Evaluation of energy efficiency and moisture diffusivity for convective drying of large cardamom

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Abstract: The drying behavior of freshly harvested large cardamom capsules were studied in a hot air dryer within the temperature range of 50-80°C. The study on drying rate showed that the constant rate drying period was very short, and capsules mostly followed the falling rate drying period. The drying during falling rate drying was followed unsteady state mass transfer and was governed by Fick’s diffusion law. The drying rate was faster initially when the moisture content in the product was high but with a decrease of moisture content, the drying rate was found to be decreased. Nine different drying kinetics models were fitted to find the best suitable model to predict the drying kinetics of large cardamom capsules. The two-term model was the best-suited model out of the nine different models, representing the drying properties of large cardamom with the highest R² and the lowest RMSE and

χ² values. The maximum effective moisture diffusivity D_{eff} value of 3.898×10^{-10} was obtained at a drying temperature of 80°C, while the lowest value was 1.949×10^{-10} at 50°C. The dependency of effective moisture diffusivity with drying temperature was correlated by Arrhenius equation. The activation energy showing the minimum energy needed to extract moisture from a solid matrix of large cardamom capsule was calculated as 32.54 kJ/mol and the pre-exponential factor of Arrhenius equation was calculated at 7.6×10^{-4} m^2/s.

Keywords: large cardamom; thin layer drying; effective moisture diffusivity; activation energy.

1. Introduction

Drying is basically a simultaneous heat transfer and mass transfer process. The heat needed for the evaporation of moisture was supplied from the hot air circulating around the product. During the process, moisture from the product was transferred to the surrounding hot air during the drying process. Diffusion is a characteristic activity of drying materials and the transfer of water vapor from the inside of the food material to the outer surface during drying is controlled or regulated by the diffusion process. Drying requires the simultaneous transfer of heat and mass. Drying is primarily aimed at reducing moisture present in the product to enhance storage stability. Therefore, drying of fruits and vegetables has been done as a way of enhancing storability.

Large cardamom has a leading role among different spices and has immense commercial significance. Large cardamom (Amomum subulatum Roxb. Family: Zingiberaceae) is the value-added cash crop and the primary source of cash income for eastern Himalayan farmers. It is also known as black cardamom, and reinforces and intensifies the recipes’ taste. The main production centers in India are the sub-Himalayan ranges of Arunachal Pradesh, a part of Nagaland, Sikkim and Darjeeling district of West Bengal. Drying is the most critical operation after harvesting the large cardamom. The cardamom capsule moisture content has to be reduced to a safe level for a longer storage period. Proper drying will maintain the quality of the product and minimize losses. Delays in drying, inadequate drying, or ineffective drying may decrease the consistency of the capsule and cause losses.
Drying results in a substantial decrease of space demand for storage of the commodity for longer length. The different drying methods implemented for drying of fruits and vegetables includes tray drying, vacuum drying (Khawas et al., 2016), microwave drying (Dash and Das, 2020; Dash and Das, 2019a), microwave vacuum drying (Raj and Dash, 2020; Dash, Chakraborty, and Singh, 2020), osmotic drying (Prithani, and Dash, 2020; Dash and Balasubramaniam, 2018), and fluidized bed drying (Dash and Das, 2019b). The prediction of drying behavior can be obtained from suitable drying models. The drying of different food products was predicted through different drying model in different food products such as onions (Singh and Sodhi, 2000), green bean (Doymaz, 2005), hawthorn fruit (Sousa et al., 2018), ear corn (Friant et al., 2004), apricots (Doymaz, 2004a), and mulberry (Doymaz, 2004b) are available. Each food material has unique behavior due to the difference in structure and composition. The drying kinetics study can be implemented to design suitable dryers and optimize the drying parameters (Kingsly et al., 2006). The different thin-layer drying kinetics model studied for drying of food materials are toria seeds (Rangroo and Rao, 1992), dates (Hassan and Hobani, 2000), chilling pepper (Tunde-Akintunde and Ajala, 2010), millet samples (Ojendiran and Raji, 2010), sirilankan paddy (Syamali et al., 2009), sesame seeds (Khazaei and Daneshmandi, 2007), amaranth grain (Ronoh et al., 2010), and parboiled wheat (Debabandya et al., 2005). The different kinetic models were implemented to evaluate the effective moisture diffusivity of the product. The effective moisture diffusivity obtained at different temperature were implemented to evaluate the activation energy in different products such as star fruit (Dash, Gope, Sethi, and Doloj, 2013), kachkal banana peel (Khawas et al., 2015), and elephant apple (Nag and Dash, 2016). However, a very limited study had been conducted on the drying of freshly harvested spices like large cardamom. Based on this, the objective of the study was to observe the drying behavior of freshly harvested large cardamom. Different thin layer model was fitted to the drying data to obtain the most suitable model to represent the kinetics behavior of the drying process. The effective moisture diffusivity and activation energy for the process was evaluated.

2. Materials and method

2.1. Drying procedure

The freshly harvested large cardamom capsules of Arunachal Pradesh, Itanagar, were collected from local farmers. Freshly harvested cardamom capsule has a moisture content of 78.59±3.65 percent (wet basis). The raw material was dried immediately by hot air drying until it reaches a moisture content (8.2±0.5 percent wet basis). The drying experiments were conducted using a laboratory tray dryer at a specific temperature. The moisture loss due to drying was recorded during the experiment with the aid of an electronic balance.

2.2. Mathematical modeling

The drying of large cardamom was conducted at four different temperatures, such as 50, 60, 70, and 80°C. The moisture content during the drying was obtained at an interval of 30 min. The obtained moisture content was expressed in dimensionless moisture ratio as presented in Eqn. (1).

\[
MR = \frac{M_t - M_e}{M_o - M_e}
\]  

(1)

In Eqn. (1) the parameter $MR$, $M_t$, $M_o$, $M_e$ are expressed in terms of kg water/kg dry matter) and the parameters are defined as follows.

MR = Moisture Ratio  
$M_t$ = Moisture content at time $t = t$  
$M_o$ = Initial moisture content at time $t = 0$  
$M_e$ = Equilibrium moisture content at time $t = \infty$

The dimensionless moisture ratio was fitted with different models present in Table (1).
2.3. Estimation of Effective Moisture Diffusivity

The drying of biological material such as fruits and vegetables follows the falling rate period. The drying process follows the falling rate period was generally described by Fick’s second Law of mass transfer, as shown in Eqn. (2)

\[ \frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial^2 M}{\partial x^2} \]  

(2)

The large cardamom capsule was considered as geometrically spherical in shape and hence, the solution of diffusion models for spheres was applied. The different assumptions were:

i. Initial moisture content across the fresh capsule was uniform.

ii. The capsule was believed to be homogeneous and isotropic solids and the transition of mass to the core was symmetric.

iii. The moisture was assumed to be dispersed uniformly across the cardamom capsule in the initial state (i.e., at time t=0)

iv. Thermal equilibrium occurs between the capsule surface and the drying air.

v. The coefficient of diffusion is constant, and the shrinkage is negligible.

vi. Migration of moisture is by diffusion only.

The solution of Eqn. (2) for spherical geometry is presented in given Eq. (3) (Crank, 1975).

\[ MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(n\pi)^2} \exp \left( -\frac{(n\pi)^2 D_{\text{eff}} t}{r^2} \right) \]  

(3)

Where \( r \) = radius of the cardamom capsule. On neglecting the higher order terms, the equation (3) reduces to Eqn. (4).

\[ MR = \frac{6}{\pi^2} \exp \left( -\frac{\pi^2 D_{\text{eff}} t}{r^2} \right) \]  

(4)

Taking natural logarithm on both sides of Eqn. (4) the obtained equation is presented in Eqn. (5).

\[ \ln MR = \ln \frac{6}{\pi^2} - \frac{\pi^2 D_{\text{eff}} t}{r^2} \]  

(5)

The slope of the graph plotted between ln(MR) and drying time would be used to calculate the effective moisture diffusivity of the product during drying.

\[ \text{slope} = \frac{-\pi^2 D_{\text{eff}}}{r^2} \]  

(6)

\[ D_{\text{eff}} = -\frac{\text{slope} r^2}{\pi^2} \]  

(7)

The effective moisture diffusivity was correlated with different drying temperatures by using the Arrhenius equation to obtain the activation energy (Wang et al., 2018).

\[ D_e = D_0 \exp \left( \frac{E_a}{RT} \right) \]  

(8)

\[ \ln D_e = \ln D_0 - \frac{E_a}{RT} \]  

(9)

In Eqn. (8) and (9), the parameters \( E_a, R, T, \) and \( D_0 \) are defined as following.

\( E_a = \text{Energy of activation (kJ/mol)} \)

\( R = \text{universal gas constant (8.3143 kJ/mol)} \)

\( T = \text{absolute air temperature (K)} \)

\( D_0 = \text{preexponential factor of the Arrhenius equation (m}^2\text{/s)} \)

The activation energy represented the minimal energy to be supplied in order to disrupt the interactions between water-solid or water-water and transfer water molecules in the solid from one point to another point within the solid. The smaller activation energy indicated that the water molecule could pass in the sample more readily. The activation energy needed for the initiation of drying was determined using the Arrhenius equation.

2.4. Statistical analysis

The different statistical parameters such as coefficient of determination (R²), chi-square (\( \chi^2 \)), and root mean square error (RMSE) were evaluated to select the best suitable model to represent the drying kinetics. The best suited model was chosen based on the highest R² and lowest (\( \chi^2 \)) values (Khawas et al., 2016; Togrul and Pehlivan, 2002). R² value indicates the correctness in fitting and \( \chi^2 \) and RMSE value indicates bias error, i.e., deviation in the fitting.
Table 1: The Different mathematical models applied to the experimental data

| Model No. | Model Name            | Model                                                                 | References                     |
|-----------|-----------------------|----------------------------------------------------------------------|--------------------------------|
| 1         | Newton                | $MR = \exp(-kt)$                                                     | Westerman et al., 1973         |
| 2         | Page                  | $MR = \exp(-kt^n)$                                                   | Page, 1949                     |
| 3         | Modified page         | $MR = \exp[-(kt)^n]$                                                | Yaldiz et al., 2001            |
| 4         | Henderson and Pabis   | $MR = a \exp(-kt)$                                                  | Yagcioglu et al., 1999         |
| 5         | Logarithmic           | $MR = a \exp(-kt) + c$                                              | Yaldiz and Ertekin, 2001       |
| 6         | Verma et al.          | $MR = a \exp(-kt) + (1 - a)\exp(-gt)$                               | Verma et al., 1985             |
| 7         | Wang and Singh        | $MR = Mo + at + bt^2$                                                | Ozdemir and Devres, 1999       |
| 8         | Two term              | $MR = a \exp(-kt) + b \exp(-kt1) - a)\exp(-kt)$                    | Rahman et al., 1998            |
| 9         | Two term exponential  | $MR = a \exp(-kt) + (1 - a)\exp(-kt)$                               | Yaldiz et al., 2001            |

3. Results and Discussions

3.1. Drying behavior of large cardamom

The variation of moisture ratio of large cardamom at four different drying temperatures is 50, 60, 70, and 80°C, as shown in Fig. (1). It was observed that the moisture content of the product was reduced at a faster rate during the initial drying period. The moisture content curves were complex in nature. The rate of moisture loss was higher with an increase in drying air temperature, causing a reduction in drying time to attain a particular level of moisture content. The faster moisture vaporization at higher temperatures was due to an increase of vapor pressure with the product at an elevated temperature level. In addition to this, the relative humidity of drying air also decreases with an increase in temperature, causing an increased moisture removal rate. The equilibrium moisture content of the cardamom capsules within the temperature was 50-80°C were 6.29-8.75 kg/kg dry matter. With an increase in drying air temperature, the relative humidity of drying air was decreased. Low temperature at higher temperatures was able to reduce the equilibrium moisture content to a lower level. The time taken to attend a particular moisture content was decreased by 16.4% and 11.2% when the drying temperature was increased from 50 to 60°C and 60 to 70°C, respectively.

Fig.1: Plot of moisture ratio and time of large cardamom at different temperatures
3.2. Fitting of drying model for drying of large cardamom

The drying constants, root mean square error (RMSE), reduced chi-square value ($\chi^2$) and coefficient of determination ($R^2$) were calculated for all the nine models at 50, 60, 70, and 80°C. The obtained values of $R^2$ and $\chi^2$ and RMSE for different models are presented in Table (2). The most suitable model capable of predicting the drying of large cardamom was selected based on the highest $R^2$ and lowest RMSE and $\chi^2$ values.

Fitting moisture ratio data in Newton model within the temperature range of 50-80°C had the $R^2$, $\chi^2$ and RMSE values of 0.952-0.987, 0.003-0.021, and 0.03-0.06 respectively. The $k$ value for newton model was found to increase from 0.0036 to 0.01108 with an increase of temperature from 50-80°C. Moisture ratio data fitting in the 50-80°C temperature range for Page model had the $R^2$, $\chi^2$ and RMSE values of 0.971-0.994, 0.0106-0.0314, and 0.0190-0.0249 respectively. The $k$ value for the Page model was found to rise from 0.0007 to 0.0483 with a temperature increase from 50-80°C. Moisture ratio results fitting in the Modified Page model within the 50-80°C temperature range resulted in the $R^2$, $\chi^2$ and RMSE values of 0.951-0.994, 0.0104-0.0260, and 0.0190-0.0249 respectively. The $k$ value for Modified Page model was found to rise from 0.00359 to 0.01243, with a temperature increase from 50-80°C. Fitting of moisture ratio data in Henderson and Pabis model within the temperature range of 50-80°C had the $R^2$, $\chi^2$, and RMSE values of 0.960-0.991, 0.0106-0.0213, and 0.0238-0.0520 respectively. The $k$ value for Henderson and Pabis model was found to increase from 0.00379 to 0.01001 with an increase of temperature from 50-80°C. Moisture ratio fitting of the Logarithmic model fitting within the 50-80°C temperature range had $R^2$, $\chi^2$, and RMSE values of 0.9621-0.9916, 0.0019-0.0203, and 0.0231-0.0432, respectively. The $k$ value for the Logarithmic model was observed to increase from 0.00214 to 0.01326 with temperature increase from 50-80°C. Fitting of moisture ratio data in Verma et al. model within the temperature range of 50-80°C had the $R^2$, $\chi^2$ and RMSE values of 0.9541-0.9972, 0.0106-0.0211, and 0.0133-0.0409 respectively. The $k$ value for Verma et al. model was found to increase from 0.00392 to 0.00779 with an increase of temperature from 50-80°C. Fitting of moisture ratio data in Wang and Singh model within the temperature range of 50-80°C had the $R^2$, $\chi^2$ and RMSE values of 0.873-0.984, 0.0097-0.0227, and 0.0215-0.1937 respectively. The $k$ value for Wang and Singh model was found to increase from 0.00277 to 0.00768 with an increase of temperature from 50-80°C. Fitting of moisture ratio data in the two-term exponential model within the temperature range of 50-80°C had the $R^2$, $\chi^2$ and RMSE values of 0.7593-0.9967, 0.0015-0.0176, and 0.0150-0.1371 respectively. The $k$ value for the two-term exponential model was found to increase from 0.00523 to 0.0478 with an increase of temperature from 50-80°C.

| Table 2: Drying kinetics parameters of convective drying of large cardamom |
|-----------------------------|--------|-------------------|--------|--------|
| Drying models              | Temperature | Parameters      | $R^2$  | $\chi^2$ | RMSE  |
| Newton                      | 50      | $k = 0.0036$     | 0.9738 | 0.0022  | 0.0474 |
|                             | 60      | $k = 0.00602$    | 0.9872 | 0.0109  | 0.0305 |
|                             | 70      | $k = 0.00809$    | 0.9752 | 0.0218  | 0.0426 |
|                             | 80      | $k = 0.01108$    | 0.9526 | 0.0036  | 0.0600 |
| Page                        | 50      | $k = 0.000724703$| 0.9831 | 0.0106  | 0.0236 |
|                             | 60      | $k = 0.01255$    | 0.9847 | 0.0204  | 0.0190 |
|                             | 70      | $k = 0.02433$    | 0.9946 | 0.0314  | 0.0191 |
|                             | 80      | $k = 0.0483$     | 0.9710 | 0.0107  | 0.0249 |
| Modified page               | 50      | $k = 0.00359$    | 0.9731 | 0.0260  | 0.0236 |
|                             | 60      | $k = 0.00618$    | 0.9947 | 0.0116  | 0.0190 |
| Henderson and Pabis | Logarithmic | Verma et al. | Wang & Singh | Two term |
|--------------------|------------|-------------|-------------|----------|
| 70                 | 50         | 50          | 50          | 50       |
| $k = 0.00862$      | $c = -0.36734$ | $a = 1.08004$ | $b = 0.00277$ | $k_0 = 0.00392$ |
| $n = 0.78309$      | $k = 0.00608$ | $k = 0.00532$ | $a = -0.00477$ | $k_1 = 1.9681$ |
| $k = 0.01243$      | $a = 0.93017$ | $a = 0.89145$ | $a = -0.00584$ | $a = 1.08006$ |
| $n = 0.69176$      | $c = 0.02483$ | $g = 2.2$    | $b = 0.00000196201$ | $b = -0.08006$ |
| $k = 0.00379$      | $k = 0.00887$ | $g = 2.2$    | $a = 0.994643$ | $k_0 = 0.0053$ |
| $a = 1.049$        | $a = 0.9006$ | $a = 0.82127$ | $a = 0.87654$ | $k_1 = 0.10317$ |
|                    | $c = 0.05042$ | $g = 2.2$    | $c = 0.07347$ | $a = 0.8878$ |
|                    | $k = 0.01326$ | $k = 0.00779$ | $k = 0.00392$ | $b = 0.11226$ |
|                    | $a = 0.9821$ | $a = 0.9510$ | $a = 0.91298$ | $b = 0.00000630586$ |
|                    | $k = 0.01001$ | $k = 0.0106$ | $k = 0.00214$ | $b = 0.00000901659$ |
|                    | $a = 0.92707$ | $a = 0.9916$ | $a = 1.36948$ | $b = 0.0000154222$ |
|                    | $k = 0.00746$ | $k = 0.9510$ | $c = -0.36734$ | $k_0 = 0.00392$ |
|                    | $n = 0.9646$ | $k = 0.9968$ | $k = 0.00532$ | $k_1 = 1.9681$ |
|                    | $0.0104$    | $0.0120$    | $a = 1.049$  | $a = 1.08006$ |
|                    | $0.0191$    | $0.0435$    | $k = 0.00862$ | $b = -0.08006$ |
|                    | 0.9646     | 0.9767     | $n = 0.78309$ | $k_0 = 0.0053$ |
|                    | 0.9510     | 0.9916     | $k = 0.01243$ | $k_1 = 0.10317$ |
|                    | 0.0107     | 0.0106     | $n = 0.69176$ | $a = 1.08006$ |
|                    | 0.0249     | 0.0238     | $k = 0.00379$ | $b = -0.08006$ |
|                    | 0.9608     | 0.9608     | $a = 1.049$  | $k_0 = 0.00392$ |
|                    | 0.0130     | 0.0130     | $k = 0.01001$ | $k_1 = 0.10317$ |
|                    | 0.0520     | 0.0520     | $a = 1.049$  | $b = 0.11226$ |
|                    | 0.9621     | 0.9621     | $n = 0.9646$ | $0.9608$ |
|                    | 0.0107     | 0.0107     | $0.0120$    | 0.9968$ |
|                    | 0.0246     | 0.0246     | $0.0435$    | 0.9968$ |
|                    | 0.9821     | 0.9821     | $k = 0.00746$ | $0.9968$ |
|                    | 0.0213     | 0.0213     | $0.0120$    | 0.9968$ |
|                    | 0.0349     | 0.0349     | $0.0435$    | 0.9968$ |
|                    | 0.9916     | 0.9916     | $k = 0.01001$ | $0.9968$ |
|                    | 0.0130     | 0.0130     | $k = 0.00746$ | $0.9968$ |
|                    | 0.0520     | 0.0520     | $a = 1.049$  | $0.9968$ |
|                    | 0.9608     | 0.9608     | $k = 0.01001$ | $0.9968$ |
|                    | 0.0130     | 0.0130     | $k = 0.00746$ | $0.9968$ |
|                    | 0.0520     | 0.0520     | $a = 1.049$  | $0.9968$ |
|                    | 0.9608     | 0.9608     | $k = 0.01001$ | $0.9968$ |
|                    | 0.0130     | 0.0130     | $k = 0.00746$ | $0.9968$ |
|                    | 0.0520     | 0.0520     | $a = 1.049$  | $0.9968$ |
Among the different models discussed, two-term model had a most significant fitting of data in terms of average $R^2$ (0.998) and $\chi^2$ (1.17×10$^{-3}$) values and hence proposed as the best model describing the drying behavior of large cardamom. Fitting of moisture ratio data in two-term model within the temperature range of 50-80°C had the $R^2$, $\chi^2$ and RMSE values of 0.9936-0.9970, 0.0002-0.20, and 0.0039-0.0188 respectively. It was observed that among the four drying constants of two-term model, ‘$k_0$’ and ‘$b$’ increased with temperature while ‘$k_1$’ and ‘$a$’ decreased with temperature. The ‘$k_0$’ and ‘$b$’ value for the two-term model was found to increase in the range of 0.00392-0.00764 respectivly whereas the ‘$k_1$’ and ‘$a$’ value was found to decrease in the range of 1.9681-0.00764 and 1.08006-0.70558 with the increase of temperature from 50-80°C.

### 3.3. Effective moisture diffusivity for drying of large cardamom

Predicted moisture ratios were plotted against time at different temperatures as 50, 60, 70, and 80°C to obtain the effective moisture diffusivity. From the respective slope, moisture diffusivity values were determined using Eqns. (6 and 7). The highest effective diffusivity ($D_{eff}$) value of 3.898×10$^{-10}$ was obtained at drying temperature 80°C while the lowest value of 1.949×10$^{-10}$ at 50°C (Table 3). The diffusivity for drying of different food was found to be in the same range as obtained for the convective drying of large cardamom. Effective diffusivity in the temperature range of 50-120°C for rough rice and brown rice with the moisture content of 15% (db) was observed to be 1.3×10$^{-10}$ - 3.2×10$^{-9}$ and 4.5×10$^{-10}$ - 3.9×10$^{-9}$ m$^2$.s$^{-1}$ respectively (Bakshi and Singh, 1980). Drying analyses of two types of millet i.e. SOSAT C88 and EXBORNO with an initial moisture content of 31.6±1% (wb) and 22.75±2.25% (wb) was conducted at drying temperatures of 40, 50, 60, and 70°C. The effective moisture diffusivity within the temperature range of 40-70°C was increased and the obtained values were in the range of 2.86×10$^{-9}$ – 5.27×10$^{-9}$ and 1.17×10$^{-9}$ – 2.98×10$^{-9}$ m$^2$.s$^{-1}$ respectively (Ojediran and Raji, 2010). A study of effective diffusivity of barley grain assuming the shape of the grain as spherical geometry showed that the diffusivity was varied in the range of 1.99 ×10$^{-11}$ - 5.31 ×10$^{-11}$ m$^2$.s$^{-1}$ (Markowski et al., 2010). The hot air drying and vacuum drying of bee pollen within the temperature range of 40-50°C revealed that the two-term model was the most suitable model to predict the moisture ratio values. The effective moisture diffusivity values for drying bee pollen were varied between 8.40×10$^{-11}$ - 6.29×10$^{-10}$ m$^2$.s$^{-1}$ (Kayacan et al., 2018). The moisture diffusivity of red pepper was studied under three drying conditions such as hot air drying (HAD), infrared-assisted hot air drying (IAHD), and pulsed vacuum drying (PVD). The diffusivity values for HAD, IAHD, and PVD were varied between 1.33 –5.83 ×10$^{-10}$, 1.38–6.87×10$^{-10}$, and 1.75–8.97×10$^{-10}$ m$^2$.s$^{-1}$, respectively (Deng et al., 2018).
Table 3: Effective moisture diffusivities of black cardamom capsule at different temperatures

| Temperature | $D_{eff}$ | Ln $D_{eff}$ | $R^2$ | Chi Square |
|-------------|-----------|--------------|-------|------------|
| 50°C        | 1.949×10^{-10} | -22.3583     | 0.866 | 0.0281     |
| 60°C        | 2.729×10^{-10} | -22.0219     | 0.913 | 0.0763     |
| 70°C        | 3.508×10^{-10} | -21.7706     | 0.953 | 0.0459     |
| 80°C        | 3.898×10^{-10} | -21.6652     | 0.959 | 0.0174     |

3.4. Activation energy for drying of large cardamom

In order to determine the pre-exponential component ($D_o$) and activation energy ($E_a$) of the Arrhenius equation (Eqns. 8-9), the logarithm of effective moisture diffusivities ($D_{eff}$) was plotted against the reciprocal of absolute temperature (Fig. 2). From the intercept of linear fit equation (Eqn. 2), the value of $D_o$ for large cardamom was evaluated as 7.61×10^{-4} m^2 s^{-1} and the value of $E_a$ was found to be 32.55 kJ.mol^{-1}.

$$D_{eff} = \left(7.61 \times 10^{-4}\right) \exp\left(-\frac{32.55 \times 10^5}{RT}\right)$$  \hspace{1cm} (10)

The amount of energy barrier that has to overcome i.e., the threshold barrier to activate the diffusion of moisture is the activation energy and the estimated activation energy value was 32.55 kJ / mol. The activation energy can be decreased by increasing the temperature and the drying rate, but the product quality can be degraded. The drying of *Phyllanthus amarus* and *Phyllanthus niruri* showed that an activation energy values of 22.828 and 43.129 kJ/mol, respectively (Sousa et al., 2018). The obtained results are similar to the results obtained in the drying of various food products such as apple with activation energy value 19.96 – 22.62 kJ mol^{-1} (Teixeira and Tobinaga, 1998), carrot with activation energy value 22.43 kJ mol^{-1} (Togrul, 2006) and red pepper with activation energy value 24.76 kJ mol^{-1} (Kaleemullah and Kailappan, 2005).

3.5. Conclusion

The drying behavior of larger cardamom was applied to nine different models in the literature to establish the drying kinetic model for the drying of large fresh cardamom. The two-term model delivered the best results among these models and showed good agreement with the experimental data obtained from the experiments, including the thin layer drying process. When the effects of drying air temperature on the constants and coefficients of the two-term model were examined, the $R^2$, $\chi^2$ and RMSE values were found to be in the range of 0.9936-0.9970, 0.0002-0.020, and 0.0039-0.0188 respectively. Therefore, the two-term model adequately described the drying behavior of large cardamom in the drying process within the temperature range of 50-80°C. The effective diffusivities increased with the drying temperature and varied from 1.949×10^{-10} to 3.898×10^{-10} m^2/s. The temperature dependence of
diffusivity follows the Arrhenius relationship, and the activation energy for the diffusion of moisture was found to be 32.55 kJ/mol.

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