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ORIGINAL ARTICLE

# Validation of drying models and rehydration characteristics of betel (*Piper betel* L.) leaves

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**Abstract** Effect of temperature on drying behaviour of betel leaves at drying air temperatures of 50, 60 and 70°C was investigated in tunnel as well as cabinet dryer. The L* and b* values increased whereas, a* values decreased, as the drying air temperature increased from 50 to 70°C in both the dryers, but the colour values remained higher for cabinet dryer than tunnel dryer in all cases. Eleven different drying models were compared according to their coefficients of determination ($R^2$), root mean square error (RMSE) and chi square ($\chi^2$) to estimate drying curves. The results indicated that, logarithmic model and modified Page model could satisfactorily describe the drying curve of betel leaves for tunnel drying and cabinet dryer, respectively. In terms of colour quality, drying of betel leaves at 60°C in tunnel dryer and at 50°C in cabinet dryer was found optimum whereas, rehydration at 40°C produced the best acceptable product.

**Keywords** Betel leaves · *Piper betel* · Tunnel dryer · Cabinet dryer · Drying models

## Introduction

Fresh leaves of betel vine (*Piper betel* L.) popularly known as *Paan* in India are consumed by 15–20 million people in India. About 66% of this production is contributed by West Bengal (Guha 2006). Betel leaf is an aromatic plant and used as a masticatory along with lime and arecanut for its flavour and nutrition. The vine is dioecious, shade loving perennial root climber. There are about 100 varieties of betel vine in the world, of which about 40 are found in India. The leaves are aromatic, warm, pungent and sharp in taste. The fresh leaves are exported to Nepal, Canada, Gulf and European countries. There is a high wastage of leaves during storage and transportation. The losses due to spoilage range between 35 and 75% (Rao and Narsimhan 1997). Moreover, the surplus leaves, if not disposed off properly may cause environmental pollution and health hazards. Wastage may be minimized by drying the leaves for further value addition and by extraction of essential oil from the surplus betel leaves. This oil may be used as an industrial raw material for manufacturing medicines, perfumes, mouth fresheners, tonics and food additives. The betel leaves contain anti-carcinogens showing promise for manufacturing of a blood cancer drug (Guha 2006).

Dehydration is an essential method of processing of betel leaf that can avoid spoilage and facilitate preservation. Shade drying of betel leaves in dark rooms is a time consuming process, resulting into a product with inferior quality. Sun drying is widely practiced, but prolonged direct exposure to solar radiation leads to adverse changes in colour, texture and flavour, contamination with sand, soil and foreign matter (Adom et al. 1997; Midilli 2001). Because of these reasons, using hot air dryers seems inevitable for drying to improve the quality of the final product (Doymaz and Pala 2002; Ertekin and Yaldiz 2004). Many researches on the mathematical modeling of thin layer drying of garlic (Madamba et al. 1996), red pepper (Doymaz and Pala 2002), purslane (Kashaninejad and Tabil 2004), eggplant (Akpinar and Bicer 2005; Ertekin and Yaldiz 2004), onion (Sarsavadia et al. 1999), mint and dill leaves (Doymaz 2006) and parsley leaves (Doymaz et al. 2006) have been conducted. Available literature on drying and rehydration characteristics of betel

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**Table 1** Selected drying models for describing thin layer drying behaviour of betel leaves

| Model name | Model equation | References |
|---|---|---|
| Newton | MR = exp(-kt) | Bruce 1985; Yaldiz and Ertekin 2001 |
| Page | MR = exp(-kt$^n$) | Diamante and Munro 1993; Doymaz and Pala 2002; Kar and Gupta 2003; Friant et al. 2004 |
| Modified Page | MR = exp[-(kt)$^n$] | Overhults et al. 1973; White et al. 1981 |
| Henderson and Pabis | MR = a exp(-kt) | Zhang and Litchfield 1991 |
| Logarithmic | MR = a exp(-kt) + c | Yagcioglu et al. 1999 |
| Two term | MR = a exp(-k$_o$t) + b exp(-k$_1$t) | Henderson 1974 |
| Wang and Singh | MR = 1 + at +bt$^2$ | Wang and Singh 1978 |
| Approximation of diffusion | MR = a exp(-kt) + (1-a) exp(-kbt) | Yaldız and Ertekin 2001 |
| Verma et al | MR = a exp(-kt) + (1-a) exp(-gt) | Verma et al. 1985 |
| Modified Henderson and Pabis | MR = a exp(-kt) + b exp(-gt) + c exp(-ht) | Karathanos 1999 |
| Two-term exponential | MR = a exp(-kt) + (1-a) exp(-kat) | Sharaf-Eldeen et al. 1980 |

leaves is scanty. This study therefore investigated the effect of drying air temperatures on betel leaf quality using tunnel and cabinet dryers.

## Materials and methods

Fresh betel (*Piper betel* L.) leaves were procured from local market. The stem and rotten leaves were removed manually. After washing, the surface water was drip dried and cleaned leaves were cut into 25±0.2 mm size.

*Drying equipments* The thin-layer drying experiments were performed in a pilot plant cross-flow tunnel dryer and cabinet dryer. The tunnel dryer (NSW-600, Narang Scientific Works, New Delhi) consisted of a tunnel, electrical heater, fan and a temperature controller (30 to 110°C, dry bulb temperature). The speed of tunnel was fixed at 0.004 m/sec. The samples were dried in multiple passes in the dryer. It took 8 min for the trays to complete a single passage in the tunnel. The cabinet dryer (M/s Standard Instruments Corporation, Patiala, India) was equipped with an electrical heater, fan and temperature indicators. It consisted of trays (800×400×30 mm), temperature controller (0–300°C, dry bulb temperature) and a centrifugal fan for airflow (1.2 m/sec).

*Drying experiment* The initial moisture content of the fresh betel leaves was determined (AOAC 1990). Air-drying temperatures of 50, 60 and 70°C were selected. The sample size was kept constant at 100±1 g for each run. After dryers reached steady-state for the set temperature, the cut betel leaves were distributed uniformly in the mesh trays. Moisture loss was recorded at every 10 min interval during drying, till the constant weight was achieved. The drying experiment was repeated twice for all the experimental conditions. The dried samples were cooled at normal room temperature (30±2°C), packed in polyethylene bags (film thickness 90 μm) and sealed.

*Colour measurement* The colour of dried leaves was measured by Hunter colour measuring system (Hunter colour difference meter, Miniscan XE plus, Hunter Associates Laboratory Inc., Reston, VA). As the surface area of the dried leaves was less than the light port of colourimeter, the dried leaves were ground in a laboratory grinder (Sujata, New Delhi, India) and passed through 80 mesh sieve to obtain fine powder of uniform particle size. The colourimeter was calibrated and a cylindrical plastic dish (58 mm diameter and 15 mm depth) containing sample was placed at the light port. The colour was measured in 2 replications in terms of L*, a* and b* coordinates, where L* is the lightness (0 = black, 100 = white), a* for the red-purple (positive values) to the bluish-green (negative values) and b* indicates the yellowness (positive values) and blueness (negative values). L* and a*/b*values were used as an index to report the colour quality (Shi et al. 1999).

*Mathematical modeling of drying curves* The moisture ratio and drying rate of betel leaves were calculated

**Table 2** Effect of temperature on Hunter colour characteristics of dried betel leaves

| Dryer type | Drying air temp, °C | L* | a* | b* | a*/b* |
|---|---|---|---|---|---|
| Tunnel | 50 | 42.5 | 0.21 | 4.5 | 0.101 |
| | 60 | 38.5 | 0.65 | 6.3 | 0.103 |
| | 70 | 39.6 | 1.09 | 6.4 | 0.169 |
| Cabinet | 50 | 44.6 | 1.14 | 5.9 | 0.193 |
| | 60 | 38.4 | 2.77 | 6.1 | 0.457 |
| | 70 | 28.0 | 2.34 | 6.5 | 0.359 |

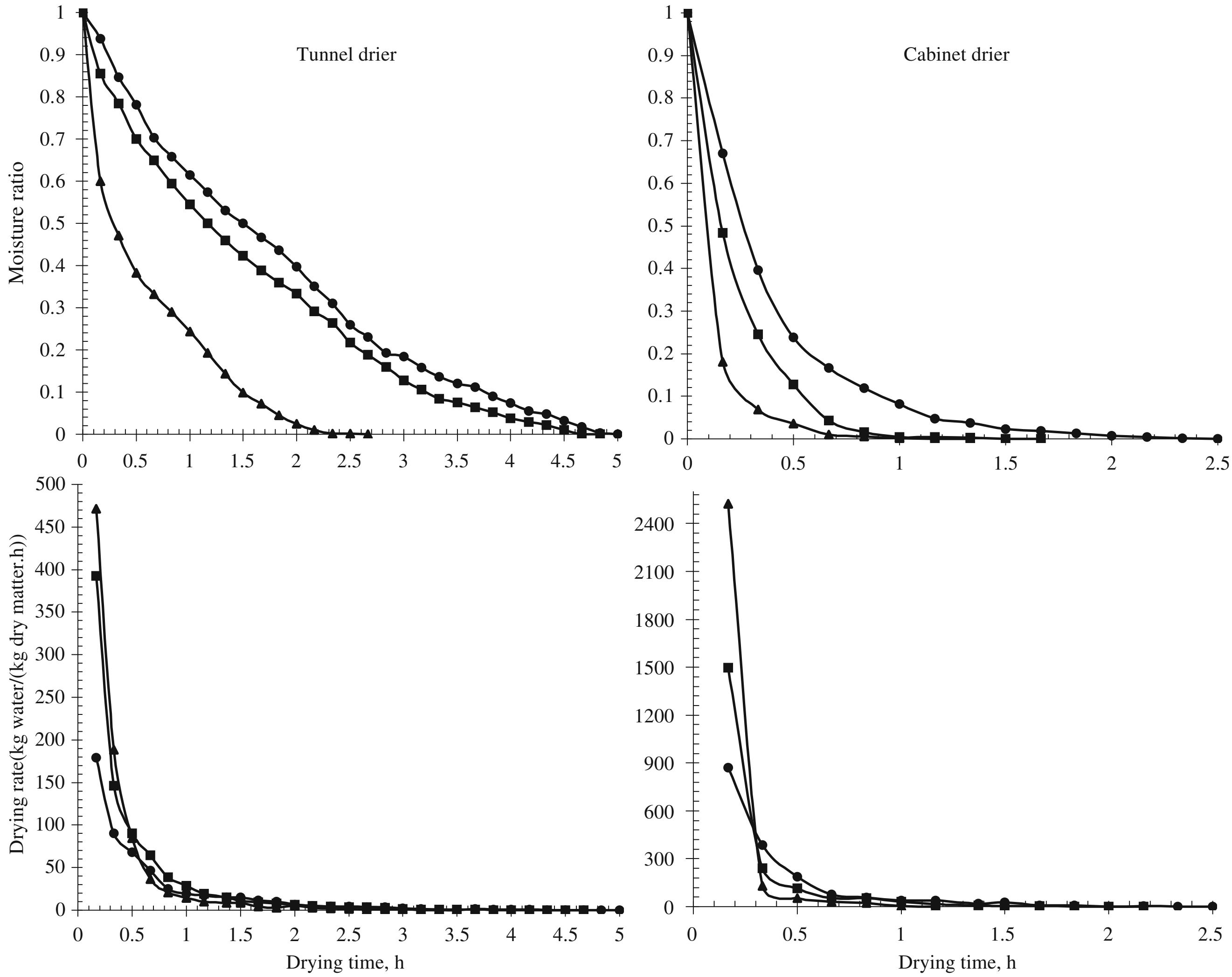


**Fig. 1** Variations of moisture ratio and drying rate of betel leaves at different temperatures (50ºC (●), 60ºC (■), 70ºC (▲)) in tunnel and cabinet driers

**Table 3** Values of drying constants and coefficients of different models for betel leaves dried in tunnel dryer at 60°C

| Model name | Constants | $R^2$ | RMSE | Chi square |
|---|---|---|---|---|
| Newton | k=0.0094764 | 0.979 | 7.74392 E-4 | 1.60219 E-3 |
| Page | k=0.0078742, *n*=1.038187364 | 0.979 | 7.56443 E-4 | 1.62095 E-3 |
| Modified Page | k=0.0094099, *n*=1.0381860 | 0.979 | 7.56443 E-4 | 1.62095 E-3 |
| Henderson and Pabis | k=0.0092516, a=0.9766796 | 0.980 | 7.45297 E-4 | 1.59707 E-3 |
| Logarithmic | k=0.0060207, a=1.1256985, c=-0.1986304 | 0.994 | 2.30524 E-4 | 0.51228 E-3 |
| Two term | $k_0$=0.0092516, a=0.4990909, b=0.4775887, $k_1$=0.0092516 | 0.980 | 7.45299 E-4 | 1.71992 E-3 |
| Wang and Singh | a=−0.0069540, b=0.0000126 | 0.976 | 8.88072 E-4 | 1.90301 E-3 |
| Approximation of diffusion | k=0.0088057, a=1.0024316, b=−1.4139041 | 0.989 | 8.88072 E-4 | 1.97349 E-3 |
| Verma et al | k=0.0094764, a=0.5023159, g=0.0094764 | 0.979 | 4.00846 E-4 | 0.89077 E-3 |
| Modified Henderson and Pabis | k=0.1171242, a=1.000453201, b=−0.8552030, c=−0.2442101, g=−0.116907412, h=0.0395036 | 0.980 | 7.74389 E-4 | 1.93597 E-3 |
| Two term exponential | k=0.2980154, a=0.0308066 | 0.980 | 7.45292 E-4 | 1.59705 E-3 |

$R^2$: Coefficients of determination, RMSE: root mean square error

**Table 4** Values of drying constants and coefficients of different models for betel leaves dried in cabinet dryer at 50°C

| Model | Constants | $R^2$ | RMSE | Chi square |
|---|---|---|---|---|
| Newton | k=0.0426741 | 0.996 | 1.4101 E-4 | 3.01187 E-4 |
| Page | k=0.0316553, *n*=1.0892743 | 0.997 | 0.9781 E-4 | 2.23649 E-4 |
| Modified Page | k=0.0420094, *n*=1.0892743 | 0.997 | 0.0078 E-4 | 2.23639 E-4 |
| Henderson and Pabis | k=0.0434226, a=1.0189290 | 0.996 | 0.0127 E-4 | 2.91375 E-4 |
| Logarithmic | k=0.0435527, a=1.0183582, c=0.0009276 | 0.996 | 0.0125 E-4 | 3.13324 E-4 |
| Two term | $k_0$=0.0434226, a=0.5899973, b=0.4289316, $k_1$=0.0434226 | 0.996 | 0.0121 E-4 | 3.39937 E-4 |
| Wang and Singh | a=−0.0214404, b=0.0001050 | 0.856 | 0.5591 E-4 | 7.78571 E-4 |
| Approximation of diffusion | k=4.3661385, a=−7.4809150, b=2.8308922 | 0.375 | 2.4777 E-4 | 9.90228 E-4 |
| Verma et al | k=0.0426740, a=0.4999994, g=0.0426741 | 0.996 | 0.0141 E-4 | 3.47524 E-4 |
| Modified Henderson and Pabis | k=0.0434224, a=0.3671054, b=0.3259117, c=0.3259117, g=0.0434271, h=0.0434227 | 0.996 | 0.0127 E-4 | 4.07925 E-4 |
| Two term exponential | k=0.0529812, a=1.5816747 | 0.997 | 0.0104 E-4 | 2.36822 E-4 |

$R^2$: Coefficients of determination, RMSE: root mean square error

using the following equations (Akpinar and Bicer 2005),

$$\text{Moisture ratio} = \frac{M - M_e}{M_o - M_e} \quad (1)$$

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{d_t} \quad (2)$$

where M = moisture content at any given instant, % db, $M_e$ = equilibrium moisture content, % db, $M_o$ = initial moisture content, % db, $M_t$ = moisture content at *t*, % db and $M_{t+dt}$ = moisture content at $t + dt$, % db.

For mathematical modeling, the thin layer drying equations presented in Table 1 were tested to select the best model for describing the drying curves of betel leaves. The regression analysis was performed using SPSS 7.5 (1996, SPSS Inc, Chicago, IL, USA) for selecting the best equation to explain the drying curve. Different drying models were compared according to their coefficients of determination ($R^2$), root mean square error (RMSE) and chi square ($\chi^2$) to determine the best fit. These critical parameters were calculated as follows.

$$\chi^2 = \sum_{i=1}^{N}\left[\frac{\left(MR_{exp.i} - MR_{pre.i}\right)^2}{(N - n)}\right] \quad (3)$$

$$RMSE = \sum_{i=1}^{N}\left[\frac{\left(MR_{exp.i} - MR_{pre.i}\right)^2}{N}\right]^{1/2} \quad (4)$$

where, $MR_{exp.i}$ is the ith experimentally observed moisture ratio, $MR_{pre.i}$ is the predicted moisture ratio, N is the number of observations and n is the number of constants of each respective model (Akpinar et al. 2003).

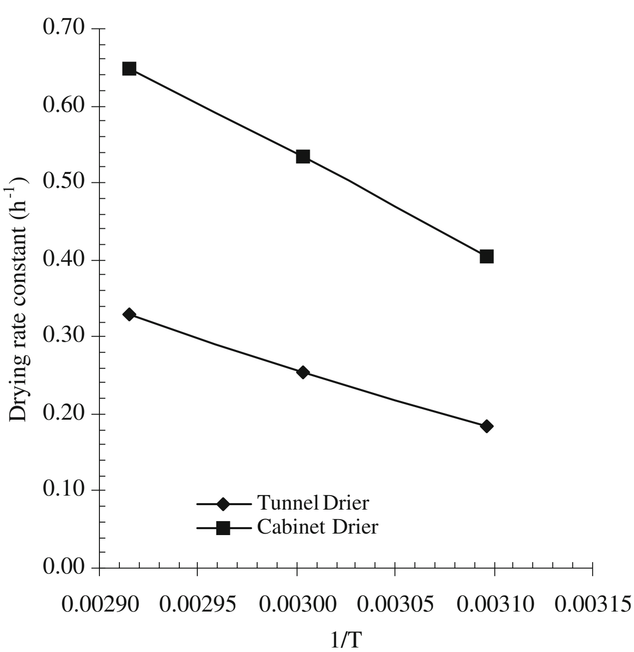


**Fig. 2** Temperature dependence of the drying rate constant

**Table 5** Effect of temperature on drying characteristics of betel leaves

| Type of dryer | $K_0$ ($h^{-1}$) | E (kJ $mol^{-1}$) | $R^2$ |
|---|---|---|---|
| Tunnel | 95.9164 | 11.1643 | 0.9912 |
| Cabinet | 14.4202 | 6.6737 | 0.9876 |

$R^2$: Coefficients of determination

**Table 6** Values of rehydration coefficients of betel leaves at different temperatures

| Type of dryer | Rehydration temp, °C | K ($h^{-1}$) | n | $R^2$ |
|---|---|---|---|---|
| Tunnel | 25 | 0.4321 | 0.3655 | 0.9565 |
| | 40 | 0.5563 | 0.3447 | 0.9734 |
| | 80 | 0.6158 | 0.3827 | 0.9884 |
| Cabinet | 25 | 0.4219 | 0.4047 | 0.9719 |
| | 40 | 0.5370 | 0.3946 | 0.9542 |
| | 80 | 0.5506 | 0.3357 | 0.9613 |

$R^2$ : Coefficients of determination

Modeling the drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationships between different variables, especially those for which no established empirical relationship exists. In this study, the relationships of the constants of the best suitable model with the drying air temperature were also determined (Yaldiz et al. 2001). The model is said to be good if $R^2$ value is high, $\chi^2$ and RMSE values are low (Sarsavadia et al. 1999; Togrul and Pehlivan 2002). The Arrhenius law was used to relate the dependence of the rate constant (k) on drying air temperature expressed by the following relationship,

$$k = k_0 \exp\left(\frac{-E}{RT}\right) \quad (5)$$

where $k_o$ = slope, E = activation energy, kJ $mol^{-1}$, $R$ = universal gas constant, T = temperature, kelvins.

*Rehydration ratio* Rehydration was carried out by immersing dried betel leaves in distilled water maintained at 25, 40 and 80°C. Approximately 5 g of dehydrated leaves were added to 150 ml of distilled water, agitated and then allowed to rehydrate. At every 30 min intervals, leaves were removed from water, drained, and weighed. The moisture content of the rehydrated leaves was determined. The experiments were carried out in duplicate and their average values are reported.

## Results and discussion

*Colour measurement* Colour is an important quality parameter in determining the leaf quality. It was observed that L* and b* values increased whereas, a* values decreased as the drying air temperatures increased from 50 to 70°C in all cases (Table 2). The L* values remained higher whereas, a/b values remained lower in cabinet dryer at all drying temperatures. The higher L* value and lower a*/b* values are desirable in the dried products (Shi et al. 1999). Thus, on the basis of these observations, drying at 60°C in tunnel dryer and 50°C in cabinet dryer was found optimum.

*Mathematical modeling and drying characteristics of betel leaves* The drying rate decreased continuously throughout the drying period (Fig. 1). It is obvious that constant rate of drying was not observed and drying of the betel leaves took place in falling rate period. These results are in good agreement with the earlier studies reported by Senadeera et al. (2003) on beans, potato and peas by Akpinar and Bicer (2005) on eggplant and by Doymaz (2005) on green beans. Experimental results showed that drying air temperature is an effective parameter for drying of betel leaves. It was observed that as the drying air temperature increased, other drying conditions being same, moisture removal increased and this resulted in substantial decrease in drying time. Several authors reported similar findings for various biological materials (Doymaz and Pala 2002; Ertekin and Yaldiz 2004; Kashaninejad and Tabil 2004.)

The moisture content data at different drying air temperatures was converted to more useful moisture ratio and the curve fitting computations with the drying time were done by using the 11 drying models as given

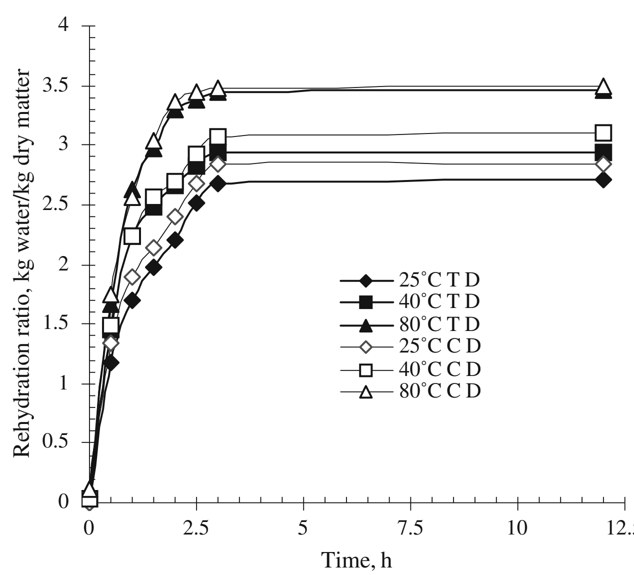


**Fig. 3** Rehydration of betel leaves dried at 60°C in tunnel drier (TD) and at 50°C in cabinet drier (CD)

in Table 1. The results of statistical analyses undertaken on these selected models are given in Tables 3 and 4. Three criterions for adequacy of the model fit such as $R^2$, RMSE and $\chi^2$ were used to validate the models. The best model describing the thin layer drying characteristics of betel leaves was chosen as the one with the highest $R^2$ value but lowest RMSE and $\chi^2$ values. Based on this criterion, the comparison of 11 models showed that logarithmic model gave the best fit for tunnel drying of betel leaves whereas modified Page model was the best for cabinet drying of leaves.

*Effect of temperature on drying characteristics* The total time of drying reduced substantially with the increase in temperature of hot air (Fig. 1). Dependence of rate constant (k) on temperature is shown in Fig. 2. The results indicate that Arrhenius law might be used to relate the dependence of the rate constant on drying air temperature. Similar findings have been reported for tomato seeds (Sogi et al. 2003). The computed values of activation energy (E) and slope ($k_o$) for both tunnel and cabinet dryer at different drying air temperatures are given in Table 5. It could be observed that in both types of dryers, the activation energy varied significantly. However, the activation energy and $K_o$ for tunnel dryer was recorded as 11.1643 kJ $mol^{-1}$ and 95.9164, whereas the corresponding values for cabinet dryer was 6.6737 kJ $mol^{-1}$ and 14.4202.

*Rehydration characteristics* The calculated value of k, n, and their respective $R^2$ for betel leaves rehydrated at various temperatures are given in Table 6. It could be observed that rehydration ratio was affected significantly at all the selected rehydration temperatures of 25, 40 and 80°C (Fig. 3). However, the rehydration ratio at 80°C was more rapid than 25°C and 40°C in all the cases, but rehydration ratio was always observed higher for the betel leaves dried using cabinet dryer as compared to tunnel dryer. It might be attributed to detrimental effect of temperature due to longer exposure of drying air temperature in tunnel dryer that caused the caramalization of sugar, and thus resulted into clogging of pores on the surface. This leads to lower diffusion of water through the surface during rehydration. The rehydration ratio increased significantly within the initial period, but slowed down gradually. The same trend was observed in green and red peppers (Ertekin 2002). Though the rehydration rate at 80°C always remained higher (Fig. 2), the colour of the product deteriorated at this temperature at the end of the rehydration process due to leaching. However, the colour of betel leaves rehydrated at 25 and 40°C resembled those of fresh ones but the samples rehydrated at 40°C produced best acceptable rehydrated product.

## Conclusion

Drying of betel leaves indicated that drying took place in the falling rate period in tunnel and cabinet dryers. The drying time reduced considerably in cabinet dryer as compared to tunnel dryer. The comparison of 11 models showed that Logarithmic model was the best for tunnel drying whereas, modified page model was the best for cabinet drying of betel leaves. The drying rate constant (k) ranged between 0.1850 and 0.3302 $h^{-1}$ for tunnel dryer and 0.4041 and 0.6471 $h^{-1}$ for cabinet dryer, while dimensionless coefficient (n) varied between 0.1134 and 0.1252, and 0.2061 and 0.4317 for tunnel and cabinet dryer, respectively. In terms of colour characteristics, drying betel leaves at 60°C in tunnel dryer and 50°C in cabinet dryer produced the best acceptable product rehydrated at 40°C.

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