thus exhibiting an increase in drying rate. Total drying times required to dehydrate safed musli roots under different drying conditions are given in Table 1. The HPD when operated with drying air temperature at 30°C took 21 hour to reduce the moisture content of safed musli roots from 400.85 to 8% m.c. (d.b.) while HAD at 45°C took 16 hour. Heat pump drying of safed musli at 30°C took the longest time with lower drying rates. The declining trend of total drying time with increase in temperature is due to (a) increase in vapor pressure within the product with increase in temperature, which results in faster migration of moisture to the surface; and (b) decrease in relative humidity of drying air with increase in temperature,

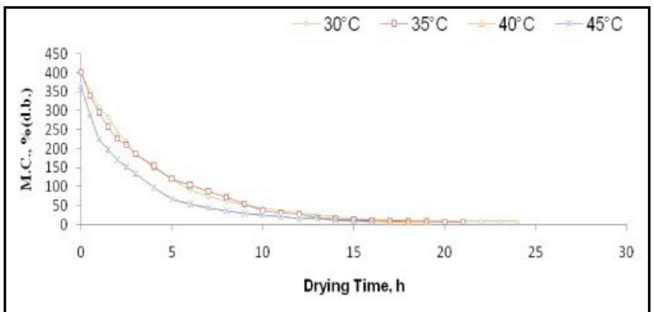

Fig. 1 : Variation in M.C. with drying time of safed musli dried in HPD at different temperatures

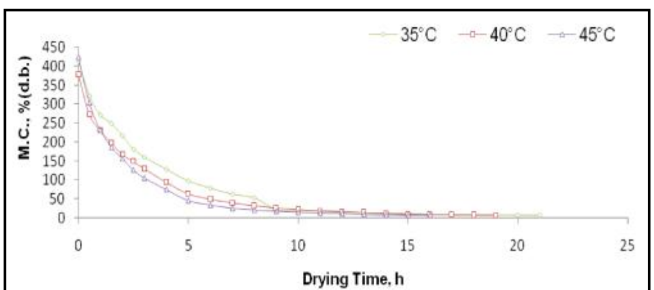

Fig. 2 : Variation in M.C. with drying time of safed musli dried in HAD at different temperatures

which enhances the moisture removal rate from the product surface. Drying of safed musli took place mainly under falling-rate period (Fig. 1 and 2). During this period, the migration of moisture occurred through the mechanism of diffusion. These results are in agreement with the observations of earlier researchers (Lahasani *et al.*, 2004).As the drying of safed musli roots occurred at a relatively faster rate, the amount of water available at the surface soon became inadequate to maintain the supply and the rate rapidly declined to a value controlled by liquid diffusion within the roots. The peak drying rate for safed musli roots was found to be 3.861g/100g bdm-min at a moisture content of 365.58% (d.b.) with 45°C drying air temperature in HAD as compared to 1.852g/100g bdm-min at 372.24% m.c. (d.b.) in HPD with 30°C. There was not found any variation in drying rate and drying time considering pretreatments at same temperature. The drying rate increased considerably with increase in drying air temperature. Thus, a higher drying air temperature produced a higher drying rate and consequently faster reduction in moisture content.

Comparison between hot air and heat pump dryer:

Drying in a heat pump dryer not showed significant difference with respect to time compared to hot air drying at 35, 40 and 45°C for safed musli roots. The hot air dryer showed more drying rates 3.51g/100g bdm-min of control samples whereas heat pump dryer showed 2.5g/100g bdm-min at 40°C temperatures (Table 1). Initially, the drying rate was observed to be more in HAD but at the later part of drying, it was more in HPD at 40°C (Fig. 3).It may be due to in hot air drying, considerable amount of moist air is discharged outside during drying and the fresh air of low humidity is introduced to the dryer. The discharge of moist air is the only way to remove the water vapor produce during drying in hot air dryer. Whereas in dehumidified air dryer with closed loop air flow, the water vapor produced by drying is removed only by the condensation on the surface of the evaporator so that the speed of drying depends on the capacity of heat pump dryer system (Lee and Kim, 2009).The capacity of the heat pump system used in this study was not so high that the drying rate was initially low as compared to hot air dryer but as drying hours increased, relative humidity inside drying chamber of dehumidified air dryer reduced (55-35% for 40°C) and moisture extraction rate was increased but finally it equals to drying rate of heat pump dryer. The effect of temperature is observed to be prominent in the later part of drying, which acts as a driving force for moisture diffusion. The moisture

Table 1 : Drying times and peak drying rates for safed musli at different drying temperatures

Drying temp. (°C)		R.H. (%)	Drying time (h)	Final M.C. (% d.b.)	Peak drying rate (g/100g bdm-min)	Average M.C. (% d.b.)	SMER (kg/kWh)
HPD	30	19	24	8.58	1.642	376.23	0.55
	35	22	21	8.46	2.030	371.79	0.74
	40	35	19	8.37	2.470	328.04	1.10
	45	42	16	8.21	2.616	386.01	1.44
HAD	35	24	21	8.40	3.056	376.32	0.45
	40	38	19	8.35	3.509	324.56	0.93
	45	44	16	8.25	4.020	363.01	1.20

HPD: Heat Pump Drying HAD: Hot Air Dryer

Table 2 : Fitting of the experimental data of safed musli roots to the thin layer model and coefficients

		Two-term model							
Dryer	Drying temp. (°C)	a x 10^{-2}	k	b x 10^{-2}	n x 10^{-2}	R^2	χ^2 x 10^{-3}	MBE x 10^{-2}	RMSE x 10^{-1}
HPD	35	5.63	0.9	94.36	0.41	0.9980	0.136	0.1556	0.1094
	40	9.37	0.9	90.63	0.56	0.9980	0.194	-0.250	0.1318
	45	0.35	0.9	99.63	0.75	0.9969	0.251	-0.293	0.1483
HAD	35	8.88	0.9	91.1	0.51	0.9978	0.136	0.1590	0.1107
	40	13.93	0.9	86.06	0.058	0.9978	0.124	-0.164	0.1054
	45	11.59	0.9	88.4	0.77	0.9987	0.076	-0.191	0.0817

HPD: Heat Pump Drying HAD: Hot Air Dryer

Table 3 : Fitting of the experimental data of safed musli roots to the thin layer model and coefficients

		Logarithmic equation						
Dryer	Drying temp. (°C)	a x10^{-2}	k	c x 10^{-2}	R^2	χ^2 x10^{-3}	MBE x 10^{-2}	RMSE x 10^{-1}
HPD	30	1.009	0.0045	-0.0119	0.9982	0.114	0.00	0.1044

HPD: Heat Pump Drying

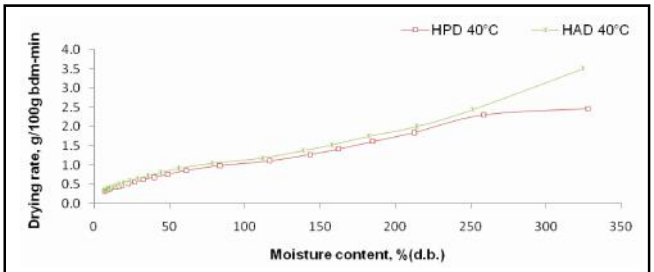

Fig. 3 : Comparison of drying rates of safed mushlim in HP and dehumidified air dryer

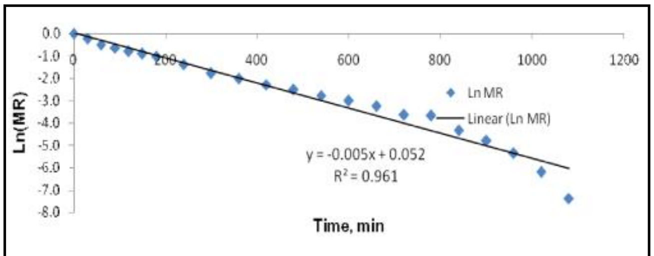

Fig. 4 : Ln (MR) at 40^{0}C during at heat pump dryer

extraction rate (SMER) value increased with increase in drying air temperature due to more drying potential of high-temperature air (Table 2). The specific moisture extraction rate for drying safed musli in the heat pump was found to be more (1.1 kg/kWh) than of hot air dryer (0.93 kg/kWh) while operating at 40°C. This might be due to lesser energy requirement and higher drying potential of low relative humidity air in heat pump dryer. The heat pump dryer was found to have a specific moisture extraction rate between 0.55 and 1.44 kg/kWh.

Curve fitting of drying data :

The moisture content data at the different drying air temperature were converted to moisture ratio and same were fitted for the mentioned thin layer drying models (Table 1). 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 c^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, 2003; Doymaz, 2004) rosehip(Erenturk *et al.*, 2004) mint leaves in tunnel dryer(Kadam *et al.*, 2011) and plum (Goyal *et al.*, 2007).The results of fitting the two-term model to drying data obtained from experimental treatments shown in Table 3. The two-term model was not fitted for temperature 30°C in dehumidified air dryer as R^2value was lower. Thus, the

Table 4 : Moisture diffusivity and its linear equation for safed musli at different drying temperatures

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

HPD: Heat Pump Drying HAD: Hot Air Dryer

Table 5 : Quality attributes of dehydrated safed musli dried under different drying air conditions

		HPD				HAD		
Quality parameters	Initial	30°C	35°C	40°C	45°C	35°C	40°C	45°C
Carbohydrate, %	42	38.2	35.7	34.4	34.2	38.1	35.7	34.0
Proteins, %	8	8	7.15	7.15	7.05	7.13	6.80	6.30
Rehydration ratio, %		3.6	3.5	3.4	3.2	3.5	3.4	3.3

HPD: Heat Pump Drying HAD: Hot Air Dryer

Table 6 : Mean sensory scores for different quality attributes of dehydrated safedmusli roots

		Sensory scores[a]						
Product		HPD				HAD		
Safed musli	Treatments	30°C	35°C	40°C	45°C	35°C	40°C	45°C
	T_1	6.33	5.67	6.00	6.00	5.67	5.67	5.33
	T_2	7.67	7.00	6.67	7.33	6.67	7.00	7.00
	T_3	8.00	8.00	7.67	7.33	7.33	7.00	7.33

[a]Each value of sensory score is average of 10 observations on a 9-point scale

logarithmic model with highest R^2 value of 0.9982 and lowest c^2 value of 0.114 x 10^{-3} adequately represented thin layer drying behavior of safed musli roots in dehumidified air dryer. The results of fitting the logarithmic equation to the drying data obtained from experimental treatment are shown in Table 4.

Moisture diffusivity:

Moisture diffusivity of safed musli increased with the increase in drying air temperature. Moisture diffusivity (D_{eff}) varied from 2.2301 x 10^{-7} to 4.43057 x 10^{-7} m^2/s for temperature range from 30 to 45°C. Table 5 also shows the linear relationship between ln(MR) and time with R^2 values. The relationship between ln (MR) and time are shown in Fig. 4 for drying of safed musli at 40°C and similar trends were observed for other drying air temperatures.

Quality characteristics of dehydrated product:

The quality attributes of dehydrated safedmusli roots are given in Table 6. The protein content of fresh sample (8%, Manikpuri *et al.*, 2010) was nearly same for dried samples at 30°C in dehumidified air dryer and hot air dryer at 45°C showed significant difference of protein content from the fresh sample. There was also significant difference between dehumidified air dryer at 7.15% (40°C), 7.05% (45°C) compared to hot air dryer at 6.80% (40°C) and 6.30% (45°C) for control samples of safed musli (Table 6). It may be due to denaturation as a result of effect of different sizes and drying temperatures on the protein content of safed musli. The heating is a denaturing agent of protein by providing energy for the bond rupture for every 10°C rise in temperature (Nogoddy and Ihenkoroye, 1985).The carbohydrate content of fresh sample 42% (Manikpuri *et al.*, 2010)was significantly different from the dried sample. The carbohydrate content at lower temperature (38.22%) was more as compared to higher temperature (34.19%). It may be due to at higher temperature degradation of carbohydrate took place. There was no significant found according to drying methods in carbohydrate content. The rehydration ratio ranged from 3.6 to 3.3 of safed musli control samples (Table 6). The rehydration ration of product decreased with increased in drying air temperature product. This might be due to the structural change to the product at higher drying air temperature that inhibits proper reconstruction (Pal *et al*., 2008).

The mean sensory scores for colour attributes of dried safed musli are presented in Table 7 for the organoleptic evaluation of dried musli samples for their appearance, it was observed that heat pump dryer samples at lower temperature were better than hot air dried product. Increase in drying air temperature from 30 to 45°C significantly decreased the colour scores.The colour scores decided according to whiteness and uniformity in colour all over the surface of sample. The score colour for KMS (T_3) samples were found more than color scores of control (T_1) and potassium aluminum sulphate (T_2). Also T_2 treated samples had white spots of potassium aluminum sulphate over the surface of roots safed musli and T_3 treated samples were uniform in colour all over the root surface. Dehumidified air dryer at 30°C showed good colour scores for T_1, T_2 and T_3 samples as compared to higher temperatures and different drying methods. The scores of colour for dehumidified air dryer were more than hot air dryer as compared with all temperatures and treatments, respectively.

Conclusion:

Drying time varied from 960 to 1440 min to dry a 200g of safed musli samples at temperatures from 30 to 45°C. The two-term model was found to represent thin layer drying kinetics with highest R^2 and lowest χ^2, RMSE and MBE values except at 30°C in heat pump dryer where logarithmic model was found as the best model having the highest R^2 and lowest χ^2, RMSE and MBE values. The effective moisture diffusivity was observed to increase with the increase in drying air temperature and ranged from 2.23010 x 10^{-7} to 4.43057 x 10^{-7} m^2/s. The SMER value of heat pump dried product (1.44 kg/h) was more as compared to hot air dryer (1.2 kg/h) at 45°C due to lower relative humidity of the drying air in the heat pump dryer. The retention of total carbohydrate content and protein content was observed to be more in heat pump dried samples with higher rehydration ratio and sensory scores. Keeping in a view the energy consumption and quality attributes of dehydrated products, it is proposed to dry safed musli roots at 30°C in heat pump dryer treated with KMS to obtain an acceptable product.

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