ANSF
APPLIED AND NATURAL SCIENCE FOUNDATION

Journal of Applied and Natural Science
15(3), 1237 - 1244 (2023)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Research Article

Drying kinetics of *Cissus quadrangularis* dried in a Fluidized bed dryer

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Article Info
https://doi.org/10.31018/jans.v15i3.4850
Received: June 22, 2023
Revised: September 6, 2023
Accepted: September 10, 2023

How to Cite

Venkatasami, M. *et al.* (2023). Drying kinetics of *Cissus quadrangularis* dried in a Fluidized bed dryer. *Journal of Applied and Natural Science*, 15(3), 1237 - 1244. https://doi.org/10.31018/jans.v15i3.4850

Abstract

Cissus quadrangularis is an extensively utilized medicinal plant in India which has numerous health benefits. Hence, the drying kinetics of *Cissus* was studied using fluidized bed dryer to identify suitable drying conditions and to understand moisture removal and its connection to process variables. The present research aimed to determine a suitable drying model of fluidized bed drying of *Cissus quadrangularis Linn.*, determine the effective moisture diffusivity of the drying process and the activation energy, and investigate the effects of temperatures on the drying kinetics of *Cissus.* The drying experiments were conducted at three different air temperatures (40, 50 and 60 ºC), bed thickness of 5 cm, constant air velocity of 8 m/s and 0.5-1 cm length *Cissus* samples. The experimental drying data was fit into thirteen thin layer models and the best model describing the drying of *Cissus* was selected based on the correlation coefficient (*R*), root mean square error (RMSE), and reduced chi-square (χ^2). The drying process occurred in a falling rate period for all the drying air temperatures and a constant rate period was not observed. Among all the thirteen models tested, approximation of diffusion was found to explain the thin layer drying behavior of *C. quadrangularis* accurately. The effective moisture diffusivity for *Cissus* was in the range of 1.54 - 3.12x 10^{-10} m^2/s and the activation energy was 30.76 kJ/ mole, respectively. Hence, fluidized bed drying is more effective for convective drying of *Cissus* and the drying models are useful for selecting the best operational condition for fluidized bed dryer and design of an equipment.

Keywords: Activation energy, *Cissus quadrangularis*, Drying kinetics, Effective diffusivity, Fluidized bed drying

INTRODUCTION

Cissus quadrangularis is a dicotyledonous flowering herb that belongs to the Vitaceae family. It is known as Pirandai, Bonesetter, Adamant creeper, Veldt-grape, Hadjod, Asthisamadhani, Hadsanka in different localities of India (Kaur and Malik, 2010; Kumar, 2019; Thakur *et al.*, 2009). It is a prominent ethnomedicine found in Ayurveda, Unani and Siddha medico-therapeutics (Kasi *et al.*, 2021). The application of *Cissus* includes external and internal in the form of juices, decoction, extract, paste and powder. It is a prominent medicinal plant known for its anti-osteoporotic and therapeutic potential. Numerous phytochemicals such as quercetin, kaempferol, resveratrol, luteolin, β-sitosterol, and friedelin from *C. quadrangularis* were reported and quantified using advanced analytical techniques. These are responsible for the therapeutic potential in analgesic, antidiabetic, antiulcer, anticancer, anti-inflammatory and estrogenic activity (Bafna *et al*., 2021). However, like other agricultural products, fresh medicinal plants occupy huge spaces and are difficult to store and transport. High moisture content after harvest accelerates fungal damage, rotting and degradation, making the medicinal crops unsuitable for consumption and industrial purposes (Kathirvel *et al*., 2006).

Drying of medicinal crops is inevitable for storing and preserving biochemical compounds (Rahimi and Farrokhi, 2019; Tanko *et al*., 2005). Hence, dried products are easier to handle and less prone to fungal and microbial degradation due to lower moisture content. Safe storage of medical crops requires the reduction of moisture to 10-12 % by adopting a suitable drying technique (Azizi *et al*., 2009; Brovelli *et al*., 2003). Applying heat reduces the moisture content and is the deciding factor for the quality of the drug from medicinal plants (Müller and Heindl, 2006). Based on the heat source, drying of medicinal crops is classified into natural drying and hot air drying. Sun drying is one of the oldest methods for drying medicinal crops and herbs in tropical and subtropical countries (Thamkaew *et al*., 2021). However, direct sun drying only applies to small quantities (Belessiotis and Delyannis, 2011). The disadvantage of open sun drying is microbial contamination, poor quality products and an uncontrollable drying process (Chen *et al*., 2005).

Hot air drying is a potential alternative to conventional drying technology. The advantage of hot air drying is the controllability of drying parameters such as drying temperature, drying time and air velocity. Controlling these parameters can produce good-quality products (Orphanides *et al*., 2016). One of the promising technologies in hot air drying is fluidized bed drying. It is increasingly recognized for its effective solid mixing, uniform reduction in moisture, high heat and mass transfer and reduced drying time (Kassem *et al*., 2011; Mujumdar, 2006). It is used in many field of applications due to its thermal efficiency and lower capital cost (Yang, 2003). Hence, considering these advantages, the thin layer drying kinetics of *Cissus quadrangularis* at various air temperatures at fixed bed height was performed in a fluidized bed dryer. The drying data was fit into various mathematical models and effective diffusivity and activation energy were determined.

MATERIALS AND METHODS

Sample and sample preparation

Fresh samples of *C. quadrangularis* were collected from the Department of Medicinal Plants, Tamilnadu Agricultural University, Coimbatore, Tamilnadu. The stems are harvested from the plant a few feet's above the ground. The stems were washed, drained and trimmed to remove leaves and tendrils. After removing the top and bottom nodes, they were cut into 0.5 – 1 cm in length. The initial moisture content of the fresh *Cissus* samples was 93% (w.b).

Fluidized bed dryer

Fluidized bed drying of *C. quadrangularis* was performed using a Lab model fluidized bed dryer (Fig. 1). The cut pieces of *Cissus* were filled up to 5 cm inside the truncated chamber. The blower was driven by the motor and the airflow rate was controlled by the butterfly valve. The drying process was conducted at three temperatures (40, 50 and 60° C) and air velocity of 8.2 m/s. The air temperature was controlled by a thermostat switch connected to the heater circuit. A timer switch range of 0 to 60 minutes was included in the circuit to put off the whole unit at a desired set time. This regulation of air was kept at a constant level of 8.2 m/s throughout the experiment.

Drying characteristics

The moisture content of *Cissus* sample was determined according to AOAC (2005). Five gram of sample was dried in hot air at 105 ºC for 24 h. Dry basis moisture content was calculated as follows:

$$Mc = \frac{M_{w-}M_d}{M_w} \tag{1}$$

where, Mc is the initial moisture content of *Cissus* in d.b.%, M_w is the wet weight and M_d is the dry weight of *Cissus* in grams.

The effect of fluidized bed dryer on the drying of *Cissus* was evaluated by determining the moisture content and drying rate. The moisture was removed by the hot air flow through an extensive area of the product (Vega -Mercado *et al*., 2001). The cut pieces of *Cissus* were weighed and the loss in moisture was estimated at 20 min intervals. The samples were weighed using a weighing balance with 0.01 g accuracy. The drying rate (DR) was calculated using the following formula.

$$MR = \frac{M_{t-}M_e}{M_{i-}M_e} \tag{2}$$

$$\text{DR}= \frac{M_{t1-}M_{t2}}{t_{2-}t_1} \tag{3}$$

where DR is the drying rate (g water/g dry matter) and $M_{t1} \text{and } M_{t2}$ are the moisture content of samples (g water/g dry matter) at time t_1 and t_2 (min), respectively

Relationship between moisture ratio and time was best described by empirical and semiempirical mathematical models (Table 1). The goodness of fit of tested models to the experimental data was evaluated using the coefficient of determination (R^2), reduced chi square (χ^2)

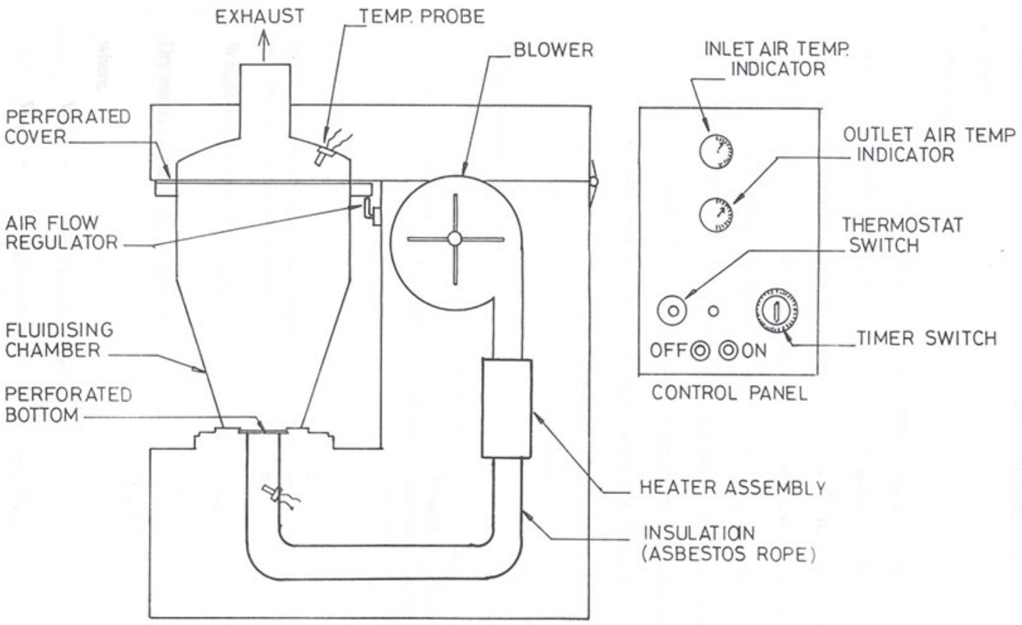

Fig. 1. *Schematic view of the lab-scale fluidized bed dryer*

and root mean square error (*RMSE*). The best model describing the solar drying of *Cissus* was selected based on higher R^2 value and lower χ^2 and RSME values. The following equations were used to calculate the above-mentioned parameters:

$$R^2 = 1- \left[\frac{\sum(MR_{Prd}-\sum MR_{Exp})2}{\sum \overline{MR}_{Prd}-\sum MR_{Exp})2}\right] \tag{4}$$

$$\chi^2 = \frac{\sum(MR_{Exp}-\sum MR_{Prd})^2}{N-n} \tag{5}$$

$$RMSE = \left(\frac{\sum(MR_{Prd}-\sum MR_{Exp})2}{N}\right)^{1/2} \tag{6}$$

Where, MR_{Exp} is experimental moisture content and MR_{Prd} is predicted moisture content and N is the number of observations.

Effective moisture diffusivity

The generally accepted physical mechanism of moisture transport from food material to the surface is through diffusion. The effective moisture diffusivity (EMD) explains the complexity of the drying process and the mechanism of moisture transfer. During the drying of *Cissus*, a constant rate period was not observed; hence the moisture movement happens during the falling rate period. The unsteady state moisture diffusion rate can be elucidated by Fick's second law. Here, the sample is assumed to be an infinite slab since moisture moves throughout the thickness and the effect of heat transfer and shrinkage was neglected. The effective moisture diffusivity was calculated by following the analytical solution of flics second law proposed by Crank (Crank, 1975)

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff}\,\frac{\partial M}{\partial x}\right) \tag{7}$$

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

where Deff is the effective moisture diffusivity (m2.s-1), L is the half thickness of slab (m), MR is the moisture ratio, t is the drying time (s). Deff is determined experimentally from drying curves (Mujumdar, 2001). To simplify the equation only the first part of the equation was accounted for by taking the natural log of both sides and assuming n is zero.

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\,t\right) \tag{9}$$

Eq.9 was fit into ln MR vs t curve to determine the effective moisture diffusivity.

Activation energy

Arrhenius-type relationship was used to express the effect of temperature on the effective diffusivity(Simal *et al.*, 2006). Ln (Deff) vs. 1/T was plotted to measure the activation energy, and the resulting slope was -Ea/R. The activation energy (Ea) was estimated using the following formula

$$D_{eff} = D_o\, exp(\frac{-E_a}{RT}) \tag{10}$$

Table 1. Thin layer drying models for fluidized bed drying of *Cissus*

S. No	Model name	Analytical expression	Reference
1.	Lewis	MR = exp(-kt)	(Bruce, 1985)
2.	Page	MR = exp(-k t^n)	(Page, 1949)
3.	Modified page	MR = exp($(-kt)^n$)	(White *et al.*, 1981)
4.	Henderson and Pabis	MR = a exp(-kt)	(Hendreson & Pabis, 1961)
5.	Wang and Singh	MR = 1 + at + bt^2	(Wang & Singh, 1978)
6.	Logarithmic	MR = a exp(-kt) + c	(Toğrul & Pehlivan, 2002)
7.	Two term	MR = a exp(-k□t) + b exp (-k□t)	(Henderson, 1974)
8.	Two term exponential	MR = a exp(-kt) + (1 -a) exp(-kat)	(Eldeen *et al.*, 1980)
9.	Modified Henderson and Pabis	MR = a exp(-kt) + b exp (-gt) + c exp(-ht)	(Karathanos, 1999)
10.	Midilli	MR = a exp($-kt^n$) + bt	(Midilli *et al.*, 2002)
11.	Approximation of diffusion	MR = a exp(-kt) + (1 -a) exp(-kbt)	(Kassem, 1998)
12.	Verma et al.	MR = a exp(-kt) + (1 -a) exp(-gt)	(Verma *et al.*, 1985)
13.	Simplified Fick's diffusion	MR = a exp(-c(t/L^2))	(Pankey *et al.*, 1965)

Where, *D*eff is the moisture diffusivity coefficient (m^2/s), *D*o is the maximum diffusion coefficient (at infinite temperature), *E*a is the activation energy for diffusion (kJ/mol), *T* is the temperature (C) and R is the gas constant (kJ/mol K).

RESULTS AND DISCUSSION

Drying characteristics

In present study, the moisture content of the slices was reduced from 674.46% (d.b) to 4% (d.b.). The moisture content data obtained at three different temperatures of 40 ºC, 50 ºC and 60 ºC; and 20 mins interval was converted to a dimensionless parameter called moisture ratio vs time (Fig.2). Constant rate period was not observed in the drying of *Cissus*. A falling rate period was observed for the *Cissus* samples, irrespective of drying temperature. Hence, diffusion was the main mechanism governing the water removal from Cissus under all drying te temperatures. From Fig. 2, it is evident that increasing the drying air temperature increased the drying rate, decreasing the drying time. Generally, the drying rate decreases for time due to moisture reduction in the sample. The initial drying rate was high because of initial high moisture (674.46% d.b.) in *Cissus*. Increasing the temperature from 40 ºC to 50 ºC and 60 ºC resulted in a 27.2% and 40.9 % reduction in drying time. The best drying rate was obtained at 60 ◦C and an air velocity of 8.2 m/s among all the drying temperatures. Also, the higher surface area of the *Cissus* resulted in rapid heat transfer and more water evaporation. Curve fitting for the selected thirteen models was performed and the statistical results are presented in Table 2. From the table, R^2 value ranged from 0.94871 to 0.99855. All the models except Logarithmic, two terms, Modified Henderson and Pabis and Midli exhibited higher correlation coefficients and acceptably described the drying behavior. From the thirteen models, the approximation of diffusion showed a higher R^2 value correlation coefficient increased with an increase in temperature. At 60 ºC, the RMSE and $\chi 2$ value of the diffusion model approximation were lower than 40 ºC and 50 ºC and the rest of the model. Hence, this model was chosen to describe the drying behaviour of *Cissus* based on higher R^2 value and lower RMSE and $\chi 2$. This model has successfully demonstrated the drying characteristics of yam slices (Sobukola *et al.*, 2008), red pepper (Akpinar *et al.*, 2003), tomato (Sacilik *et al.*, 2006) and pumpkin and green pepper (Ertekin and Yaldiz, 2001). For each temperature value of 40 ºC, 50 ºC and 60 ºC, the drying constant, k (min^{-1}) and coefficient a, b was calculated for the approximation of diffusion model and the results are shown in Table 3. The predicted MR of the approximation of diffusion model compared with the experimental results are depicted in Fig. 3. The data mainly scattered adjacent to the straight line, thus strengthening the view that this model could represent the drying characteristic of *Cissus* uadrangularis accurately.

Effective moisture diffusivity

The effective moisture diffusivity calculated using the formula (Eq. 9) for three temperatures is given in Table

Table 2. Statistical results obtained for the thin layer drying models for *Cissus quadrangularis*.

S. No.	Model	Temperature (°C)	R^2	RMSE	χ2
1	Lewis	40	0.99515	0.130077	0.01692
		50	0.99741	0.079624	0.00634
		60	0.99341	0.114368	0.01308
2	Page	40	0.99633	0.113137	0.0128
		50	0.9979	0.071554	0.00512
		60	0.99797	0.063561	0.00404
3	Modified Page	40	0.99634	0.113093	0.01279
		50	0.9979	0.071554	0.00512
		60	0.99797	0.063561	0.00404
4	Henderson and Pabis	40	0.99567	0.122923	0.01511
		50	0.99748	0.078422	0.00615
		60	0.99557	0.093808	0.0088
5	Wang and Singh	40	0.98758	0.041952	0.00176
		50	0.98072	0.216979	0.04708
		60	0.94871	0.319108	0.10183
6	Logarithmic	40	-0.75666	2.475946	6.13031
		50	-0.34323	1.811356	3.28101
		60	-0.14729	1.509285	2.27794
7	Two term	40	-0.75666	2.475946	6.13031
		50	-0.34323	1.811356	3.28101
		60	-0.14729	1.509285	2.27794
8	Two term exponentials	40	0.99651	0.110408	0.01219
		50	0.99807	0.068702	0.00472
		60	0.99843	0.055767	0.00311
9	Modified Henderson and Pabis	40	-0.75666	2.475946	6.13031
		50	-0.34323	1.811356	3.28101
		60	-0.14729	1.509285	2.27794
10	Midilli	40	0.60909	1.167977	1.36417
		50	0.45528	1.153499	1.33056
		60	0.34589	1.139614	1.29872
11	Approximation of diffusion	40	0.99664	0.108351	0.01174
		50	0.99741	0.079624	0.00634
		60	0.99855	0.053666	0.00288
12	Verma et al.	40	0.99586	0.120167	0.01444
		50	0.99753	0.077589	0.00602
		60	0.99765	0.068337	0.00467
13	Simplified Fick's equation	40	0.99567	0.122923	0.01511
		50	0.99748	0.078422	0.00615
		60	0.99557	0.093808	0.0088

4. The D_{eff} values of *Cissus* were 1.54 x 10^{-10}, 2.57 x 10^{-10}, and 3.12x 10^{-10} m^2/s at 40, 50 and 60 °C, respectively. The highest D_{eff} value was observed at 60 °C. For food materials, the Deff value ranges from 10^{-11} m^2/s to 10^{-9} m^2/s and agrees with the reported values (Zogzas *et al.*, 1996). In fluidized bed drying, fluidization can expedite heat and mass transfer between the air and product through an effective mixing mechanism. Thin layer drying of *Cissus* was carried out at an air velocity of 8.2 m/s at all temperatures. This high air velocity facilitates the heat transfer between the internal and surface of the sample by reducing the boundary layer on the sample. It is evident that the ef-

Table 3. Drying constant and coefficient values of the approximation of the diffusion model for each temperature.

Temperature (ºC)	k (min^{-1})	a	b	R^2	RMSE	χ2
40	0.00527 ± 0.00021	-5.48111E11 ± 4.84057E11	1 ± 5.27732E-13	0.99664	0.108351	0.01174
50	0.00674 ± 106.42617	-5.06635E4 ± 3.17896E11	1 ± 0.30836	0.99741	0.079624	0.00634
60	0.03946 ± 0.01098	0.15292 ± 0.03058	0.18653 ± 0.04816	0.99855	0.053666	0.00288

Table 4. Effective moisture diffusivity of *Cissus* for different temperatures

Temperature, º C	Effective moisture diffusivity, m^2 /s	R²
40	1.54E-10	0.9256
50	2.57E-10	0.9164
60	2.67E-10	0.9248

fective moisture diffusivity increased with an increase in drying air temperature. Since raising the temperature from 40 ºC to 60 ºC increases the heating energy of the air, increasing the kinetic energy of water molecules. At higher temperature vapor pressure inside the sample increases, which causes moisture migration to the surface. The increased air velocity quickly removes the difference between surface and interior moisture, and the sample interior moisture diffuses from inside to outside with increased driving force (Aral and Bese, 2016). Similar results have been reported for *Cissus*'s convective hot air drying (Jongyingcharoen, 2020).

Activation energy

The activation energy calculated by plotting Deff's natural logarithm as a function of the reciprocal of absolute temperature 1/(T+273.15) (1/K) is presented in Fig 4. From the slope of the straight line, the activation energy calculated was 30.76 kJ/ mole for the drying of *Cissus*. The Lower Ea value is due to high temperature, air velocity, smaller size and peeling of the *Cissus* stem (Elmas *et al.*, 2019). The obtained value for *Cissus* was also lower than Green beans 35.43 kJ/ mole (İ. Doymaz, 2005), sliced kiwi fruit 34.34 kJ/ mole (Darıcı and Şen, 2015), parboiled wheat 37.01 kJ/ mole (Mohapatra and Rao, 2005) and closer to Corn 29.56 kJ/ mole (Doymaz and Pala, 2003), Carrots 28.36 kJ/ mole (Doymaz, 2004) and jujube slices 28.18 kJ/ mole (Elmas *et al.*, 2019). The straight line of activation energy in the temperature range indicated Arrhenius dependence. Activation energy is a measure of the temperature sensitivity of D_{eff} and it was the energy needed to initiate the moisture diffusion within the sample.

Conclusion

The thin layer drying of *C. quadrangularis* was performed in a fluidized bed dryer at different air temperatures ranging from 40 to 60 ºC, constant air velocity of 8.2 m/s and bed thickness of 5 cm. The drying process took place at a falling rate period for *Cissus*. The drying

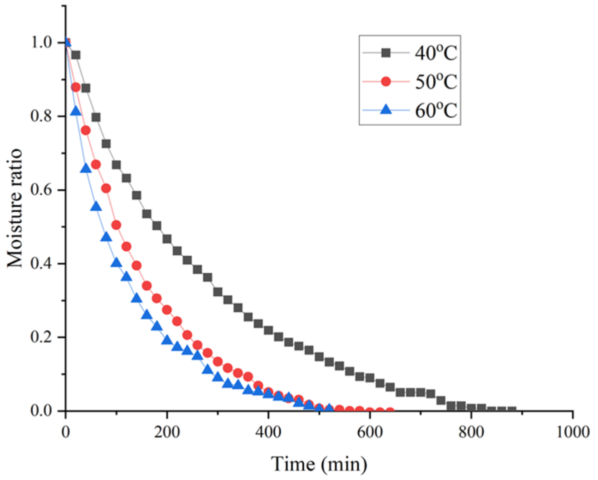

Fig. 2. *Moisture ratio vs. time Drying curves of Cissus drying at different drying temperatures*

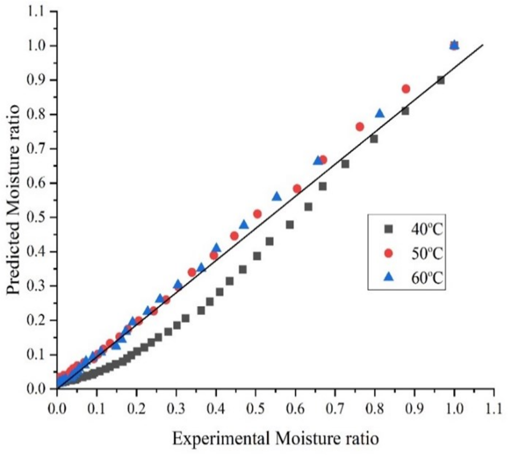

Fig. 3. *Predicted vs experimental moisture ratio Experimental and predicted drying curves of Cissus drying for the approximation of diffusion model*

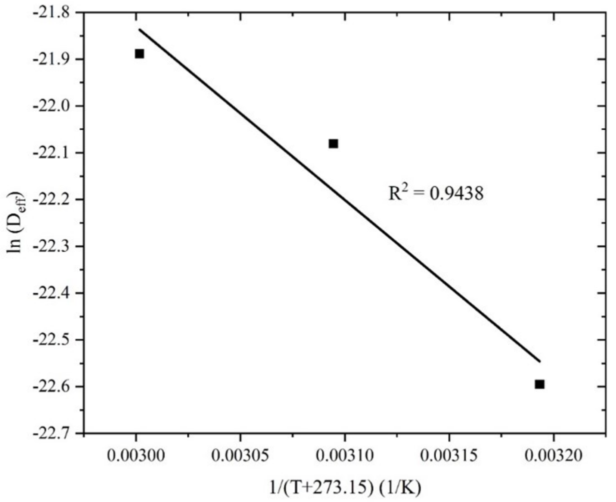

Fig. 4. *Plot of Natural logarithm of effective moisture diffusivity vs. reciprocal of absolute temperature of fluidized bed drying of Cissus*

data was fitted to thirteen thin layer models, where the diffusion model approximation precisely described *Cissus*'s drying process. Statistical analysis inferred that the highest determination coefficient, lowest chi-square and root mean square error was observed at an air temperature of 60 °C. The effective moisture diffusivity increased with an increase in temperature and the values ranged from 1.54 - 3.12x $10^{-10}\ m^2/s$. Activation energy for moisture diffusion was found to be 30.76 kJ/ mole. Hence, fluidized bed drying provides fast drying of *Cissus* at low temperatures and may enable the production of high-quality dried products.

Conflict of interest

The authors declare that they have no conflict of interest.

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