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

M. Venkatasami
Department of Food Process Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003 (Tamil Nadu), India

P. Rajkumar
Department of Food Process Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003 (Tamil Nadu), India

M. Balakrishnan
Department of Food Process Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003 (Tamil Nadu), India

C. Indu Rani
Department of Fruit Science, Horticultural college and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003 (Tamil Nadu), India

D. Amirtham
Department of Biochemistry, Centre for Plant Molecular Biology and Biotechnology, Tamil Nadu Agricultural University, Coimbatore-641003 (Tamil Nadu), India

A. Lakshmanan
Center for Agricultural Nanotechnology, Tamil Nadu Agricultural University, Coimbatore-641003 (Tamil Nadu), India

*Corresponding author. E-mail: venkatasami.m@gmail.com*

**How to Cite**

**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 °C), 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 ($\chi^2$). 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 medicotherapeutics (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 60º 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:

\[
MC = \frac{M_w-M_d}{M_w} \quad (1)
\]

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;

\[
MR = \frac{M_{e}-M_{f}}{M_{f}-M_{e}} \quad (2)
\]

\[
DR=\frac{M_{t_{1}}-M_{t_{2}}}{t_{2}-t_{1}} \quad (3)
\]

where DR is the drying rate (g water/g dry matter) and \( M_{t_{1}} \) and \( M_{t_{2}} \) 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 (\( \chi^2 \))
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 $\chi^2$ and RMSE values. The following equations were used to calculate the above-mentioned parameters:

\[
R^2 = 1 - \frac{\sum (MR_{Pred} - \sum MR_{Exp})^2}{\sum MR_{Exp}^2}
\]

\[
\chi^2 = \frac{\sum (MR_{Exp} - \sum MR_{Pred})^2}{N-n}
\]

\[
RMSE = \left( \frac{\sum (MR_{Pred} - \sum MR_{Exp})^2}{N} \right)^{1/2}
\]

Where, $MR_{Exp}$ is experimental moisture content and $MR_{Pred}$ 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 Fick’s second law proposed by Crank (Crank, 1975)

\[
\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D_{eff} \frac{\partial M}{\partial x} \right)
\]

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

where $D_{eff}$ is the effective moisture diffusivity $(m^2 \cdot s^{-1})$, $L$ is the half thickness of slab (m), $MR$ is the moisture ratio, $t$ is the drying time (s). $D_{eff}$ 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.

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

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 ($D_{eff}$) vs. $1/T$ was plotted to measure the activation energy, and the resulting slope was $-E_a/R$. The activation energy ($E_a$) was estimated using the following formula

\[
D_{eff} = D_0 \exp \left( -\frac{E_a}{RT} \right)
\]
Table 1. Thin layer drying models for fluidized bed drying of Cissus

<table>
<thead>
<tr>
<th>S. No</th>
<th>Model name</th>
<th>Analytical expression</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lewis</td>
<td>( MR = \exp(-kt) )</td>
<td>(Bruce, 1985)</td>
</tr>
<tr>
<td>2.</td>
<td>Page</td>
<td>( MR = \exp(-k^\alpha t) )</td>
<td>(Page, 1949)</td>
</tr>
<tr>
<td>3.</td>
<td>Modified page</td>
<td>( MR = \exp((kt)^n) )</td>
<td>(White et al., 1981)</td>
</tr>
<tr>
<td>4.</td>
<td>Henderson and Pabis</td>
<td>( MR = a \exp(-kt) )</td>
<td>(Henderson &amp; Pabis, 1961)</td>
</tr>
<tr>
<td>5.</td>
<td>Wang and Singh</td>
<td>( MR = 1 + at + bt^2 )</td>
<td>(Wang &amp; Singh, 1978)</td>
</tr>
<tr>
<td>6.</td>
<td>Logarithmic</td>
<td>( MR = a \exp(-kt) + c )</td>
<td>(Toğrul &amp; Pehlivan, 2002)</td>
</tr>
<tr>
<td>7.</td>
<td>Two term</td>
<td>( MR = a \exp(-kt) + b \exp(-kt) )</td>
<td>(Henderson, 1974)</td>
</tr>
<tr>
<td>8.</td>
<td>Two term exponential</td>
<td>( MR = a \exp(-kt) + (1 - a) \exp(-kt) )</td>
<td>(Edelen et al., 1980)</td>
</tr>
<tr>
<td>9.</td>
<td>Modified Henderson and Pabis</td>
<td>( MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht) )</td>
<td>(Karathanos, 1999)</td>
</tr>
<tr>
<td>10.</td>
<td>Midilli</td>
<td>( MR = a \exp(-kt^n) + bt )</td>
<td>(Midilli et al., 2002)</td>
</tr>
<tr>
<td>11.</td>
<td>Approximation of diffusion</td>
<td>( MR = a \exp(-kt) + (1 - a) \exp(-ktb) )</td>
<td>(Kassem, 1998)</td>
</tr>
<tr>
<td>12.</td>
<td>Verma et al.</td>
<td>( MR = a \exp(-kt) + (1 - a) \exp(-gt) )</td>
<td>(Verma et al., 1985)</td>
</tr>
<tr>
<td>13.</td>
<td>Simplified Fick’s diffusion</td>
<td>( MR = a \exp(-c(L + t)) )</td>
<td>(Pankey et al., 1965)</td>
</tr>
</tbody>
</table>

Where, \( D_{eff} \) is the moisture diffusivity coefficient (m\(^2\)/s), \( D_0 \) 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 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 ºC 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 Midilli 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, \( k \) (m\(^{-1}\) 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
4. The $D_{eff}$ values of *Cissus* were $1.54 \times 10^{-10}$, $2.57 \times 10^{-10}$, and $3.12 \times 10^{-10}$ $m^2/s$ at 40, 50 and 60 °C, respectively. The highest $D_{eff}$ value was observed at 60 °C. For food materials, the $D_{eff}$ 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>
<thead>
<tr>
<th>S. No.</th>
<th>Model</th>
<th>Temperature (°C)</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lewis</td>
<td>40</td>
<td>0.99515</td>
<td>0.130077</td>
<td>0.01692</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.99741</td>
<td>0.079624</td>
<td>0.00634</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99341</td>
<td>0.114368</td>
<td>0.01308</td>
</tr>
<tr>
<td>2</td>
<td>Page</td>
<td>40</td>
<td>0.99633</td>
<td>0.111313</td>
<td>0.0128</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.9979</td>
<td>0.071554</td>
<td>0.00512</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99797</td>
<td>0.063561</td>
<td>0.00404</td>
</tr>
<tr>
<td>3</td>
<td>Modified Page</td>
<td>40</td>
<td>0.99634</td>
<td>0.111303</td>
<td>0.01279</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.9979</td>
<td>0.071554</td>
<td>0.00512</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99797</td>
<td>0.063561</td>
<td>0.00404</td>
</tr>
<tr>
<td>4</td>
<td>Henderson and Pabis</td>
<td>40</td>
<td>0.99567</td>
<td>0.122923</td>
<td>0.01511</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.99748</td>
<td>0.078422</td>
<td>0.00615</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99557</td>
<td>0.093808</td>
<td>0.0088</td>
</tr>
<tr>
<td>5</td>
<td>Wang and Singh</td>
<td>40</td>
<td>0.98758</td>
<td>0.041952</td>
<td>0.00176</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.98072</td>
<td>0.216979</td>
<td>0.04708</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.94871</td>
<td>0.319108</td>
<td>0.10183</td>
</tr>
<tr>
<td>6</td>
<td>Logarithmic</td>
<td>40</td>
<td>-0.75666</td>
<td>2.475946</td>
<td>6.13031</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>-0.34323</td>
<td>1.811356</td>
<td>3.28101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>-0.14729</td>
<td>1.509285</td>
<td>2.27794</td>
</tr>
<tr>
<td>7</td>
<td>Two term</td>
<td>40</td>
<td>-0.75666</td>
<td>2.475946</td>
<td>6.13031</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>-0.34323</td>
<td>1.811356</td>
<td>3.28101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>-0.14729</td>
<td>1.509285</td>
<td>2.27794</td>
</tr>
<tr>
<td>8</td>
<td>Two term exponentials</td>
<td>40</td>
<td>0.99651</td>
<td>0.110408</td>
<td>0.01219</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.99807</td>
<td>0.068702</td>
<td>0.00472</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99843</td>
<td>0.055767</td>
<td>0.00311</td>
</tr>
<tr>
<td>9</td>
<td>Modified Henderson and Pabis</td>
<td>40</td>
<td>-0.75666</td>
<td>2.475946</td>
<td>6.13031</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>-0.34323</td>
<td>1.811356</td>
<td>3.28101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>-0.14729</td>
<td>1.509285</td>
<td>2.27794</td>
</tr>
<tr>
<td>10</td>
<td>Midilli</td>
<td>40</td>
<td>0.60909</td>
<td>1.167977</td>
<td>1.36417</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.45528</td>
<td>1.153499</td>
<td>1.33056</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.34589</td>
<td>1.139614</td>
<td>1.29872</td>
</tr>
<tr>
<td>11</td>
<td>Approximation of diffusion</td>
<td>40</td>
<td>0.99664</td>
<td>0.108351</td>
<td>0.01174</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.99741</td>
<td>0.079624</td>
<td>0.00634</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99855</td>
<td>0.053666</td>
<td>0.00288</td>
</tr>
<tr>
<td>12</td>
<td>Verma et al.</td>
<td>40</td>
<td>0.99586</td>
<td>0.120167</td>
<td>0.01444</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.99753</td>
<td>0.077589</td>
<td>0.00602</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99765</td>
<td>0.068337</td>
<td>0.00467</td>
</tr>
<tr>
<td>13</td>
<td>Simplified Fick’s equation</td>
<td>40</td>
<td>0.99567</td>
<td>0.122923</td>
<td>0.01511</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>0.99748</td>
<td>0.078422</td>
<td>0.00615</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.99557</td>
<td>0.093808</td>
<td>0.0088</td>
</tr>
</tbody>
</table>

The effective 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 (Elnas 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 Deff 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

---

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

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>k (min⁻¹)</th>
<th>a</th>
<th>b</th>
<th>R²</th>
<th>RMSE</th>
<th>χ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.00527 ±</td>
<td>4.84057E11</td>
<td>1 ± 5.27732E-13</td>
<td>0.99664</td>
<td>0.108351</td>
<td>0.01174</td>
</tr>
<tr>
<td>50</td>
<td>0.00674 ±</td>
<td>3.17896E11</td>
<td>1 ± 0.30836</td>
<td>0.99741</td>
<td>0.079624</td>
<td>0.00634</td>
</tr>
<tr>
<td>60</td>
<td>0.03946 ±</td>
<td>0.15292 ±</td>
<td>0.18653 ±</td>
<td>0.99855</td>
<td>0.053666</td>
<td>0.00288</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Effective moisture diffusivity, m²/s</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1.54E-10</td>
<td>0.9256</td>
</tr>
<tr>
<td>50</td>
<td>2.57E-10</td>
<td>0.9164</td>
</tr>
<tr>
<td>60</td>
<td>2.67E-10</td>
<td>0.9248</td>
</tr>
</tbody>
</table>

---

**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**
REFERENCES

Conflict of interest
The authors declare that they have no conflict of interest.


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.

REFERENCES


1244