Defence Life Science Journal, Vol. 4, No. 2, April 2019, pp. 140-149, DOI : 10.14429/dlsj.4.12176
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# Mathematical Modelling the Drying Kinetics of Beetroot Strips during Convective Drying at Different Temperatures

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## ABSTRACT

The thin layer drying of beetroot strips was evaluated at drying temperatures from 60 °C to 90 °C using convective dryer at inlet air velocity of 1.0 m/s. The different drying models were tested to evaluate the drying characteristics of beetroot strips. The investigations showed that Page's and modified Page's equations were satisfactorily describing the drying behaviour of beetroot strips during convective drying with appreciable high correlation coefficient ($0.9971<r<0.9990$) with low error values. The effective moisture diffusivity was increased from 3.563 x $10^{-10}$ $m^2/s$ to 8.038 x $10^{-10}$ $m^2/s$ with increase in drying temperature. The temperature dependency of effective moisture diffusivity was described by Arrhenius equation and activation energy for moisture diffusivity was 30.08 KJ/mol. The drying kinetic coefficients were significantly ($p<0.05$) affected by drying air temperature. The exponents of models were decreased linearly with drying air temperature during drying of beetroot strips. The equilibrium moisture content was markedly affected by drying air temperature and it decreased linearly with drying air temperature. The results were very useful in standardisation and optimisation of drying process of beetroot strips in large scale commercial production.

**Key words:** Beetroot strips; *Beta vulgaris* L.; Convective drying; Drying models; Arrhenius equation; Effective moisture diffusivity; Activation energy.

## NOMENCLATURE

| | |
|---|---|
| MR | Moisture ratio |
| $m$ | moisture content at time $t$ (db) |
| $m_0$ | initial moisture content (db) |
| $m_e$ | equilibrium moisture content (db) |
| $MR_{expt}$ | Experimental moisture ratio |
| $MR_{pred}$ | predicted moisture ratio |
| $N$ | number of data sets |
| $n$ | number of constants of the model equation |
| $D\ K\ P$ | Drying kinetic parameter |
| $T$ | Temperature (K) |
| $k_P$ | Page's kinetic coefficient |
| $k_{MP}$ | modified Page's kinetic coefficient |
| $D_{eff}$ | Effective moisture diffusivity |
| $t$ | Drying time |
| $L$ | thickness of the material |
| $D_0$ | pre-exponential coefficient/frequency factor |
| $E_a$ | Activation energy |
| $R$ | universal gas constant |

## 1. INTRODUCTION

Drying is a one of most important technique in preservation of food and agricultural products. Drying of agricultural raw materials and their products as a means of improving storability has been practiced for centuries. The dried products can keep for several day compared to that of fresh produce which is having a shelf life of few days at ambient conditions. Dried products can be stored for months and even a year without appreciable change in nutrition as well as sensory characteristics. Drying is a complex process, which involves simultaneous phenomena such as transient heat, mass and momentum transfer; it is accompanied by several chemical and bio-chemical changes and physico-chemical transformations. The macroscopic and microscopic changes during drying have been described using drying kinetics by evaluating heat and mass transfer coefficients. The understanding of drying operation and mechanism is of great practical and economic importance in development of better quality dried products. An understanding of basic fundamental mechanism of drying process, which includes knowledge of moisture and temperature distribution within the product and its thermophysical properties are crucial for process design, standardisation and optimisation. It is also important in quality control, product handling and energy savings[1-2].

The mathematical modelling of food processing unit operations is very much useful in design of equipment, designing, standardisation and optimisation of processing. Several complex theoretical models to describe the heat and mass transfer phenomena during drying of food and agricultural raw material and their products are available in literature. The mathematical models are classified as theoretical, semi-

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Received : 25 October 2017, Revised : 26 February 2019
Accepted : 05 March 2019, Online published : 11 April 2019

**Table 1. Drying model equations**

| Model No. | Model name | Model equation |
|---|---|---|
| 1 | Newton (Lewis )[18] | $MR = Exp(-k\ t)$ |
| 2 | Page[19] | $MR = Exp\ (-k\ t^n)$ |
| 3 | Modified Page[20] | $MR = Exp\ (-k\ t)^n$ |
| 4 | Henderson & Pebis[21] | $MR = a\ Exp(-k\ t)$ |
| 5 | Logarithmic[22] | $MR = a\ Exp(-k\ t) + b$ |
| 6 | Two term[23] | $MR = a\ Exp\ (-k_0 t) + b\ Exp\ (k_1 t)$ |
| 7 | Wang & Singh[24] | $MR = 1 + at + bt^2$ |
| 8 | Two term exponential[22] | $MR = a\ Exp\ (-k\ t) + (1-a)\ Exp\ (-k\ a\ t)$ |
| 9 | Approximation of diffusion[25] | $MR = a\ Exp\ (-k\ t) + (1-a)\ Exp\ (-k\ b\ t)$ |
| 10 | Verma[26], *et al.* | $MR = a\ Exp\ (-k\ t) + (1-a)\ exp\ (-g\ t)$ |
| 11 | Midilli[27], *et al.* | $MR = a\ Exp(-k\ t) + b\ t$ |
| 12 | Demir[28], *et al.* | $MR = a\ Exp(-k\ t)^n + b$ |
| 13 | Modified Henderson & Pebis[29] | $MR = a\ Exp\ (-k\ t) + b\ Exp\ (-g\ t) + c\ Exp\ (-h\ t)$ |
| 14 | Aghbashlo[30], *et al.* | $MR = Exp\ (-k_1\ t/\ (1 + k_2\ t))$ |
| 15 | Thompson[31] | $t = a\ Ln\ (MR) + b\ (Ln\ (MR))^2$ |
| 16 | Geometric | $MR= a\ t^{-n}$ |

theoretical and empirical models[3-4]. These mathematical models in drying are widely used for designing of new equipments, modification of existing drying equipments, controlling of the process[5-6].

Beetroot is an important vegetable crop available throughout the world. Beetroot or red beet is a potential source of betalains which consists of two main group's betacyanin which is red in colour and betaxanthin which is yellow in colour. Beetroot contains several bioactive compounds namely betalains, carotenoids, saponins, glycine betain, folates, polyphenols and flavonoids which have properties like free radical scavenging properties[7-9].

Dehydration of red beet (*Beta vulgaris*) by hot air drying and process optimisation was investigated. The results indicated that better drying conditions required sequential reduction of drying air temperature from 120 °C to 50 °C resulting in good color retention[10]. Drying kinetics and quality characteristics of beetroot cubes was evaluated during convective and vacuum-microwave drying[11-12]. Optimisation of convective dehydration of beetroot for color retention was investigated[13]. However, there is no information on drying kinetics of beetroot strips during convective drying which is very important for development of process conditions and optimisation of development of dried products from beetroot. The present investigation was undertaken to study the drying kinetics of beetroot strips during convective drying at different drying temperatures.

## 2. MATERIAL AND METHODS

### 2.1 Raw Material

Fresh beetroot (variety: Ooty 1) was procured from local market Mysore, India and washed thoroughly with water. The peeling of beetroot was carried out using abrasive peeler (Continental India Ltd, New Delhi, India). The beetroot strips of size 6 mm x 6 mm x 60 mm were diced using dicer (Urschel; Model: G 1656, Urschel laboratories Inc, Valparaiso, USA). The beetroot strips were steam blanched at a pressure of 15 Psi for one minute using pressure cooker for inactivation of enzymes. The blanched material was cooled to room temperature and subjected for drying.

### 2.2 Drying

Drying was carried out using cabinet drier (Model: SDA, Kilburns, Macneill and Magor Limited, Bombay, India) at air velocity of 1.0 m/s at tray load of 3.125 kg/m$^2$ at different air temperatures 60 °C, 70 °C, 80 °C and 90 °C. The beetroot strips were spread equally across the tray and drying was carried out at different drying temperatures. The representative samples were drawn at different intervals for moisture estimation.

### 2.3 Moisture

Moisture content of beetroot strips was estimated gravimetrically by hot air oven method as described by Ranganna[14].

### 2.4 Mathematical Modelling

Mathematical models represent the drying phenomenon of these materials which can be categorised into three groups such as empirical, theoretical and semi-theoretical models, assuming that material is homogenous isotropic in nature and resistance to moisture transfer resistance is uniform inside the material and the diffusion coefficient, volume shrinkage during drying is negligible. The diffusion coefficient (*D*) is evaluated using the Fick's second law of diffusion and is described as

$$\frac{\partial M}{\partial t} = D\ \nabla^2 M \tag{1}$$

The analytical solution of Eqn. (1) was given by Crank[15] for various shapes of the materials, such as rectangular, cylindrical and spherical bodies. Drying of many food products have been successfully explained using Fick's second law of diffusion with Arrhenius type equation for temperature dependency of diffusion coefficient.

The Fick's second law of diffusion equation has been used in dehydration of food materials (Eqn. (1)). Drying of several food products has been successfully predicted using Fick's second law of diffusion with Arrhenius-type temperature dependent moisture diffusivity[16-17]. Empirical models derive a direct relationship between average moisture content and drying time at different drying conditions. Sixteen different drying models, (Table 1) namely, theoretical, semi theoretical and empirical models were taken to study the drying behaviour of beetroot strips at different drying temperatures[18-31]. The moisture ratio (MR) of beetroot strips during drying was calculated using the following equation

$$MR = \frac{m - m_e}{m_0 - m_e} \tag{2}$$

The suitability of the model was evaluated based on correlation coefficient ($r$) and mean error values, viz Chi square ($\chi^2$), Mean bias error (MBE) and Root mean square error (RMSE) values which were evaluated by following equations

$$\textit{Chi sqaure } (\chi^2) = \sum_{i=1}^{n} \frac{(MR_{\mathrm{e}xpti} - MR_{predi})^2}{(N - n)}$$

$$\textit{Mean bias error (MBE)} = \frac{1}{N} \sum_{i=1}^{n} (MR_{\mathrm{e}xpt\ i} - MR_{pred\ i}) \tag{3}$$

$$\textit{Root mean square error } (RMSE)$$

$$= \left[ \frac{1}{N} \sum_{i=1}^{n} (MR_{\mathrm{e}xpti} - MR_{predi})^2 \right]^{\frac{1}{2}}$$

Suitability of the model was evaluated by high correlation coefficient and low error values.

### 2.5 Drying Rate

Drying rate was calculated using the following equation as described[51].

$$\textit{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \tag{4}$$

where $M_t$ and $M_{t+dt}$ are the moisture contents of beetroot strips at time $t$ and $t+dt$ respectively, $dt$ is the drying time interval.

### 2.6 Statistical Analysis

The data analysis, curve fitting and other statistical analysis were carried out using statistical software (Statistica 7.0, Stat Soft Tulsa, USA). The fitting and estimates were calculated at 95 per cent confidence level ($p<0.05$).

## 3. RESULTS AND DISCUSSION

### 3.1 Drying Characteristics

The initial moisture content of beetroot strips was 8.58 kg/kg solids db (89.56 % wb) and it reduced to value of 0.064, 0.045, 0.031 and 0.012 at different drying air temperatures of 60 °C, 70 °C, 80 °C and 90 °C respectively during convective drying of beetroot strips. The variation of moisture content with time during convective drying of beetroot strips at different drying air temperatures is reported in Fig. 1. The moisture loss was high during initial drying process followed by decrease in moisture loss and the process was pronounced at higher drying air temperature. The variation of drying rate with drying time during convective drying of beetroot strips at different drying air temperatures is reported in Fig. 2. The drying rate increased from 3.177 kg to 5.211 kg moisture per kg solid per hour with increase in drying temperature from 60 °C to 90 °C at one hour of drying. This showed that during drying the moisture diffusion is mainly by physical mechanism in beetroot strips. Amount of moisture loss depends on drying time as well as drying air temperature. Variation of drying rate with moisture content during convective drying of beetroot strips at different drying air temperatures is reported in Fig. 3. The rate of drying reduces from 7.161 kg moisture per kg solids per hour to 0.0091 kg moisture per kg solids per hour at the end of drying at drying temperature of 90 °C. Similar results were observed with lower drying rates at lower temperatures of drying.

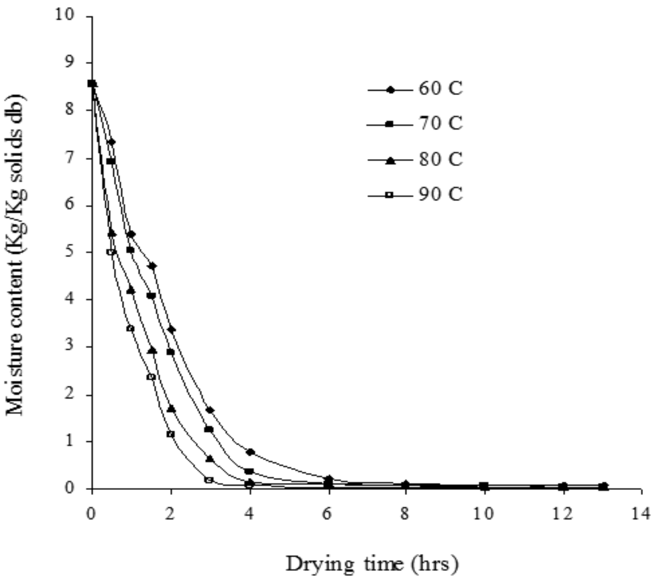

**Figure 1. Variation of moisture content with time during convective drying of beetroot strips at different drying air temperatures.**

The relative humidity of drying air is low at higher drying air temperatures compared to that at low drying air temperatures. Due to this, the difference in partial vapour pressure of beetroot strips and surrounding air is high at higher drying air temperature environment. Hence moisture transfer rate was high at higher drying air temperatures. The figures showed that drying took place at falling rate period. Similar type of falling rate period drying behaviour was observed for different agricultural produces[10,32-34]. The drying rate was significantly affected by air temperature and air velocity during drying of black tea[32]. The drying air temperature, drying air velocity and relative humidity of air significantly affected the drying characteristics of apricots during solar drying[34]. Beltagy[35] et al. reported that the drying constant was markedly affected by product surface area, drying temperature and ratio of projected surface area to product of strawberries during solar forced drying and the required drying time was dependent on shape/size of the product.

The drying air temperature is the main factor that influences the drying behaviour of prickly pear fruit and drying rate increased with higher drying air temperature and higher air flow rate[36]. The drying air temperature, air velocity and slice thickness of carrot markedly affect the drying characteristics of carrot slices and process condition was satisfactorily described by using artificial neural network method. A single equation was proposed for drying kinetic parameters of carrot during

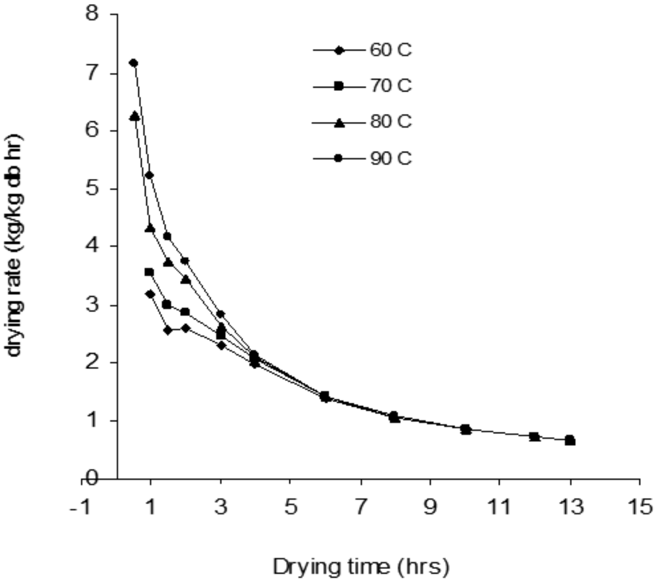

**Figure 2. Variation of drying rate with time during convective drying of beetroot strips at different drying air temperatures.**

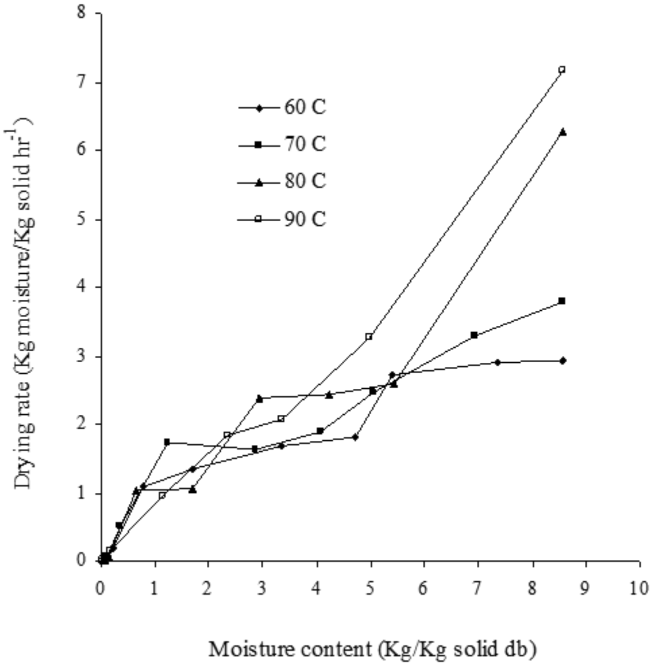

**Figure 3. Variation of drying rate with moisture content during convective drying of beetroot strips at different drying air temperatures.**

different drying conditions[37]. Drying rate of carrot depends on air velocity, air temperature and nature of the sample[38]. It was concluded that drying rate was markedly affected by drying air temperature, velocity and relative humidity of air, processing conditions, pretreatments, initial moisture content, product shape and size.

## 3.2 Drying Kinetics

The drying behaviour of beetroot strips at different drying air temperatures was modelled with different theoretical, semi-theoretical and empirical models as mentioned in Table 1 by method of least square approximation. The suitability of model was evaluated based on higher correlation coefficient (*r*) and lower error (Chi square ($\chi^2$), mean bias error (MBE) and root mean square error (RMSE)) values as reported in Eqn. (3) and shown in Table 2, and Table 3, respectively. The Page's and modified Page's equations were suitable to describe the drying behaviour of beetroot strips at different drying air temperatures during convective drying due to higher correlation coefficient (*r*) and low error values. The models parameters of Page's and modified Page's equations were reported in Table 4 and drying rate (*k*) of both the models increased significantly ($p<0.05$) with increase in drying air temperature and as a result, the moisture loss is high at higher temperatures of drying. The exponent (*n*) decreased significantly ($p<0.05$) from 1.276 to 0.983 with increase in drying air temperature. This indicated the variation of moisture loss dependent on drying temperature. Similar type of results were reported for products[39,40]. The drying constant (k) of Page's equation was increased with microwave power level whereas the exponent (*n*) had no specific trend with power level of microwave energy during microwave drying of spinach[41]. The drying rate was significantly influenced by infrared power, air temperature and air velocity during infrared drying of onion slices[42]. The slice thickness and drying temperature are most affecting factors compare to that relative humidity and velocity of air on drying rate during dehydration of garlic slices[43]. Similar result was observed in present investigation for variation drying temperature during drying of beetroot strips. The magnitude of drying rate depends on nature of product, its moisture content, drying conditions which include drying air temperature, air velocity, amount of air mass flow, relative humidity of air, pre-treatments, product shape, size, etc.

## 3.3 Effect of Drying Air Temperature on Kinetic Parameters

The drying kinetic parameters were significantly affected by drying air temperature. The drying rate constants of Page's and modified Page's model increased significantly ($p<0.05$) from 0.400 $h^{-1}$ to 0.981 $h^{-1}$ and 0.488 $h^{-1}$ to 0.980 $h^{-1}$, respectively whereas the exponent (*n*) significantly ($p<0.05$) decreased from 1.276 to 0.983 with increase in drying air temperature during convective drying of beetroot strips at different drying temperatures as reported in Table 6. The equilibrium moisture content ($M_{eq}$) is markedly decreased from 0.0644 kg/kg to 0.0122 kg/kg solids db with increase in drying air temperature from 60 °C to 90 °C during convective drying of beetroot strips. The drying air temperature had significant effect on drying kinetic parameters of drying models. Several researchers suggested different empirical equation relating drying kinetics parameters with drying air temperature[1,32,34-37] and different empirical equations are:

Linear equation : $DKP = a+b\,T$
Quadratic equation : $DKP = a+b\,T + c\,T^2$
Exponential equation : $DKP = a\,Exp(b\,T)$
Power law equation : $DKP = a\,(T)^b$ (5)

where DKP is the drying kinetic parameter, *T* is the absolute temperature in Kelvin (K), *a, b* and *c* are empirical constants. The parameters of the above model equation with drying kinetic parameters such as equilibrium moisture content ($M_{eq}$), drying

**Table 2. Coefficient of correlation (r) and Chi square ($\chi^2$) values of different models at different drying temperatures of beetroot strips during convective drying**

| Model no | Model name | Coefficient of correlation (r) | | | | Chi square ($\chi^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 60 °C | 70 °C | 80 °C | 90 °C | 60 °C | 70 °C | 80 °C | 90 °C |
| 1 | Newton (Lewis )[18] | 0.9943 | 0.9955 | 0.9970 | 0.9979 | 0.001519 | 0.001148 | 0.000537 | 0.000451 |
| 2 | Page [19] | 0.9988 | 0.9990 | 0.9975 | 0.9980 | 0.000363 | 0.000283 | 0.000446 | 0.000439 |
| 3 | Modified Page [20] | 0.9988 | 0.9990 | 0.9975 | 0.9980 | 0.000363 | 0.000283 | 0.000446 | 0.000439 |
| 4 | Henderson & Pebis[21] | 0.9955 | 0.9961 | 0.9971 | 0.9975 | 0.001325 | 0.001072 | 0.000583 | 0.000457 |
| 5 | Logarithmic[22] | 0.9960 | 0.9966 | 0.9970 | 0.9977 | 0.001187 | 0.000939 | 0.000564 | 0.000469 |
| 6 | Two term[23] | 0.9955 | 0.9961 | 0.9972 | 0.9972 | 0.001325 | 0.001072 | 0.000583 | 0.000477 |
| 7 | Wang & Singh[24] | 0.9520 | 0.9228 | 0.7960 | 0.6733 | 0.013727 | 0.020685 | 0.042772 | 0.060077 |
| 8 | Two term exponential[22] | 0.9986 | 0.9988 | 0.9970 | 0.9972 | 0.000383 | 0.000295 | 0.000514 | 0.000446 |
| 9 | Approximation of diffusion[25] | 0.9962 | 0.9989 | 0.9969 | 0.9973 | 0.001003 | 0.000301 | 0.000466 | 0.000472 |
| 10 | Verma[26], *et al.* | 0.9962 | 0.9975 | 0.9968 | 0.9972 | 0.001003 | 0.000640 | 0.000466 | 0.000472 |
| 11 | Midilli[27], *et al.* | 0.9957 | 0.9963 | 0.9969 | 0.9970 | 0.001147 | 0.000967 | 0.000959 | 0.000527 |
| 12 | Demir [28], *et al.* | 0.9911 | 0.9920 | 0.9960 | 0.9971 | 0.004107 | 0.003464 | 0.001321 | 0.000629 |
| 13 | Modified Henderson & Pebis[29] | 0.9921 | 0.9962 | 0.9971 | 0.9973 | 0.001893 | 0.001531 | 0.000833 | 0.000625 |
| 14 | Aghbashlo[30], *et al.* | 0.9870 | 0.9892 | 0.9959 | 0.9973 | 0.005977 | 0.004511 | 0.001395 | 0.0001651 |
| 15 | Thompson[31] | 0.9948 | 0.9854 | 0.9869 | 0.9798 | 0.247853 | 0.693571 | 0.623294 | 0.9541657 |
| 16 | Geometric | 0.9357 | 0.9463 | 0.9568 | 0.9741 | 1.095192 | 1.058350 | 0.674101 | 0.414147 |

rates of Page's ($k_p$), modified Page's ($k_{MP}$) and exponent ($n$) were evaluated using method of least square approximation. Suitability of the model was decided based on correlation coefficient ($r$) and level of significance ($p<0.05$). The parameters of the models equation and correlation coefficients of models were reported in Table 5. The results indicated that the equilibrium moisture content ($M_{eq}$) decreased linearly with increase in drying air temperature since the correlation coefficient is high compared to that of other models. The suggested model equation can be represented as

$$M_{eq} = 0.6323-0.0017\,T, \qquad (r = 0.9978, p < 0.01)$$

At higher temperatures of drying the relative humidity of drying air is less compared to that of low temperature drying. Due to this phenomenon, the difference in partial pressure between beetroot strips and surroundings at higher temperatures of drying is large compared to that at low temperatures of drying. This leads to more moisture migration from material to surroundings which reduces the equilibrium moisture content at higher drying air temperatures. The extent of moisture removal is markedly dependent on drying temperature. The equilibrium moisture content is decreased linearly with drying air temperature. The equilibrium moisture content of spent grains namely, brewers' spent grains and distillers' spent grains are markedly affected by steam temperature and exponential relation was proposed[44].

Kinetic rate constants of Page's ($k_p$) and modified Page's ($k_{MP}$) equation were increased significantly ($p<0.05$) with increase in drying air temperature and reported in Table 6. The variation of rate constant of Page's and modified Page's equation with drying air temperature was modelled using different models (Eqn. (5)). The model parameters were reported in Table 5. The power law relation satisfactorily described the variation in rate constant with drying air temperature during convective drying of beetroot strips since the correlation coefficient is high and it is significant ($p<0.001$). The suggested model equations are

$$k_p = 2.632\ \mathrm{X}\ 10^{-28}\ (\mathrm{T})^{10.929}, \qquad (r = 0.9889, p < 0.001)$$

$$k_{MP} = 7.546\ \mathrm{X}\ 10^{-23}\ (T)^{8.658}, \qquad (r = 0.9928, p < 0.001)$$

where $k_p$ and $k_{MP}$ are the drying constants of Page's and modified Page's equation in hr$^{-1}$ and $T$ is absolute temperature in Kelvin (K). This indicated that the variation of kinetic rate constant

**Table 3. Mean bias error (MBE) and Root mean square error (RMSE) values of different models at different drying temperatures of beetroot strips during convective drying**

| Model no | Model name | Mean bias error (MBE) | | | | Root mean square error (RMSE) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 60 °C | 70 °C | 80 °C | 90 °C | 60 °C | 70 °C | 80 °C | 90 °C |
| 1 | Newton (Lewis )[18] | 0.0262 | 0.0226 | 0.0152 | 0.0136 | 0.0107 | 0.0094 | 0.0073 | 0.0065 |
| 2 | Page[19] | 0.0102 | 0.0103 | 0.0148 | 0.0127 | 0.0050 | 0.0044 | 0.0063 | 0.0045 |
| 3 | Modified Page[20] | 0.0102 | 0.0103 | 0.0148 | 0.0127 | 0.0050 | 0.0044 | 0.0063 | 0.0045 |
| 4 | Henderson & Pebis[21] | 0.0254 | 0.0222 | 0.0156 | 0.0131 | 0.0096 | 0.0086 | 0.0073 | 0.0055 |
| 5 | Logarithmic[22] | 0.0257 | 0.0233 | 0.0172 | 0.0143 | 0.0091 | 0.0081 | 0.0072 | 0.0055 |
| 6 | Two term[23] | 0.0252 | 0.0222 | 0.0156 | 0.0131 | 0.0096 | 0.0086 | 0.0073 | 0.0056 |
| 7 | Wang & Singh[24] | 0.0918 | 0.1165 | 0.1683 | 0.1961 | 0.0309 | 0.0379 | 0.0545 | 0.0646 |
| 8 | Two term exponential[22] | 0.0112 | 0.0109 | 0.0151 | 0.0497 | 0.0053 | 0.0047 | 0.0072 | 0.0055 |
| 9 | Approximation of diffusion[25] | 0.0230 | 0.0109 | 0.0152 | 0.0132 | 0.0088 | 0.0048 | 0.0079 | 0.0053 |
| 10 | Verma[26], *et al.* | 0.0230 | 0.0191 | 0.0162 | 0.0133 | 0.0088 | 0.0077 | 0.0069 | 0.0054 |
| 11 | Midilli[27], *et al.* | 0.0256 | 0.0237 | 0.0164 | 0.0136 | 0.0093 | 0.0086 | 0.0069 | 0.0055 |
| 12 | Demir[28], *et al.* | 0.0375 | 0.0352 | 0.0185 | 0.0131 | 0.0129 | 0.0119 | 0.0074 | 0.0051 |
| 13 | Modified Henderson & Pebis[29] | 0.0232 | 0.0205 | 0.0154 | 0.0488 | 0.0089 | 0.0080 | 0.0068 | 0.0049 |
| 14 | Aghbashlo[30], *et al.* | 0.0406 | 0.0355 | 0.0176 | 0.0137 | 0.0156 | 0.0136 | 0.0076 | 0.0052 |
| 15 | Thompson[31] | 0.2800 | 0.4785 | 0.3780 | 0.5428 | 0.1010 | 0.1695 | 0.1602 | 0.1982 |
| 16 | Geometric | 0.5767 | 0.5432 | 0.4168 | 0.3398 | 0.2125 | 0.2093 | 0.1671 | 0.1310 |

with temperature were in power law relation. The rate constant of Page's equation was increased linearly with increase in drying air temperature and decreased linearly with increase in relative humidity of drying air during low-temperature, low-relative humidity drying of rough rice[45]. Linear model was proposed for change in magnitude of drying constant of logarithmic drying model with drying air temperature, air velocity and relative humidity of air during solar drying of apricot in thin layers[34]. Linear model was proposed for rate constant with drying air temperature during drying thin-layer garlic slices[43]. Several authors proposed the exponential Arrhenius type equation for variation of drying constant of different models with drying air temperature of different agricultural product during drying[30,32,38]. The variation in the models may be due to nature of the product, drying conditions, moisture content, drying method, pre-treatments, product size and shape.

The exponent (n) of Page's and modified Page's equation decreased significantly with increase in drying air temperature as reported in Table 6. The variation of magnitude of exponent (n) of Page's and modified Page's equation with drying air temperature was modelled using different models (equation 5). The model parameters were reported in Table 7. The linear model is suitable to describe the variation of exponent of drying models with drying air temperature during convective drying of beetroot strips and suggested model equation represented as

$$n = 5.0187 - 0.0122\,T, \qquad (r = 0.9409,\ p < 0.05)$$

where $n$ is exponent of drying models (-), T is drying air temperature in Kelvin (K). The exponent of drying equations was decreased linearly with drying air temperature. The power law relation was reported for variation in magnitude of exponent of Page's equation with drying air temperature during infrared radiation drying of onion slices[42], where as exponential Arrhenius type relation was reported for drying carrot[37].

### 3.4 Calculation of Effective Moisture Diffusivity and Activation Energy

The moisture diffusion coefficient of beetroot strips was evaluated by the Fick's second law of diffusion as reported in Eqn. (1) and the solution of this equation for different type geometry was suggested[15]. The solution of Fick's second law for infinite slab is given by

$$MR = \frac{m - m_e}{m_0 - m_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2}\, Exp\left[\frac{-(2n+1)^2\, \pi^2\, D_{eff}\, t}{L^2}\right] \qquad (6)$$

**Table 4. Parameters of the Page's and modified Page's equation at different drying temperatures of beetroot strips**

| Model | Drying constant (k) ($hr^{-1}$) | | | | Exponent (n) (-) | | | |
|---|---|---|---|---|---|---|---|---|
| | 60 °C | 70 °C | 80 °C | 90 °C | 60 °C | 70 °C | 80 °C | 90 °C |
| Page's equation<br>MR = Exp ($-k_P\ t^n$) | $0.400^a \pm$ 0.004 | $0.490^b \pm$ 0.004 | $0.784^c \pm$ 0.011 | $0.981^d \pm$ 0.001 | $1.276^a \pm$ 0.002 | $1.245^b \pm$ 0.007 | $1.009^c \pm$ 0.017 | $0.983^d \pm$ 0.006 |
| Modified Page's equation<br>MR = Exp ($-k_{MP}\ t)^n$ | $0.488^a \pm$ 0.003 | $0.564^b \pm$ 0.002 | $0.786^c \pm$ 0.009 | $0.980^d \pm$ 0.001 | $1.276^a \pm$ 0.002 | $1.245^b \pm$ 0.007 | $1.009^c \pm$ 0.017 | $0.983^d \pm$ 0.006 |

Mean ± SD (n=3), Different superscripts in a row shows values are significantly different at $p<0.05$

**Table 5. Parameters of different models relating to equilibrium moisture content ($M_{eq}$), kinetic rate constants of Page's and modified Page's equation ($k_P$, and $k_{MP}$) and kinetic exponent coefficient (n) with drying air temperature during convective drying of beetroot strips**

| Model | Model parameters | | | r |
|---|---|---|---|---|
| | a | b | c | |
| $M_{eq}$=a + b T | $0.6323^{**}$ | $-0.0017^{**}$ | - | 0.9978 |
| $M_{eq}$=a + b T+ c $T^2$ | $0.8339^{ns}$ | $-0.00163^{ns}$ | $0.0000017^{ns}$ | 0.9980 |
| $M_{eq}$= a Exp (b T) | $1.425\ x10^{5ns}$ | $-0.0438^{*}$ | - | 0.9855 |
| $M_{eq}$= a $(T)^b$ | $7.513 \times 10^{36***}$ | $-15.070^{***}$ | - | 0.9802 |
| $k_P$= a + b T | $-6.4183^{*}$ | $0.0204^{*}$ | - | 0.9824 |
| $k_P$ =a + b T+ c $T^2$ | $25.943^{ns}$ | $-0.166^{ns}$ | $0.00027^{ns}$ | 0.9893 |
| $k_P$ = a Exp (b T) | $1.224 \times 10^{-5ns}$ | $0.0312^{*}$ | - | 0.9876 |
| $k_P$ = a $(T)^b$ | $2.632 \times 10^{-28***}$ | $10.929^{***}$ | - | 0.9889 |
| $k_{MP}$= a + b T | $-5.206^{*}$ | $0.0170^{*}$ | - | 0.9829 |
| $k_P$ =a + b T+ c $T^2$ | $30.696^{ns}$ | $-0.1896^{ns}$ | $0.00029^{ns}$ | 0.9949 |
| $k_P$ = a Exp (b T) | $1.243 \times 10^{-4ns}$ | $0.0247^{**}$ | - | 0.9931 |
| $k_P$ = a $(T)^b$ | $7.546 \times 10^{-23***}$ | $8.658^{***}$ | - | 0.9928 |
| n =a + b T | $5.0187^{*}$ | $-0.0112^{*}$ | - | 0.9409 |
| n =a + b T+ c $T^2$ | $6.3086^{ns}$ | $-0.0186^{ns}$ | $1.067 \times 10^{-5ns}$ | 0.9377 |
| n= a Exp (b T) | $35.27^{ns}$ | $-0.0099^{ns}$ | - | 0.9367 |
| n = a $(T)^b$ | $2.798 \times 10^{9ns}$ | $-3.429^{ns}$ | - | 0.9358 |

where MR is the moisture ratio, $D_{eff}$ is effective diffusivity in $m^2/s$, $t$ is time and $L$ is the thickness of the material and n is the positive integer. The above equation may be simplified by taking first term of the equation and calculate the effective moisture diffusivity by the method of least square approximation. The effective moisture diffusivity ($D_{eff}$) is markedly increased from $3.563 \times 10^{-10}$ $m^2/s$ to $8.038 \times 10^{-10}$ $m^2/s$ with increase in drying air temperature of beetroot strips during convective drying. Similar type of results have been reported for drying some agricultural products[39,46,47]. The magnitude of effective moisture diffusivity of beetroot strips during thin layer convective drying is comparable to that of effective moisture diffusivity during drying of other agriculture products [38,42,46-49]. The drying conditions such as product moisture content, air velocity, drying temperature and power level were affect significantly the effective moisture diffusivity of onion slices during infrared radiation drying[42]. The effective moisture diffusivity of hazelnuts was increasing from $2.301 \times 10^{-7}$ to $11.759 \times 10^{-7}$ $m^2/s$ with increase in roasting temperature ranging from 100 to 160 °C and it is high compared to that drying. This was due to the higher roasting temperature compared to that drying temperature[16]. The effective moisture diffusivity is markedly affected by the processing conditions during convective drying of carrot. It is increased with air velocity and drying air temperature, the peeling and blanching has enhanced the effective diffusivity of carrot[38]. The effective moisture diffusivity markedly affected by drying conditions such as drying air temperature, air velocity, moisture content, pretreatments, nature of the product, its moisture content, shape and size and air mass flow.

The effective moisture diffusivity of beetroot strips was increased markedly with increase in drying air temperature and the variation was described by Arrhenius equation which can be represented as follows.

$$D_{eff} = D_0\ Exp\left[\frac{-E_a}{RT}\right] \qquad (7)$$

The activation energy ($E_a$) is evaluated by the method of least square approximation. The activation energy for moisture diffusion was found to be 30.08 KJ/mol. The magnitude of activation energy for moisture diffusion during drying of beetroot strips was comparable to that of other agricultural during drying[38-39,46-48]. Gaston[50], *et al.* reported that the activation energy of moisture diffusion was markedly affected by moisture content and shape of grain during thin layer drying of wheat. The activation energy for moisture diffusion was significantly affected by drying air velocity as well as maturity stage during air drying of mango and is decreased with increase in drying air velocity. Half ripe mango showed lower activation energy compare to that of green mango[51]. The activation energy of beetroot pulp dehydration is about 24.37 KJ/mol which may be due to nature of material[10]. Elmas[52], *et al.* reported the average activation energy for moisture diffusivity is 28.183 kJ/mol for drying of jujube (*Zizyphus jujuba*) slices at different air velocities. The activation energy was 17.14 kJ/mol, 32.33 kJ/mol, and 35.14 kJ/mol for blanch, citric acid, and control samples during thin layer drying of broccoli[53]. The activation energy of moisture diffusion during drying is depended on air velocity, pretreatment, product size and shape. This study is very helpful in understanding of drying behaviour of beetroot strips at different drying air temperatures and is essential to design suitable drying equipment in large scale industrial production.

## 4. CONCLUSIONS

The falling rate characteristic was observed during drying of beetroot strips. The results indicated that Page's and modified Page's equations were suitable to describe the drying behaviour of beetroot strips. The effective moisture diffusivity ($D_{eff}$) was increased with increase in drying air temperature of beetroot strips during convective drying. The effect of drying air temperature on effective moisture diffusivity ($D_{eff}$) was described by Arrhenius equation and activation energy ($E_a$) for moisture diffusion is 30.08 kJ/mol. The drying kinetic parameters of Page's and modified Page's equations were significantly affected by drying air temperature. The drying rate constants were increased significantly ($p<0.05$) whereas exponents ($n$) of models decreased significantly ($p<0.05$) with drying air temperature during drying of beetroot strips. The equilibrium moisture content ($M_{eq}$), drying rate constants ($k_P$ and $k_{MP}$) and exponent ($n$) of the models equation were modelled with drying air temperature. These results are useful in standardisation and optimisation of drying process of beetroot strips for development of dehydrated vegetable curry and other products

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## ACKNOWLEDGEMENT

Authors thank Director, Defence Food Research Laboratory, Siddarthanagar, Mysore, India for constant encouragement and permission for publication of this research work.

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