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Solar cabinet vacuum drying system and its drying kinetics of curry leaves

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ABSTRACT

A vacuum assisted solar cabinet drying system was used for drying curry leaves in the month of September and October 2021 In India. In this system a vacuum circulation system was arranged where drying will be done and vacuum is created inside the drying chamber by using a vacuum pump. In this study two drying processes were used namely solar cabinet drying (SCD) and Solar cabinet vacuum drying (SCVD) with 250, 400 and 600 mmHg is used to dehydrate the curry leaves. The quality of dried leaves were analysed for its Vitamin C and color change. The vacuum-assisted solar drying of curry leaves were of superior quality in terms of color change and Vitamin C. The average drying temperature in solar cabinet and solar cabinet vacuum drying was 54.4 ˚C and 50.53˚C respectively where itis a suitable drying temperature for fruits and vegetables. Four mathematical drying models were compared using the regression coefficients (R^2), root mean square error (RMSE) and sum of square error (SSE) between the observed and predicted moisture ratios. The activation energy required for vacuum assisted solar cabinet drying of curry leaves was found to be 30.48 kJ/mol. It is found Midilli et al. and modified Henderson and Pebis model are the best fitted model to characterize drying kinetics of curry leaves.

Keywords: Activation energy, color, curry leaves, drying, diffusion, energy, kinetics, vitamin, vacuum

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INTRODUCTION

Solar energy is one of the purest and clean forms of energy we receive on earth, without any environmental degradation. Due to the increasing rate of fuel consumption in agriculture it is not only become essential to save energy by application of the solar drying process but also by making significant usage of solar energy as a source for drying processes in food processing industries. In many nations across the globe, the application of solar thermal systems in the agricultural area to conserve vegetables, fruits, coffee and other crops is very common. Curry tree (*Murraya koenigii*) is Indian native subtropical tree from the family Rutaceae (the rue family, which includes rue, citrus and sandalwood) (Ramakrishnarao, 2016). Curry leaves are rich in carbazole alkaloids and bioactive compounds of which the most important are total phenols, phenolic acids, flavonoids, carotenoids and acridinecarbazole (Jain, 2012). These compounds interact in such a way to stimulate the pharmaceutical properties, cytotoxic, antiulcer, antimicrobial, antibacterial, anti-oxidative, antifungal, anti-inflammatory, and anti-cholesterolemic activities (Rahman and Gray, 2005). Drying of curry leaves is considered as an important process as it plays a significant role in preservation and retention of nutritional and sensorial values. Drying at high temperatures result in changes in the quality

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specially, the concentration of nutrients, sensory characteristics like color, texture and flavor and heat sensitive parameters like total phenols, total flavonoids and carotenoids. Further, more frequently observed objectionable quality change in the dehydrated food products is oxidation reaction, which is happens due to the presence of oxygen in the drying medium. Dehydration of food materials, especially fruits and vegetables, with antioxidant properties is a difficult food process operation, mainly because of undesirable changes in quality of the dehydrated products (Rajkumar et al., 2010). To reduce the oxidation reactions and preserve heat sensitive properties, application of vacuum for drying of heat sensitive food material is often used. The lower pressure (vacuum) in the system lowers the drying temperature in order to reach the similar final moisture content of the product when compared to other drying methods (Rajkumar et al., 2010).The vacuum assisted solar cabinet dryers have advantageous such retention of nutrients, consistent drying rate, less activation energy and producing good quality product when compared to other drying modes. The thin layer drying equations are used to describe the drying characteristics of the product. They are used to estimate the drying periods of the products and to generalize drying curves (Midilli et al., 2002). From the foregoing literature study, it was observed only few studies has been carried out on drying kinetics of solar cabinet and vacuum assisted solar cabinet drying; and no literatures were found on thin layer drying characteristics of curry leaves under vacuum assisted solar cabinet drying. Hence, forced convection solar cabinet drying and vacuum assisted solar cabinet drying was selected to investigate the influence of independent process parameter vacuum level on the drying time, energy consumption activation energy and color change of the drying process.

MATERIALS AND METHODS

Curry leaves

Fresh and matured curry leaves were collected from the Dharani Agro farms from Moinabad, Hyderabad. The leaves are separated from stems and washed with 0.1% of hypo chloride solution to disinfect the leaves. The washed curry leaves were dried using solar cabinet and solar cabinet vacuum drying (SCVD) with 250, 400 and 600 mmHg.

Solar cabinet dryer

It consists of closed cabinet with 70 cm height, 59 cm length with the arrangement of glazing glass which is fixed at 20° angle. It is constructed with non-corrosive S.S trays of 304 stainless steel and hardware of stainless steel and brass. The glazing glass allows the solar radiation inside the cabinet and heats up the air molecules. The wave length of solar radiation shifts from visible region to infrared region (Ramakrisnarao, 2011). A photovoltaic panel of 3.5 W capacities is fixed on the top of solar cabinet dryer which generates the current through the radiation simultaneously incident on the panel. An exhaust fan is fixed back wall of the dryer to remove the moisture out from the drying material by radiations. And also it consists of two trays for loading the product (Fig. 1).

Solar cabinet vacuum dryer

To the above described solar cabinet dryer a vacuum pump with the range of 0-760 mmHg (DELTA;L199031) was attached to create a vacuum in the circular (150 mm diameter) glass container in which the vacuum level was controlled outside of the solar cabinet dryer with an open-ended valve. A temperature probe was fixed to the drying chamber to know the temperatures inside the vacuum drying chamber. Humidity of the solar cabinet dryer was recorded by using humidity sensor (Linpicco-A0545) with accuracy of 0-99% RH (Fig. 2).

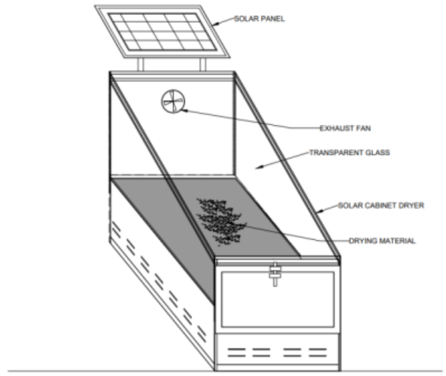

Fig. 1: Solar cabinet dryer

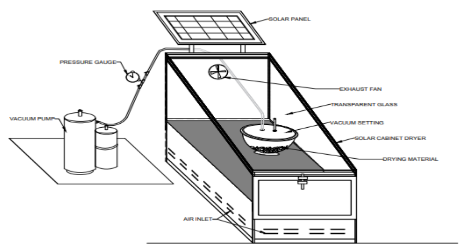

Fig. 2: Solar cabinet vacuum dryer

Moisture content

The moisture content of the curry leaves was determined by the hot air oven method (AOAC, 1990) at 105±5˚C for 4 hrs. This process is done in triplicates and an average values were reported.

$$\text{MC}\,\% = \frac{\text{Intial weight} - \text{Final weight}}{\text{Intial weight}} \times 100 \quad (1)$$

MATHEMATICAL MODELLING

Moisture ratio

Drying mechanism changes with the drying process due to the moisture lose in curry leaves. Moisture ratio (MR) was calculated using MR=Mt/Mo as stated by several researchers (Midilli and Kucuk 2003)Henderson and Pebis (Karathanos, 1999);Lewis (Ayensu, 1997), Weibull (Midilli et al., 2002) due to the continuous fluctuation of the relative humidity of the drying air during the solar cabinet drying process.MR is calculated by the following equation 2.

$$MR = \frac{Mt}{M_o} \qquad (2)$$

Table 1: Thin layer drying models

Model	Equation	References
Lewis thin layer	$Y = e^{-kt}$	Ayensu, (1997)
Midlli et all	$Y = a.e^{-k.tn} + bt$	Midilli etal. (2002)
Modified Henderson andPebis Model	$Y = a.e^{-kt} + b.e^{-gt} + c\ .e^{-ht}$	Karathanos(1999)
Weibull distribution model	Y = exp −(t/b) α	Midilli etal. (2002)

In the above models MR is moisture ratio, t is time, k is drying rate constant, a, b, c, g and n are model coefficients.

STATISTICAL ANALYSIS

Four thin layer drying models in Table 1 were tested to select the best model for describing the drying curve equation of the curry leaves drying during solar cabinet and solar cabinet vacuum drying. Mathcad, version 6.0 was used to fit experimental data. It is necessary to calculate the correlation coefficient R^2, sum of square error (SSE) and root mean square error (RMSE) to fit the best mathematical models for curry leaves drying. The model with the highest value of R^2 as the primary criterion was selected as a best suitable equation and lowest SSE and RMSE indicate the best fit of the model. R^2 as the mean square of the deviations between the experimental and calculated values for the models and RMSE analysis were used to determine the goodness of fit (Akpinar et al., 2003. Demir et al., 2004. Midilli and Kucuk 2003. Yaldiz and Ertekin 2001). The R^2, SSE and RMSE were calculated by the following equations from 3, 4 and 5. N is the number of observations, MR_{cal},i is the predicted moisture ratio and MR_{exp},i is the experimental moisture ratio.

$$R^2 = \frac{\sum_{i=1}^{N}(MR_i - MR_{cal,i}).\sum_{i=1}^{N}(MR_i - MR_{exp,i})}{\sqrt{[\sum_{i=1}^{N}(MR_i - MR_{cal,i})^2].\ [\sum_{i=1}^{N}(MR_i - MR_{exp,i})^2]}} \quad (3)$$

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

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

DETERMINATION OF EFFECTIVE MOISTURE DIFFUSIVITY

Moisture diffusion was calculated based on Fick's second law by considering the curry leaves height in tray as a thin slab (Crank, 1975)

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{\pi^2(2n+1)^2}{4L^2}D_{eff}t\right)(6)$$

Where Eq. (6) relies on the postulation that the moisture distribution in the samples is uniform and has a stable diffusivity with negligible shrinkage: The slope (u) obtained from plotting ln (MR) against time issued in Eq. (8) to compute the moisture diffusivity of the samples.

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

Where MR is moisture ratio, D_{eff} is the effective moisture diffusivity (m^2/s) and L is the half-thickness (m) of the samples.

$$\varphi = \frac{\pi^2 D_{eff}}{4L^2} (8)$$

DETERMINATION OF ACTIVATION ENERGY

The activation energy of the drying process was obtained using Eqs. (9)–(11) (Miranda et.at.(2009)

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) (9)$$

Eq. (9) could be expressed or re-written as Eq. (10) by taking the logarithm of both sides

$$\ln(D_{eff}) = \text{In}(D_0) - \frac{E_a}{RT_{abs}} (10)$$

Where Do is the Arrhenius factor (m2 /s), Ea is the activation energy (kJ/mol), R is the universal gas constant (8.314 X 10^3 kJ/mol K), k is slope and T is the temperature (°C).

$$k = -\frac{E_a}{R} (11)$$

ln D_{eff} was plotted against the absolute values of the given temperatures ($1/T_{abs}$). The slope (k) of the plot is equal to (-Ea/R).

Colour

The color of the curry leaves samples was assessed by using a Hunter Lab Colorflex colorimeter with illuminant D65 and 10º observer angle. Each sample was placed onto a white tile and values of CIE (Commission Internationale de Elcairage) color space co-ordinates L* a* b* values were acquired. Where L* indicates lightness, a* indicates the grade of greenness/redness and b* indicates the grade of blueness/yellowness. The curry leaves color data is shown in table.3.The mean color varied across the applied drying temperatures, vacuum pressures and time range. This variation was expected as dissimilar drying conditions were used in this study. L*, a*, b* ΔE, and a* /b* ranged from.

RESULTS AND DISCUSSION

Drying characteristics of curry leaves due to weather parameters

During the experiments of solar cabinet and solar cabinet vacuum drying in the month of July 2021,the ambient relative humidity, atmospheric temperature, solar cabinet and solar cabinet vacuum temperatures ranged from 31 to 48.9%, and 31 to 41.5^{o}C, 35 to 38.8^{o}C and 47.33 to 59.88 ^{o}C respectively, in Hyderabad, India. When drying of curry leaves in in solar cabinet drying, temperatures recorded were 38.8–59.88 ˚C in solar cabinet dryer (SCD) and 35.16 ˚C to 54.44 ˚C, 36.61 to 47.33 ˚C 35to 51.25 ˚C solar cabinet vacuum drying (SCVD) with 250mmHg, 400mmHg and 600mmHg respectively. Maximum drying temperature observed in SCD is 54.44 ˚C and followed by SCVD at 600mmHG is 51.25 ˚C.

Drying characteristics

The initial moisture content of the curry leaves was found to be 70.01 % (w. b). The changes in moisture ratio with drying time of curry leaves in solar cabinet drying (SCD) and solar cabinet vacuum drying (SCVD) methods are shown in Fig. 3. The time required to dry the curry leaves in solar cabinet was 220 min and solar cabinet vacuum drying with 250 mmHg, 400mmHgand 600mmHg was 180, 220 and 280 min respectively. Between the drying methods, the time taken to dry the sample was lower in SCVD with 250mmHg then the Solar cabinet drying. The decrease in drying time was mainly due to the higher vapor pressure gradient created in the vacuum, which helped in faster removal of moisture from the sample (Rajkumar et al., 2007). It is observed that the difference in the pressures and temperatures affects the drying time especially at lower drying temperatures. The similar results were reported to the previous works on onion slices by Praveenkumar et al.(2006). To calculate the moisture ratio as a function of drying time, thin layer models Lewis thin layer, Midlli et al. Modified Henderson and Pebis Model and Weibull distribution models were fitted and coefficient of determinations (R^2) were estimated.

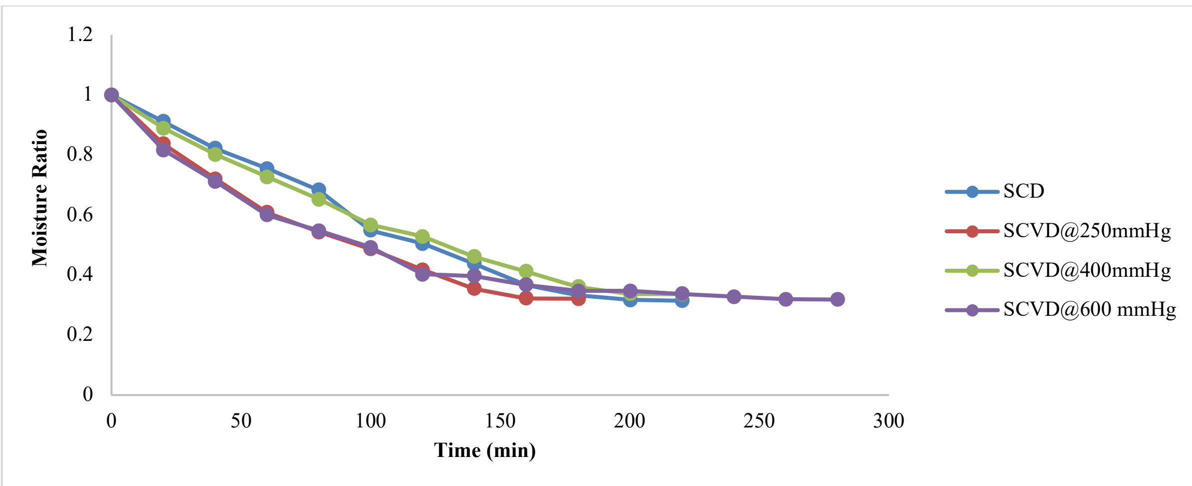

Fig. 3: Moisture ratio Vs drying time SCD: solar cabinet drying SCVD- solar cabinet vacuum drying at 250, 400 and 600mmHg pressures

Apart from the all four tested methods Table2 shows Medili et al., and modified Henderson and Pebis models are satisfied the significant factor hence these two are chosen outstanding model due to its high R^2 (0.995- 0.997) in SCD, and SCVD at 600 mmHg and R^2 (0.995-0.999) at 400 and 250mmHg respectively while its lowest value of SSE (0.002963-0.00045) SCD and in SCVD 600 mmHg and SSE (0.003825-0.00172) at 250mmHg and 400mmHg of SCVD respectively.

The Medili et al., and Modified Henderson and Pebis model curve fit for curry leaves drying characteristics of SCD and SCVD at 250mmHg, 400mmHg and 600mmHg are shown in fig. 4 and fig 5. The ability, evenness and uniformity of Medili et al., and Modified Henderson and Pebis model was substantiated by plotting the calculated moisture ratios obtained from the models against the experimental moisture ratio data at vacuum pressures 250, 400 and 600 mmHg are shown in Fig. 6 (A,B,C and D). There is a good relationship between the experimental and the predicted data for SCVD dried curry leaves when compared with SCD curry leaves.

Table 2: Drying statistical data of curry leaves

Model	Treatment	n	a	B	g	c	h	t (min)	RMSE	RSQR	SSE	K
Lewis thin layer	SCD	-	-	-	-	-	-	220	0.0279262	0.989396	0.00858	0.33935
	SCVD@250	-	-	-	-	-	-	180	0.0257124	0.992342	0.00595	0.43893
	SCVD@400	-	-	-	-	-	-	220	0.0463019	0.96853	0.02358	0.34828
	SCVD@600	-	-	-	-	-	-	280	0.0760993	0.934725	0.08108	0.35482
Average									**0.04401**	**0.97125**	**0.0298**	**0.3703**
Midlli et al		1.38613	0.9852	0.04876	-	-	-	220	0.0164118	0.995177	0.00296	0.34805
	SCVD@250	SCD	0.99885	0.02736	-	-	-	180	0.0111874	0.997652	0.00113	0.52507
	SCVD@400	0.41704	1.00103	-0.17	-	-	-	220	0.0321629	0.983656	0.01138	0.10691
	SCVD@600	0.92334	0.99837	0.0501	-	-	-	280	0.0110828	0.997187	0.00172	0.58131
Average									**0.017711**	**0.99342**	**0.0043**	**0.3903**
Modified Henderson &Pebis Mode	SCD	-	0.05072	0.66212	0.35247	0.31312	0.352475	220	0.0241979	0.989226	0.00644	0.35247
	SCVD@250	-	6.3E-13	0.08523	2.76812	0.91513	0.395905	180	0.0070746	0.999062	0.00045	-8.30827
	SCVD@400	-	0.99768	0.10784	-1.6048	-0.10546	-1.61168	220	0.0186471	0.995242	0.00382	0.35632
	SCVD@600	-	0.06484	0.77161	0.73168	0.1576	-0.06074	280	0.0112815	0.997032	0.00178	-0.06074
Average									0.0153	0.99514	0.0031	-1.915
Weibull distribution model	SCD	1.47225	0.24311	-0.7412	-	-	-	220	0.0167809	0.99493	0.0031	0.38999
	SCVD@250	0.96102	0.1534	-0.8456	-	-	-	180	0.0113687	0.997576	0.00116	0.59914
	SCVD@400	0.83582	-85.903	-86.897	-	-	-	220	0.032674	0.983085	0.01174	0.00304
	SCVD@600	1.02327	0.30187	-0.6936	-	-	-	280	0.0118359	0.996764	0.00196	0.82771
Average									**0.018165**	**0.99309**	**0.0045**	**0.455**

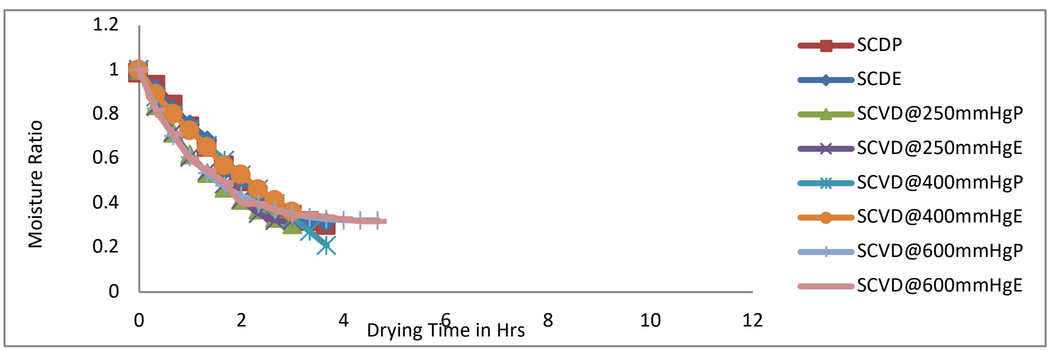

Fig. 4: Medili et al. Model curve fitting of SCD and SCVD with 250, 400 and 600mmHg vacuum pressures

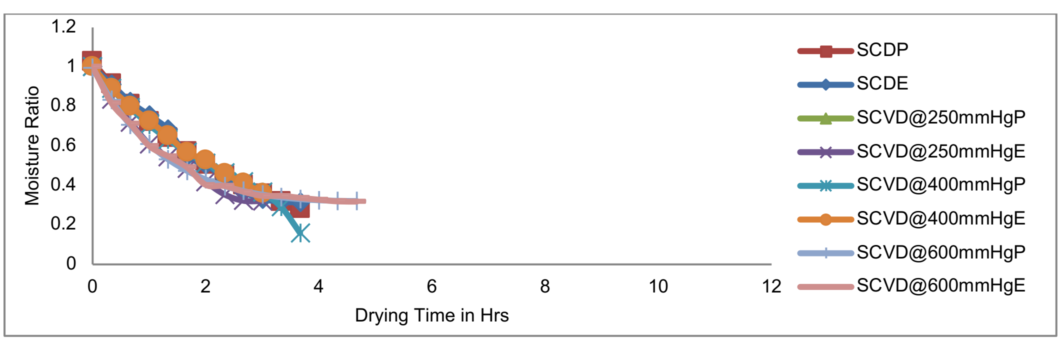

Fig. 5: Henderson and Pebis Model curves fitting of SCD and SCVD with 250, 400 and 600mmHg vacuum pressures

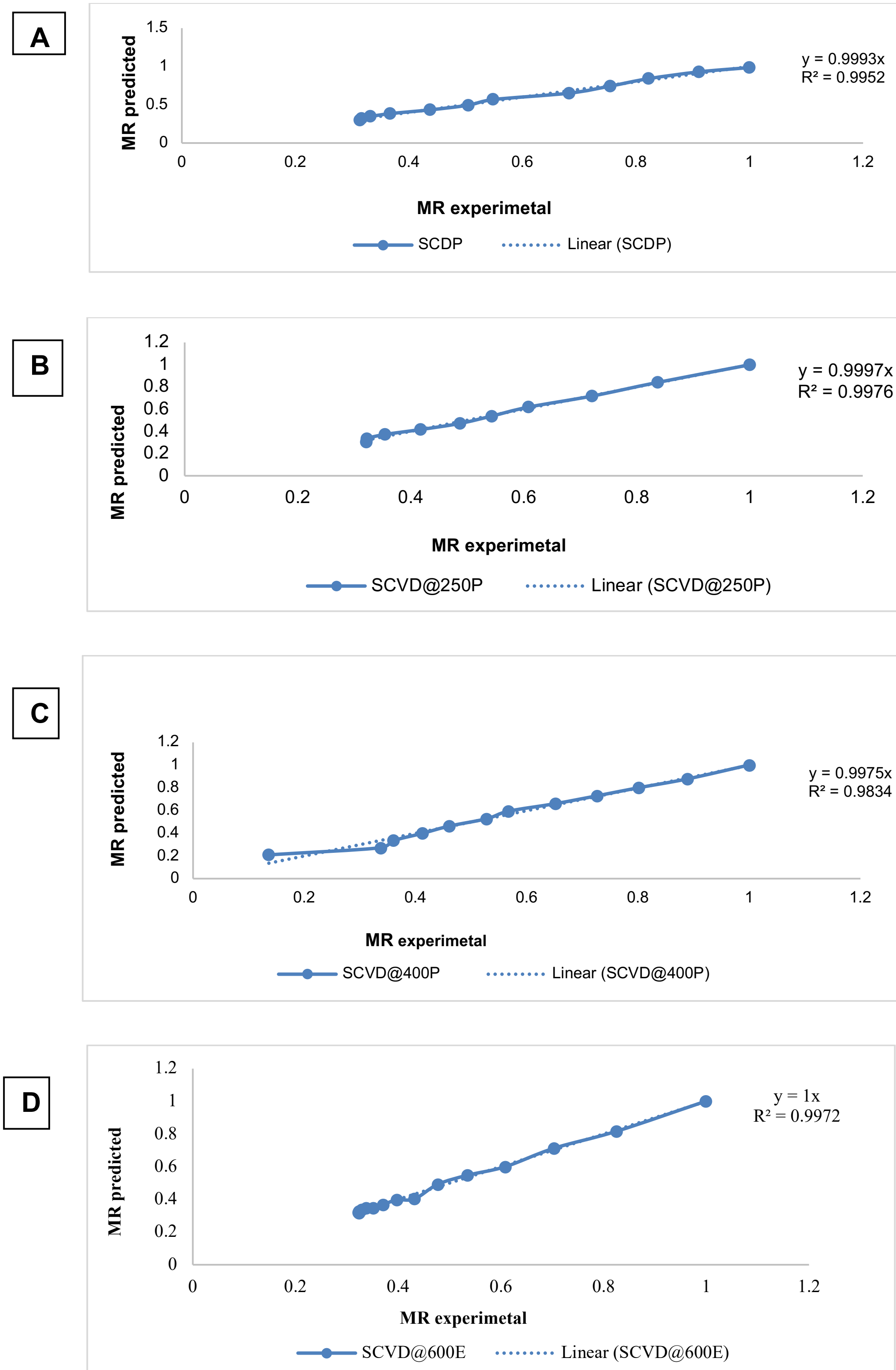

Fig. 6: (A), (B), (C) and (D): Validation of Modified Henderson and Pebis model for predicting the SCD and SCVD drying characteristics of curry leaves at 250, 400 and 600 mmHg vacuum pressures.

Effective moisture diffusivity

In the Moisture Diffusivity, the vacuum effect on solar cabinet vacuum drying of curry leaves was studied and the results are compared with solar cabinet drying. The effective moisture diffusivity of curry leaves D_{eff} values are obtained by using the Eq. (6) at different temperatures and vacuum pressures is presented in Fig. 7. The curry leaves D_{eff} in SCD and SCVD at 250,400 and 600 mmHg are 4.73×10^{-8} m^2 /s, 6.133×10^{-8} m2 /s, 6.93×10^{-8} m^2 /sand 7.00×10^{-8} m^2 /s respectively. The similar values have been reported by Rajkumar et al. for tomato slices, Adewale et al. for Jew's mallow leaves and Zogzas et al. for food products of agriculture.

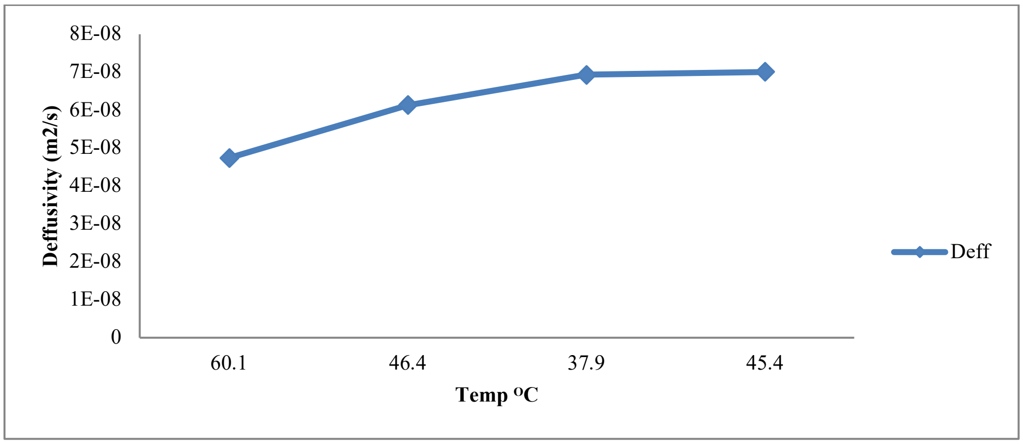

Fig. 7: Solar cabinet and solar cabinet vacuum drying effective moisture diffusivity of curry leaves

Activation energy

The activation energy for SCD and SCVD of curry leaves have been taken from the slope obtained from the plot of In D_{eff} against temperature Fig.8 was found to be 22.58 (kJ/mol). In SCVD 30.48 (kJ/mol). Kaymak EF (2002). Red pepper (42.80 kJ/mol) and Simal et al. (1996), Green peas (24.70 kJ/mol) are evident that the values are in range.

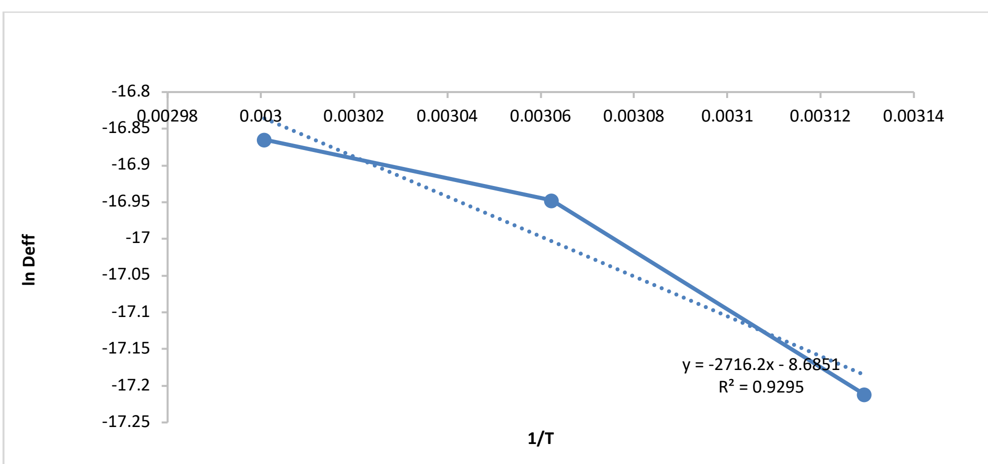

Fig. 8: Arrhenius type relationship between Modified Henderson and Pebis of effective moisture diffusivity at average temperature.

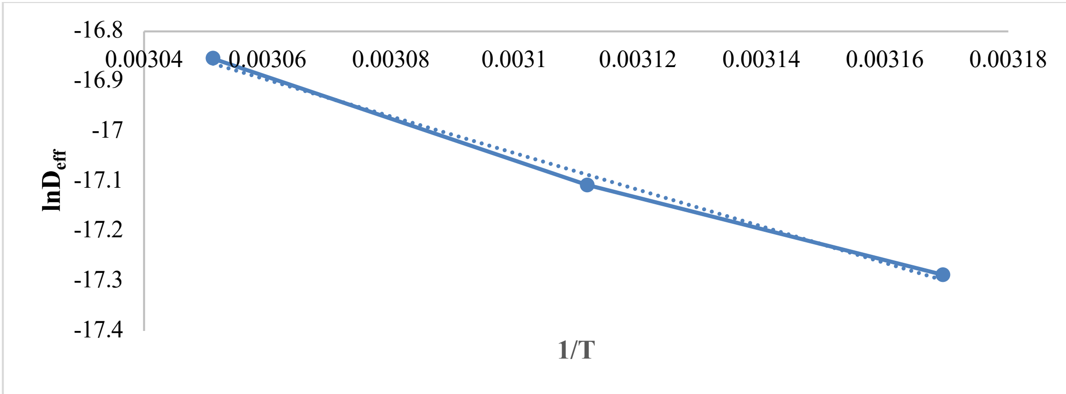

Fig. 9: Arrhenius-type relationships between Modified Henderson and Pebis of effective moisture diffusivity and absolute temperature with 250(A),400(B) and 600(C) mmHg pressures.

Colour change

The changes in color of solar cabinet and solar cabinet vacuum dried curry leaves at 250, 400 and 600mmHg vacuum pressures are shown in Table 3. From the table, it is observed that L*increased in all the dried samples when compared to fresh curry leaves. These values indicates that the dried leaves were slightly lighter than the fresh one. But a* values of dried leaves increased. Significantly in solar cabinet vacuum drying than solar cabinet drying due to indirect exposure and might be shorter drying time. There was a significant increase in b* values during drying. It is observed that the color change was lower in solar cabinet vacuum drying at 250mmHgwhen compared solar cabinet drying. It is also observed that the color change in solar cabinet drying was mainly due to the non-enzymatic browning or Maillard reaction. In vacuum drying, the color change in terms of a* was not significant due to the exclusion of air; i.e., without oxidation (Porretta and Sandai 1997).

Table 3: Color change and ascorbic acid values of solar cabinet and solar cabinet vacuum dried curry leaves

Code	Color Change(ΔE)					Ascorbic acid (mg)/100(gm)
	L*	**a***	**b***	**ΔE**	**a*/b***	
SCD	46.3	-0.3	39.7	15.20173	-0.00756	4.267
SCVD@250mmHg	40	-4.6	35.1	8.731695	-0.13105	4.771
SCVD@400mmHg	46	-5.8	43.5	13.40905	-0.13333	4.985
SCVD@600mmHg	46.3	-0.3	39.7	15.20173	-0.00756	4.975
Fresh	-	-	-	-	-	6.502

ΔE: colour change value

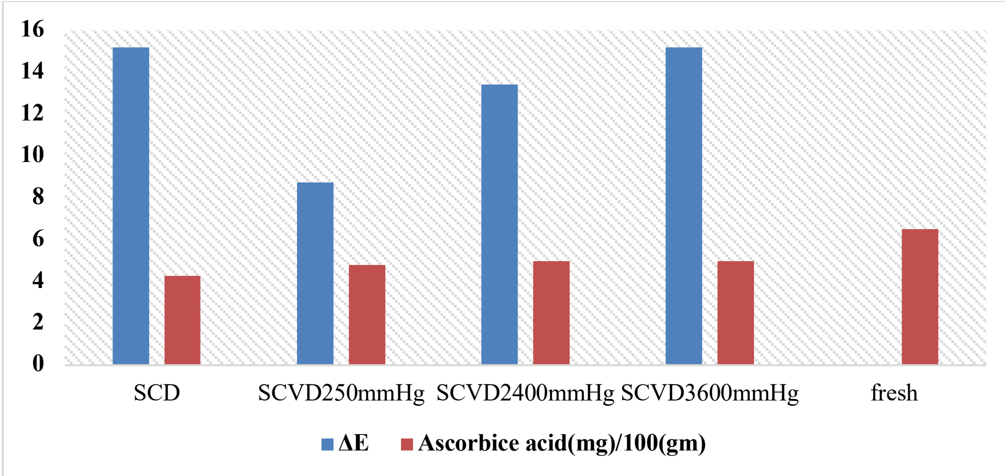

Fig. 9: Graphical representation of dried curry leaves in SCD and SCVD at 250 400 and 600mmHg

ASCORBIC ACID CONTENT

Dried curry leaves were analysed for its ascorbic acid content of SCD, SCVD methods and were compared with fresh curry leaves. Table 3 shows the ascorbic acid values where the ascorbic acid content in all the dried samples were low when compared with fresh samples. The reduction of ascorbic acid is due to the oxidative heat and drying time. This is confirmed with the result reported by Giovanelli et al. (2002) that the ascorbic acid reduced due to the, light and the presence of air. Similarly, Gould (1983) mentioned that the ascorbic acid degradation was mainly due to the temperature at which the curry leaves were heated in the presence of air. In a similar line, Gregory (1996) mentioned that the involving of chemical degradation lowers the ascorbic acid content. Between the two drying methods, the ascorbic acid content was higher in solar cabinet vacuum drying (75.13%) at 600mmHg than solar cabinet drying (72.3%) of curry leaves.

CONCLUSION

This study concluded that dehydrated curry leaves could be produced using solar cabinet vacuum dryer. The required drying time for curry leaves in solar cabinet vacuum at 250 mmHg was low when compared to solar cabinet dryer method. The drying time for solar cabinet and solar cabinet vacuum drying at 400mmHg was equal. The moisture diffusivity was higher in solar cabinet vacuum dryer with 600mmHg than all other dryings. Medilli and modified Henderson and Pebis models were found to be better in describing the drying kinetics of curry leaves dried in both solar cabinet and solar cabinet vacuum drying methods. The color, and ascorbic acid retention were comparatively higher in solar cabinet vacuum drying methods.

NOMENCLATURE

SCD	Solar cabinet drying
SCVD	Solar cabinet vacuum drying
D_{eff}	Effective moisture diffusivity, m2 /s
MR	Moisture ratio
R^2	Regression Coefficient
RMSE	Root mean square error

SSE	Sum of square error
t	Time
°C	Degree Celsius
MR_{exp}	Experimental moisture ratio
MR_{pre}	Predicted moisture ratio
Mo	Initial moisture content (kg water/kg dry matter)
MC	Moisture content
D_0	Arrhenius factor (m^2/s)
Ea	activation energy
L	half the thickness
K,n,a, b, c,g and h	Model constants;
T	Temperature (°C)
R	Universal gas constant (8.314 X 10^{-3} kJ/mol K),
w.b	Wet basis
ΔE	Change in color

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